Optimizing Fabrication Parameters for Carbon and Hemp Fiber Reinforced Bio-Composites in Automotive Applications: A Study using Response Surface Methodology

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ABSTRACT:

Composite materials with carbon fibre and hemp fibre reinforcing (CF-HF) have recently become more popular in the dynamic automotive sector as a greener and more cost-effective substitute for synthetic materials. Using a polymer matrix reinforced with carbon and hemp fibers, this novel class of bio-composite can effectively substitute traditional, non-renewable reinforcing elements. Composites made of carbon and hemp fibers were created in this Research using the vacuum-assisted resin infusion (VARI) technique. To find the best fabrication settings for CMCF-HF, the Taguchi experimental design approach was used with an L27 orthogonal array matrix. Additionally, the Response Surface Methodology (RSM) was utilised for achieving the optimal response value. The experimental factors included NaOH treatment (3, 6, 9 wt. %), post curing temperature (90, 120, 150°C), water absorption test durations (8, 16, 24 hours) and fiber types (Carbon Fiber, Hemp Fiber and a Carbon-Hemp Fiber blend). The results of this study revealed an optimised set of manufacturing parameters for CMCF-HF using RSM. Combinations X3Y3Z3 and X3Y3Z2 were determined to be the most successful, with the former producing an average flexural strength (FS) and impact strength (IS) of 94.8650 MPa and 0.241 J/mm², respectively. Researchers found that impurities and voids had a detrimental effect on the composites' mechanical properties.

KEYWORDS:

Carbon fiber; Hemp fiber; Flexural strength; Impact strength; Response surface methodology; Taguchi method

1. Introduction

Composite materials used in vehicles are the focus of research and development at the moment, due to the industry's meteoric rise in popularity. The extensive use of synthetic materials in industrial operations leads to high production costs and environmental impact [1]. The need to find affordable alternatives to synthetic fibers that do not sacrifice environmental friendliness or mechanical quality has arisen due to the negative economic and environmental impacts of these fibers. Natural fibre is an eco-friendly and practical material that is used as reinforcement in many industrial applications and bio-composites are no exception [2]. The low production costs, safety, environmental friendliness and high mechanical strength of composites bonded with natural fibers have led to their development as a synthetic alternative [3]. The referenced material states that natural fibers have certain disadvantages. Uses requiring high temperature resistance, significant water absorption or strong material strength are not appropriate for these [4].

The stalks of the Cannabis sativa plant are spun into fibers that are spun into hemp fabric, which is a sort of textile that is utilized to create ropes, bags and carpets. For bio-composite fabrication, hemp is a good fibre reinforcing material since it is inexpensive, readily available, quickly manufactured, easily processed and highly preferred by customers. Because it is less harmful to the environment than synthetic fibers, hemp has been the preferred natural fibre for reinforcing thermosets and

thermoplastics for nearly 20 years. Hemp fibre may be a cost-effective reinforcement material for high-fill rate composites [5]. Prior studies have investigated composites that incorporate hemp fibre reinforcements. Composites reinforced with hemp and vetiver fibers and based on epoxy have had their mechanical properties studied. Five unique composite laminates were created using vetiver and hemp fibers in different quantities using the hand lay-up method. Researchers found that the epoxy composite's qualities were enhanced when vetiver and hemp fibers were hybridised [6]. Hemp fibre may be responsible for the enhanced mechanical capabilities of the fiber-reinforced composites, according to Research [7]. Additionally, a multi-hybrid bio-composite made of epoxy, hemp natural fibers and Echinoidea spike particles extracted from Azadirachta indica is created and studied.

