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Effect of loading parameters on mechanical properties of ABS-HIPS-Kenaf composite via full factorial

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ABSTRACT

Natural fiber-reinforced polymer composites (NFRPCs) are becoming a sustainable alternative to traditional synthetic composites, with benefits in environmental impact and biocompatibility. This study examines the mechanical properties of NFRPCs using kenaf fibers in acrylonitrile butadiene styrene (ABS) and high-impact polystyrene (HIPS) matrices. The effects of fiber content, polymer matrix, and compatibilizer (MAPP) on elastic modulus and elongation at break were analyzed through a full factorial experimental design. Mechanical testing followed ASTM D638 standards, using a universal testing machine (UTM). Results showed that maximum composite's elastic modulus can be obtained by using the optimum parameters of the interaction between kenaf and MAPP; and kenaf and matrix only. As for maximum composite's ductility, the optimum parameters are kenaf at lower loading, MAPP at higher loading and matrix of ABS.

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1.0 INTRODUCTION

Natural fiber reinforced Polymer composites (NFRPC) have gained significant attention due to their enhanced biocompatibility and sustainability compared to traditional synthetic fiber-reinforced composites [1-4].

Several studies have explored the use of natural fibers in polymer composites, highlighting their potential for improved environmental and biological compatibility. For instance, Ramamoorthy et al. investigated the mechanical properties of polypropylene composites reinforced with banana fibers and found that the natural fiber-based composites exhibited enhanced tensile and flexural properties compared to the neat polymer [5]. Similarly, Ismail et al. reported that kenaf fiber-reinforced polylactic acid composites demonstrated improved thermal stability and biodegradability [6]. These studies demonstrate the growing interest in utilizing natural fibers to develop more sustainable and eco-friendly composite materials. The study using polymer matrix such as acrylonitrile butadiene styrene mixed with kenaf fiber and high impact polystyrene (HIPS) shows the influence of fiber loading on the mechanical properties of NFRPC [7-8].

Kenaf fibre is a natural cellulosic fibre derived from the kenaf plant, which has gained attention as a promising reinforcing filler in polymer composites due to its high specific strength, low density, and renewable nature [9-10]. Kenaf fibers are used in various commercial products such as high-quality papers, bio composites for car door trimmings, interior shelving, bioplastics, building materials such as medium-density fiberboard, textile, furniture, and many others have already been developed [11].

On the other hand, acrylonitrile butadiene styrene (ABS) is a petroleum hydrocarbon made from butane is butadiene mixed commercially with benzene and ethylene from coal to create styrene monomers [12]. ABS is one of the most widely used polymers because of its mechanical qualities, mechanical simplicity, and recyclable nature [13]. The mechanical properties for ABS are tensile strength, modulus elasticity, elongation at break. ABS has proven to be a popular choice due to its reliable tensile strength, which typically falls within the range of 32Mpa [14] to 44Mpa [15]. ABS has a moderate to high modulus of elasticity, ranging from 687 to 774.5 MPa [16]. ABS typically exhibits elongation at break is 7% [17].

Another matrix polymer is high-impact polystyrene (HIPS), that is typically made by radical polymerizing styrene monomer with polybutadiene rubber. This material is commonly used in the manufacture of toys, housewares, packaging, bottles, light-duty industrial components, and electronic gadgets [18]. High impact polystyrene (HIPS) is abundantly used as a matrix for biodegradable polymers. HIPS has the advantages of good impact resistance, low cost, and easy processing [19].

The mechanical properties of ABS and HIPS composites reinforced with kenaf fiber have been extensively studied to further enhance their performance and sustainability. The interactions between the polar kenaf fibers and the non-polar or relatively polar polymer matrices, such as ABS and HIPS, can significantly impact the mechanical performance of the resulting composites [20](Andrew et.al. 2022). In HIPS-ABS-Kenaf composites, the influence of factors like fiber loading, matrix composition, and processing conditions on the resulting mechanical performance is a topic of considerable interest. Therefore, the study aims to investigate the effect of various loading parameters on the mechanical properties of HIPS-ABS-Kenaf composites through a full factorial experimental design.

2.0 METHODOLOGY

2.1 Materials and equipment

The kenaf fibers from Lembaga Kenaf Negara are subjected to an alkaline treatment by immersing them in a 6 wt% NaOH solution (50g) and distilled water for 24 hours. Subsequently, the fibers are rinsed until neutral pH (pH 7) is achieved and then oven-dried at 40°C for an additional 24 hours. Post-treatment, the fibers are mechanically reduced to an average diameter of 150 μm for further application.