The mechanical characteristics of the composite were enhanced by incorporating sea urchin particles with a treated surface and hemp fibers, as demonstrated by the results [8]. The addition of sea urchin bio-ceramic filler improved the thermal stability of the neem epoxy biocomposites, as demonstrated by the thermal effects. The scanning electron microscopy analysis confirmed the filler's homogeneous distribution and the epoxy's enhanced adherence to the hemp fibre [9]. Hemp composites based on epoxy and incorporating cellulose nanofibers and nano clays are investigated for their effects on mechanical, morphological, thermal and dynamic mechanical properties [10]. Since carbon is abundant and cheap compared to other natural fibers, using it as a filler in composites can save manufacturing costs. In the production of CF-HF reinforcements, carbon fibre is among the most often utilized bast fibre kinds [11]. Carbon fiber's mechanical characteristics, durability and the impact of surface modification in epoxy composites have all been studied [12]. Surface modification's impact on epoxy composites reinforced with carbon fibers' characteristics and durability was the subject of Research.

Carbon fibers are now more compatible with hydrophobic epoxy matrices thanks to surface treatments. Any changes to the surface, whether from alkali treatment, silane treatment, or both, are considered [13]. It was discovered that the composite's enhanced mechanical and thermal properties were caused by the matrix's remarkable interfacial adhesion with the fibers. The fibre composite absorbed less water after being chemically treated than it would have without treatment. Composites' mechanical and thermomechanical properties were significantly diminished after contact with water [14]. Fiber breakdown and interface delamination may cause this to occur in a composite sample when it is submerged in water [15]. The next step is to investigate composites made of carbon fibre and graphene nanotubes. New fibre structure with significantly improved mechanical properties and performance was found to be natural carbon fibre coated with graphene nanotubes [16]. The physico-mechanical properties of epoxy-based hybrid composites reinforced with carbon and unidirectional banana fibers are subsequently investigated [17].

The mechanical properties of composites produced from a single natural fibre to those of composites produced from a hybrid of banana and carbon fibers.

When compared to results from composites comprised of individual fibers, the results from hybrid composites are more encouraging. This Research will provide a thorough account of how the experimental method is used in conjunction with the hybrid approach of Taguchi-Response Surface Methodology (TQ-RSM). Natural fiber-reinforced composites experimental approaches using the TQ-RSM hybrid methodology are still in their infancy. Practically, RSM and Taguchi should be seen as complementary approaches in this study; when combined, their respective strengths-the optimisation notion in RSM and the robust concept in Taguchi-will allow for a happy medium. This work can be used as an additional reference for Researchers, practitioners and enterprises in the automotive sector to optimise CMCF-HF manufacture using the TQ-RSM hybrid technique.

2. Experimental methodology

Reinforcement and matrix are the two fundamental building blocks of composites. The Bisphenol-A epoxy resin used here serves as the matrix. Hemp and Carbon fiber are used as the matrix. Table 1 gives the properties of materials used in this study. When exposed to air and moisture, the mechanical characteristics of natural Fibers decrease. This moisture must be eliminated or reduced with the use of alkaline treatment techniques [18]. The natural Fibers were washed and soaked for two hours at room temperature in warm water and a NaOH solution. In addition to improving the fiber's mechanical properties and increasing its surface roughness, the alkaline treatment also removes the fiber's waxy covering, lignin, oil and dirt. Samples were adjusted and incubated with 3, 6 and 9 wt. % NaOH for a duration of 4 hours according to the following protocols. Because of the risk of textural deterioration, hemp fibre should not be treated with a NaOH solution higher than 10 % [19]. The fibre was rinsed with distilled water to remove any residual sodium hydroxide solution after air drying for 24 hours. The composite plate underwent post-curing treatment following its manufacturing. After the Fibers have cured, their water content will have decreased. By post-curing, the modulus, strength and residual stress of polymers and composites can be enhanced. In this study, the post-curing treatments were conducted for 2 hours at temperatures of 90°C, 120°C and 150°C.

Table 1: Properties of materials

Property	Bisphenol epoxy resin	Carbon fiber	Hemp fiber
Density (g/cm³)	1.1 - 1.2	1.75 - 1.95	1.48
Water absorption (%)	0.8 - 2	0.1 - 0.2	8 - 12
Elongation at break (%)	5 - 7	1.5 - 2.5	1.6 - 3.0
Young's modulus (GPa)	2 - 4	200 - 700	70 - 80
Thermal conductivity (W/mK)	0.17 - 0.20	10 - 50 (along fiber axis)	0.04 - 0

Table 2 gives the correlations between the three regulating variables and its processing levels. Taguchi experimental design technique was implemented using Minitab 19's L27 OA matrix. Reducing the duration and cost of trials while retaining their dependability was the goal of employing Taguchi's experimental approach [20, 21]. Taguchi method offers a systematic and effective

way to improve the experimental factors with far less effort than other optimisation methodologies. Taguchi analysis also made use of the SN ratio to identify the parameters that had a substantial impact on the outcomes. When optimising process parameters, three SN ratio qualities were considered: "Smaller the better," "Larger the better" and "nominal is the best". The experimental setup of the L27 orthogonal array is shown in Table 3. This study used the SN ratio as an optimisation process parameter and applied the "larger is better" principle to it. A response of interest is generated in RSM by combining statistical and mathematical methods with system modelling and issue analysis. This response is influenced by several things, including the desired result [22]. To find the optimal course of action, RSM meticulously analyses carefully constructed trial situations. Using RSM, this study investigated the impact of various CMCF-HF production parameters on the tensile and bending strengths of the material. Countless academic disciplines rely on second-order polynomial functions.

Table 2: Input factors and its level

| Factor	Level		
	1	2	3
NaOH treatment (X)	3 %	6 %	9 %
Post curing temperature (Y)	90°C	120°C	150°C
Type of fibre (Z)	CF	HF	CF-HF

Table 3: L27 Orthogonal array design of experiments

NaOH treatment (%)	Post-curing temperature (°C)	Type of fibre
3	90	HF
3	90	HF
3	90	HF
3	120	CF
3	120	CF
3	120	CF
3	150	CF-HF
3	150	CF-HF
3	150	CF-HF
6	90	CF
6	90	CF
6	90	CF
6	120	CF-HF
6	120	CF-HF
6	120	CF-HF
6	150	HF
6	150	HF
6	150	HF
9	90	CF-HF
9	90	CF-HF
9	90	CF-HF
9	120	HF
9	120	HF
9	120	HF
9	150	CF
9	150	CF
9	150	CF

A specimen with dimensions of 140×12×3 mm (ASTM D 790-03) was used to measure the flexural strength (FS) as per the ASTM recommendations. The ASTM D 256-10 (IZOD) specified specimen, measuring 127×10×3 mm [23], was used to assess the impact strength (IS). Figs. 1(a-b) shows the outline of the flexural and impact testing machine arrangement. Table 4 gives the outcomes of the 27 individual investigations that

included flexural and impact testing. A factor value devoid of encoding represents the parameter. One way to laminate a bio-composite is using the vacuum-assisted resin infusion (VARI) approach, as shown in Fig. 2. Use of VARI for manufacturing a composite laminate composed of hemp, carbon fiber and resin, reduces the void content of the laminate [24,25]. Mechanical performance is negatively affected when composite laminates contains a high void content.