Polymer matrix ABS Toyolac 700 314 Grade and HIPS Idemitsu PS HT50 Grade are used. A polymer compatibilizer maleic anhydride grafted polypropylene (MAPP) by Sigma-Aldrich. The mixture of polymer matrix, kenaf fiber and compatibiliser are mixed in a Collin twin-screw extruder (Teach-Line ZK 25T). There are 18 mixtures ratio of matrix, fibre and compatibiliser at different loading are blended to create the composite compound. The extruder applies heat and mechanical shear to evenly disperse the fibers within the molten polymer. After moisture and volatiles are removed, the composite is shaped, cooled, and cut to the required lengths as shown in Figure 1.

Figure 1: HIPS-ABS-Kenaf blended compound

These blended compounds are then go to injection moulding process to produce ASTM D638 Type I tensile specimen. TOYO Ti-50GX injection moulding setting for specimen production is given in Table 1. INSTRON 3382 tensile test machine is used for mechanical tensile testing.

Table 1: Injection moulding setting

Injection Mould Parameter	Range
Melting Temperature (°C)	189-206
Mould Temperature (°C)	35-40
Injection Pressure (Bar)	118

2.2 Design of Experiment

A design of experiment by full factorial 2^3 with 3 replications is applied to investigate the effects of three factors, namely kenaf fiber, compatibilizer and polymer matrix loading as shown in Table 2. Kenaf fiber loading is vary between 10% and 20% by weight, MAPP compatibilizer is vary between 2.5% and 5% by weight and finally the polymer matrix is vary between ABS and ABS-HIPS make up to 100% by weight.

Table 2: Design of experiment by full factorial 3 by 2

Parameters	Level 1	Level 2
Kenaf Fiber	10	20
MAPP Compatibiliser	2.5	5
Polymer Matrix	ABS	ABS-HIPS

In the Design Expert software, a full factorial 2^3 design with 3 replications is used to assess the effects of three factors, each at two levels, on a response variable. This setup results in 24 experimental runs (8 combinations × 3 replications) to ensure reliable results. After the experiments, ANOVA (Analysis of Variance) is applied to determine the significance of the factors and their interactions. Table 3 presents all the experimental runs with their combination of factor levels.

Table 3: Factorial 2^3 Run ABS-HIPS

Experiment Run	Factor A	Factor B	Factor C
1	20	5	ABS-HIPS
2	20	5	ABS
3	20	5	ABS-HIPS
4	10	2.5	ABS-HIPS
5	10	5	ABS-HIPS
6	20	2.5	ABS
7	20	2.5	ABS-HIPS
8	10	5	ABS
9	10	2.5	ABS
10	10	5	ABS
11	10	5	ABS-HIPS
12	10	2.5	ABS-HIPS
13	10	5	ABS
14	10	5	ABS-HIPS
15	20	2.5	ABS
16	20	2.5	ABS
17	20	2.5	ABS-HIPS
18	20	2.5	ABS-HIPS
19	10	2.5	ABS
20	10	2.5	ABS
21	20	5	ABS
22	20	5	ABS-HIPS
23	10	2.5	ABS-HIPS
24	20	5	ABS

A p-value threshold of 0.05 is used to assess statistical significance, meaning that factors or interactions with p-values below 0.05 are considered significant. A log base 10 transformation of the response data also applied to stabilize variance and meet ANOVA assumptions. The transformed data is then analyzed, helping to identify key factors and interactions that influence the response, guiding optimization efforts.

3.0 RESULTS AND DISCUSSION

The design of experiment (DOE) was conducted to systematically investigate the influence of loading parameters on the mechanical properties of Natural Fiber Reinforced Polymer Composites (NFPRC), with a specific focus on elastic modulus and elongation at break. A full factorial design was employed to examine the effects of key variables, such as fiber content, matrix composition, and processing conditions, each at different levels. The choice of these factors was guided by their potential impact on the stiffness (elastic modulus) and ductility (elongation at break) of the composite material.

By varying the loading parameters across all possible combinations, the experimental design allowed for the assessment of both main effects and interactions between the factors. The mechanical properties were measured through standardized testing methods, and the data obtained was analyzed using ANOVA to determine the significance of each factor's contribution. A p-value threshold of 0.05 was set to identify statistically significant effects. This approach enabled the identification of optimal loading conditions that enhance the elastic modulus and elongation at break, contributing to the development of NFPRC with tailored mechanical performance.

3.1 Elastic modulus

The elastic modulus is a key indicator of a material's stiffness, reflecting how much it will deform under a given load. A higher elastic modulus means the material is stiffer and will deform less, while a lower modulus indicates more flexibility. The study investigates how varying fiber, matrix and compatibiliser loading will affect the elastic modulus of the composites.

Full factorial designs are a powerful and comprehensive method used in experimental design to study the effects of multiple factors on a response variable. This effect can be interpreted from the half-normal plot in Figure 2. The half-normal plot shows that interaction factor AC (Kenaf-Matrix) has the highest half-normal value indicating it has the greatest effect on the composite’s elastic modulus. This followed by interaction factor AB, BC and then all main factors A, B and C. AC is the interaction factor between kenaf and polymer matric loading. There is also indication of error from replicates. This is due to the value of pure error estimated is too small.

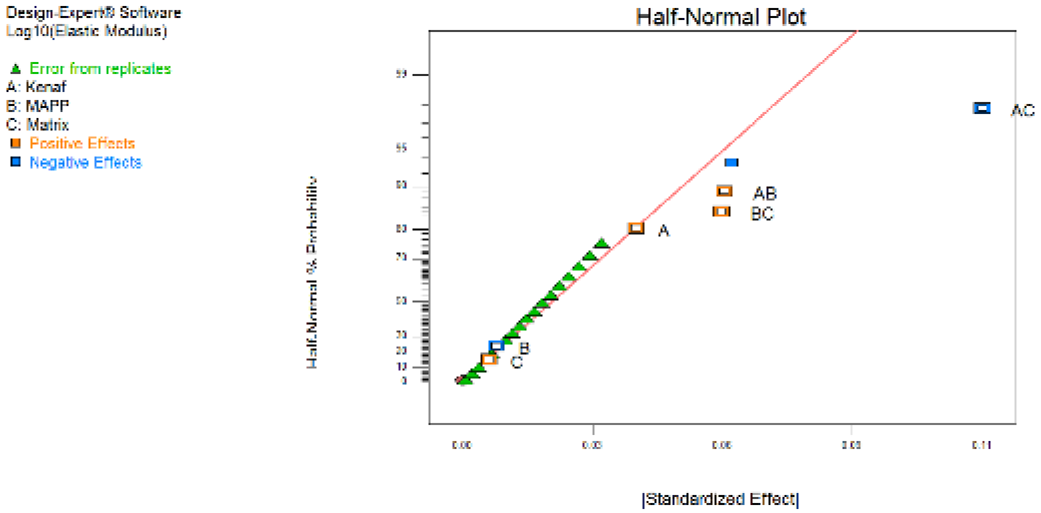

Figure 2: Half-normal plot against standardized effect

Referring to the normal probability plot in Figure 3, the data set conforms to a normal distribution. In this plot, the data points are plotted against a theoretical normal distribution. If the data are normally distributed, the points align closely with a straight line. Deviations from this line indicate potential departures from normality. A reference line is fitted to the data, and the degree of deviation from this line highlights the extent of any non-normality. Probability plots are an effective tool for assessing adherence to specific distribution assumptions. In this instance, all 24 collected data points exhibit minimal deviation from the reference line, indicating no significant departure from normality.

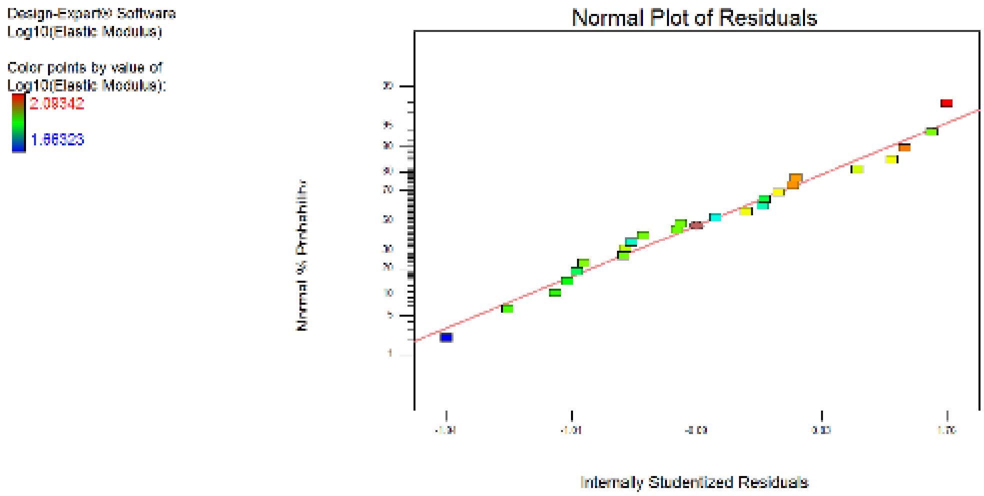

Figure 3: Normal probability plot of residuals

To identify the factors with the most significant impact on the composite's elastic modulus, the Pareto chart in Figure 4 is examined. The largest effect is attributed to the interaction between factors AC, followed by interactions AB, BC, and the main factors A, B, and C. The solid blue bar represents the interaction factor ABC, which is excluded from the ANOVA analysis.