Table 4: Experimental results of L27 orthogonal array

NaOH treatment (%)	Post-curing temperature (°C)	Type of fibre	FS (MPa)	IS (J/mm^2)
3	90	HF	67.352	0.270
3	90	HF	35.297	0.241
3	90	HF	41.264	0.265
3	120	CF	68.412	0.135
3	120	CF	72.418	0.137
3	120	CF	74.649	0.972
3	150	CF-HF	72.449	0.165
3	150	CF-HF	76.128	0.178
3	150	CF-HF	75.497	0.192
6	90	CF	58.124	0.91
6	90	CF	64.812	0.125
6	90	CF	54.297	0.981
6	120	CF-HF	69.412	0.125
6	120	CF-HF	69.401	0.139
6	120	CF-HF	72.459	0.146
6	150	H	93.514	0.181
6	150	CF-HF	95.467	0.241
6	150	CF-HF	92.467	0.178
9	90	CF-HF	73.497	0.145
9	90	CF-HF	74.167	0.135
9	90	CF-HF	73.124	0.156
9	120	HF	73.135	0.214
9	120	HF	74.521	0.199
9	120	HF	71.468	0.182
3	150	CF	94.865	0.591
3	150	CF	65.147	0.834
3	150	CF	69.127	0.589
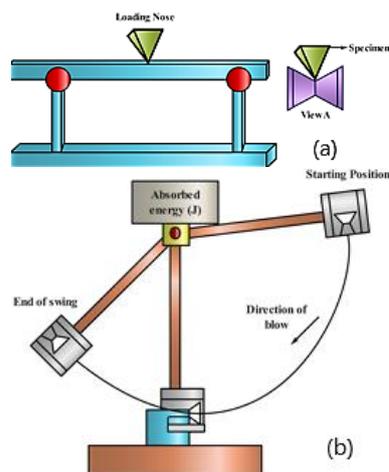
Fig. 1: Schematic diagram of (a) Flexural test and (b) Impact test
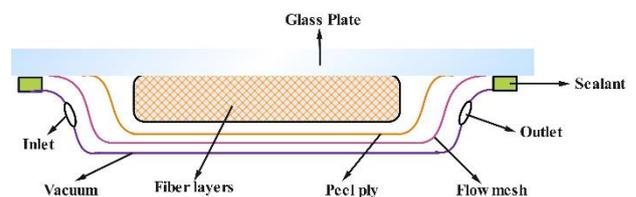
Fig. 2: Lamination steps of vacuum-assisted resin infusion

3. Results and discussions

The parameters for the most important SN ratio are given in Tables 5 and 6 to obtain the best value for the condition setting. The relationships between the various parameter values and their resulting effects and FSs are determined using multi-regression analysis. In order to find the best potential value, one should look at the maximum level of assurance (less than 5%). The effects of different variables on the parameters are examined. The optimum production factors for composites including natural fibre reinforcement are determined. The test specimen's fractures are examined under a microscope. Use of Taguchi's SN ratio became the basis of the analysis of variance. To study the scaling factor, one uses the ratio, since the standard deviation and mean strength values of a material change in a proportionate manner. The results of strength testing on composite materials made under different conditions are shown in Table 4. The CF-HF composite material's tensile strength was strong when the appropriate manufacturing. mix was used [26, 27]. The significance level for each parameter is determined using those results. By optimising the parameters, the SN ratio can be maximised.

Table 5: Response table for FS

| Control factor | X | Y | Z | X | Y | Z |
	S/N ratio for FS (dB)			Mean for FS (μm)		
Level 1	35.76	35.13	36.47	64.83	60.22	71.61
Level 2	37.25	37.11	36.60	74.44	71.76	69.10
Level 3	37.31	38.07	37.25	74.34	81.63	72.90
Delta	1.55	2.94	0.78	9.61	21.41	3.81
Rank	2	1	3	2	1	3

Table 6: Response table for IS

| Control factor | X | Y | Z | X | Y | Z |
	S/N ratio for IS (dB)			Mean for IS (μm)		
Level 1	-14.14	-14.01	-13.37	0.2839	0.3587	0.2190
Level 2	-15.00	-15.69	-10.95	0.3362	0.2499	0.5860
Level 3	-11.57	-11.01	-16.39	0.3383	0.3499	0.1534
Delta	3.43	4.67	5.44	0.0544	0.1088	0.4326
Rank	3	2	1	3	2	1

Increasing the SN ratio results in a stronger material if the best material strength value is determined by maximising the SN ratio [28]. Parameter quality is at its peak when material strength is at its maximum, as seen by this signal [29]. The optimal compositions for producing materials with high strength values, as determined by the SN ratio analysis as shown in Fig. 3, are $X_3Y_3Z_3$ and $X_3Y_3Z_2$ (IS and FS). The SN ratio in IS data was discovered to be considerably affected by factors such as alkaline content, impact curing temperature and fibre type. Selecting a low post-curing temperature and a low NaOH concentration were found to produce the optimal IS of the composite material [30]. A higher concentration of alkaline and a higher post-curing temperature both reduce the IS. According to Table 5 and 6, the type of fibre utilized has a favourable effect on the IS of hemp. Consequently, these features must be thoroughly examined in order to attain maximal IS. Statistical significance was checked for in the regression model's parameters and model coefficients using ANOVA. Tables 7 and 8 displays the ANOVA results alongside the experimental data for IS and FS. We can say with 95% confidence that the design of the experiment was effective.
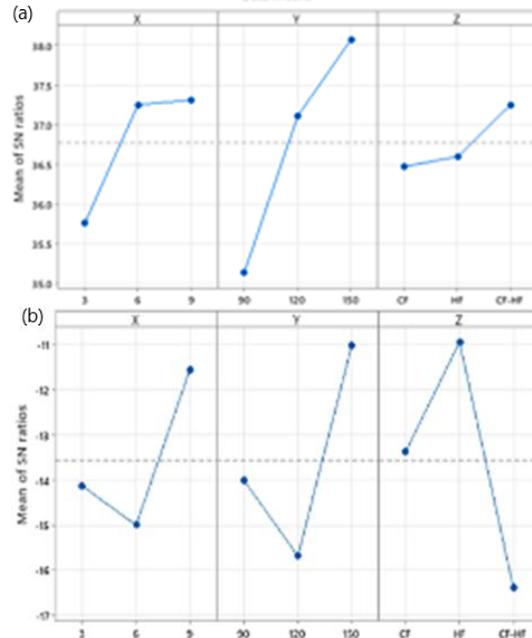
Fig. 3: Main effect SN Ratio plots for (a) FS, (b) IS

Table 7: ANOVA table for FS

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Model	8	3741.49	3741.49	467.69	7.00	0.000
X	1	406.94	406.94	406.94	6.09	0.024
Y	1	2063.50	2336.28	2336.28	34.98	0.000
Z	1	7.54	411.70	411.70	6.16	0.023
X*X	1	141.44	141.44	141.44	2.12	0.163
Y*Y	1	4.25	175.60	175.60	2.63	0.122
Z*Z	1	59.99	81.23	81.23	1.22	0.285
X*Y	1	532.03	988.51	988.51	14.80	0.001
X*Z	1	525.80	525.80	525.80	7.87	0.012
Error	18	1202.11	1202.11	66.78		
Total	26	4943.60				

Table 8: ANOVA table for IS

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Model	8	1.1203	1.1203	0.14004	2.62	0.043
X	1	0.0133	0.0133	0.01333	0.25	0.623
Y	1	0.0003	0.0248	0.02480	0.46	0.504
Z	1	0.0193	0.0030	0.00302	0.06	0.815
X*X	1	0.0037	0.0037	0.00378	0.07	0.793
Y*Y	1	0.0653	0.1046	0.10465	1.96	0.179
Z*Z	1	0.9589	0.5470	0.54705	10.24	0.005
X*Y	1	0.0175	0.0470	0.04702	0.88	0.360
X*Z	1	0.0416	0.0416	0.04166	0.78	0.389
Error	18	0.96129	0.96129	0.053405		
Total	26	2.08165				

The contribution value of a variable is considered while deciding its level of significance. The most essential parameters in determining the IS value, according to the research, are the concentration of NaOH (X) at 3.43%, the temperature after curing (Y) at 4.67% and the sort of fibre (Z) at 5.44%. The production process of CF-HF is thus more affected by the NaOH concentration. Similarly, the

most critical parameters impacting the FS value are X (1.55%), Y (2.94%) and Z (0.78%). Table. 7 displays the results of the experimental validation based on the optimal factors. For IS, the 95% confidence interval is 0.21%, whereas for FS, it is 5.23 % and 8.37%. Because of this, a 95% confidence interval is produced by the response validation test. A mathematical model can be used to determine the amount of influence as a percentage of the overall maximal material strength. An element's significance is proportional to its contribution value [31]. The second-order regression model [32] based on 3 variables that reflect production parameters (alkaline treatment, temperature of post curing process and kind of fibre) is given by,

$$FS = -190.7 + 20.61\,X + 3.19\,Y - 11.4\,Z - 0.539\,X*X - 0.00694\,Y*Y - 4.25\,Z*Z - 0.1647\,X*Y + 3.60\,X*Z \quad (1)$$

$$IS = 0.96 - 0.030\,X - 0.0492\,Y + 1.605\,Z - 0.0028\,X*X + 0.000169\,Y*Y - 0.349\,Z*Z + 0.00114\,X*Y - 0.0321\,X*Z \quad (2)$$

The R^2 values of 53.82 % for impact and 75.68 % for replication (flexural) show that the materials under examination are robust.

For a given set of design parameters, the two previously built regression models can reliably predict the material strength with an R^2 value near to 1. It is possible to predict the optimal parameter values using the RSM curvature and the desire function after building a second-order regression model and performing a variance analysis on the response data [33]. The impact of interaction elements on the material's strength through the use of a third-dimensional (3D) plot that closely resembles the second-order model [34] as shown in Fig. 4. X and Y are responsible for deciding an IS's FS, Z and X both have a hand in it. The interaction factor X*Y is the most crucial part of the material strength value. A statistically significant factor is one for which the P-value is less than 0.05.
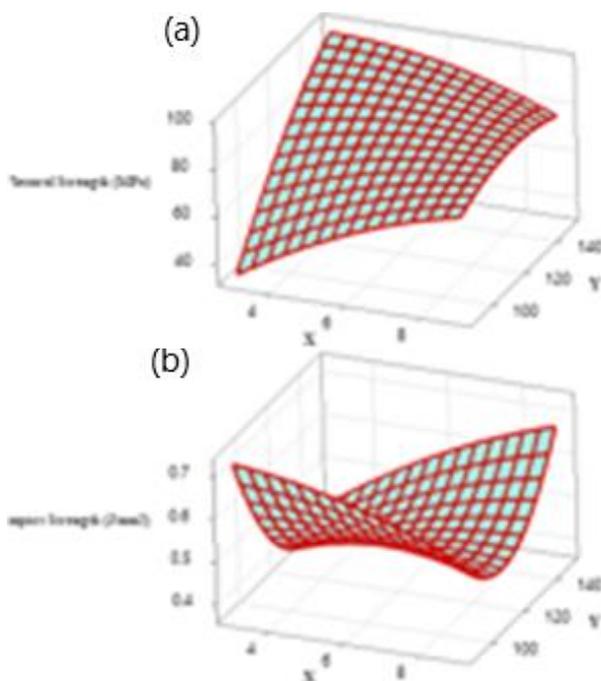
The desirability function can be used to predict parameter values using a second-order regression model and an ANOVA utilizing response data [35]. A larger number is favoured, according to the preference function. For all values of X, Y and Z, the desire function analysis yielded an ideal IS prediction of 0.241 J/mm². Similarly, the ideal FS is 94.865 MPa for the same X, Y and Z components with 1, 3 and 1 level. The material aims for an IS of 0.6996% and a FS of 1%. The ideal composition for the CF-HF production experiment was precisely and successfully identified using the Taguchi-RSM approach in this research [36]. Fig. 5 shows the desirability plot for FS and IS of the developed composites. Curing temperature and NaOH content increases the IS, as shown in the optimized response plot and interaction plot [37] Fig. 6(a-6). Nevertheless, the maximal IS decreases as the post-curing temperature and NaOH content are both raised. At the same time, response optimization plots show that for maximum FS, a higher post-curing temperature is necessary [38]. To get the required mechanical properties, all of these parameters are adjusted. Alternatively, the 0.028 J/mm² impact test specimen does not include any defects, such as holes or contaminants [39]. Consistent results were seen in the flexural test specimen. Consequently, the mechanical qualities are diminished when impurities and spaces are present. Our findings agree with earlier research [40,41] that found that impurities and gaps could impact the material's mechanical properties. The presence of more impurities and voids will lead to a decline in the material's mechanical properties.
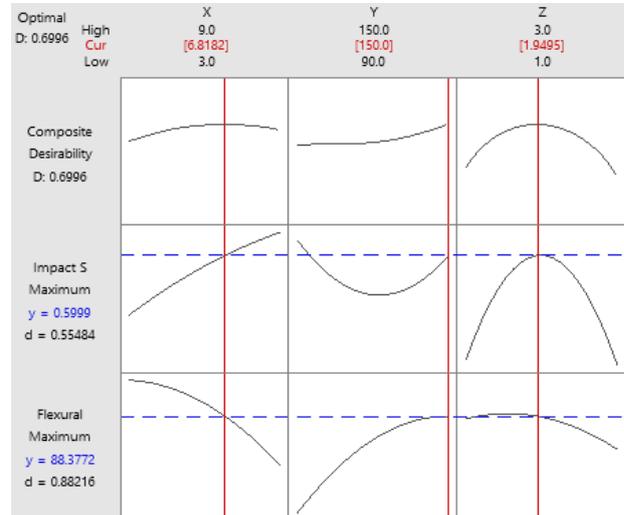

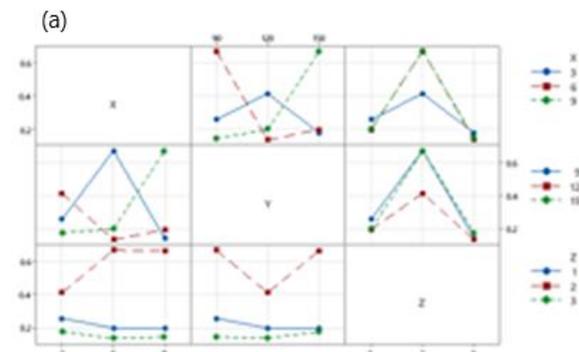**Fig. 5: Desirability plot for FS and IS**

Fig. 4: RSM Plot for X vs. Y: (a) FS, (b) IS
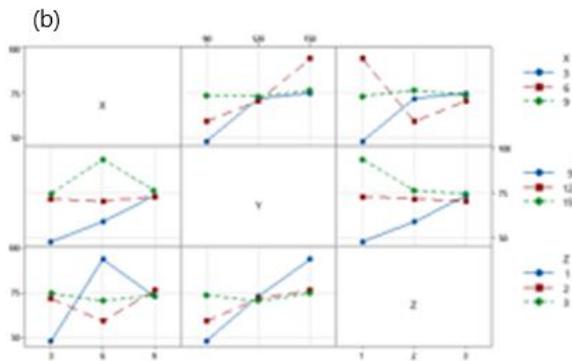

Fig. 6(a): Interaction plot - IS

Fig. 6(b): Interaction plot - FS

4. Conclusions

This study optimizes the manufacturing parameters of CF-HF using Taguchi and RSM methodologies. A FS of 94.865 MPa and an IS of 0.241 J/mm^2 were determined as the ideal material strengths according to the Taguchi method. The ideal combination is $X_3Y_3Z_3$ (FS); $X_3Y_3Z_2$ (IS). Using the RSM and the composite desirable approach, the optimum production parameters for hemp fiber according to the VARI method were found to be 0.241 J/mm^2, 90°C post-curing temperature and 3% NaOH concentration, resulting in a desirability (dF) of 0.6996. Also, using the parameters for a 4% NaOH concentration, you can get a carbon fibre type with a desire (dF) of 1.0, an average FS of 94.865 MPa with a temperature of 120°C. Because of this, the main parameters affecting IS accounted for 93 % of the effect, while FS accounted for 100%.

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