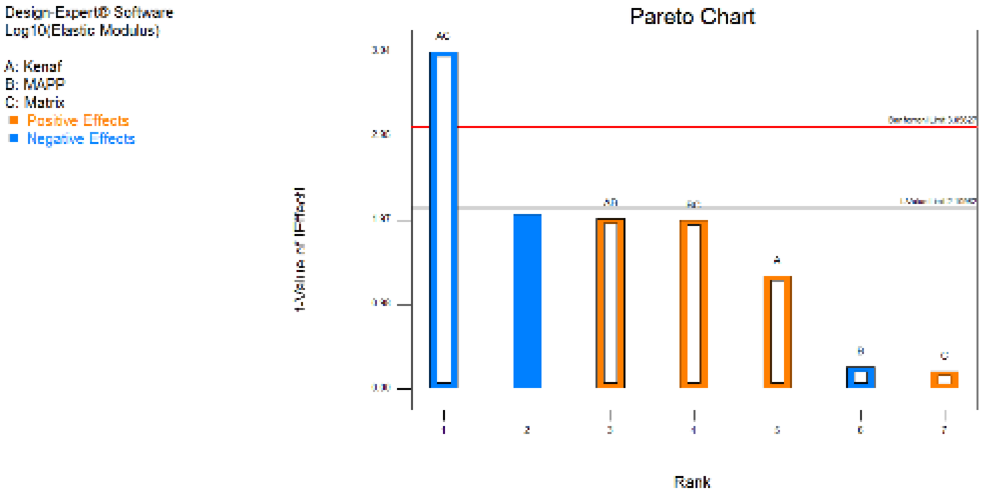

Figure 4: Pareto chart for elastic modulus response

None of the main factors alone significantly affect the composite's elastic modulus. However, factor A (kenaf loading) shows a higher effect than factors B and C. The positive effect of factor A indicates that increasing the kenaf content enhances the composite's elastic modulus.

Interactions AB and AC exhibit greater effects than the individual factor A, but AC has the highest influence. However, the interaction effect AC is negative, suggesting that a decrease in the interaction between kenaf and the polymer matrix would result in an increase in the elastic modulus. Conversely, the AB and AC interaction have a positive effect, meaning the combined influence of factors A and B; A and C also contributes positively to the elastic modulus.

The analysis of variance (ANOVA) for the elastic modulus of the ABS-HIPS-kenaf composite is presented in Table 4. Statistically, the quadratic model shows an F-value of 4.19 and a p-value of 0.0091, indicating that the model is significant. However, the main factors A, B, and C are not significant, as their p-values exceed 0.05, confirming the findings from the half-normal plot and Pareto chart.

Table 4: ANOVA analysis of elastic modulus for ABS-HIPS

Source	Sum of Squares	df	Mean Square	F Value	p-Value Prob>F	
Model	0.13	6	0.021	4.19	0.0091	significant
A-Kenaf	8.691E-003	1	8.691E-003	1.73	0.2061	
B-MAPP	3.281E-004	1	3.281E-004	0.065	0.8015	
C-Matrix	2.065E-004	1	2.065E-004	0.041	0.8419	
AB	0.020	1	0.020	3.94	0.0637	
AC	0.078	1	0.078	15.52	0.0011	
BC	0.019	1	0.019	3.86	0.0661	
Residual	0.086	17	5.030E-003			
Lack of fit	0.021	1	0.021	5.19	0.0368	significant
Pure Error	0.065	16	4.036E-003			
Cor Total	0.21	23				

Among the interaction factors, only AC is significant, with a p-value of 0.0011, while AB and BC, although showing positive effects in the Pareto chart, are not statistically significant. The lack of fit is significant relative to the pure error, suggesting that the model fits require further refinement that might be due to replication data.

Given that the interaction between factor A (kenaf loading) and factor C (ABS-HIPS matrix) is significant and has the largest negative effect on the elastic modulus, the interaction plot of AC in Figure 5 is examined. At lower kenaf loading (A), the ABS-HIPS blend (C) results in a higher elastic modulus. However, at higher kenaf loading, the elastic modulus is greater with the ABS matrix (C) alone. This behavior occurs because factor C represents a combination of ABS and HIPS, and ABS is more compatible with the natural fiber kenaf, despite its hydrophobic nature [20]. The inclusion of HIPS in the matrix negatively impacts the composite's performance when kenaf is added, making the ABS matrix more favorable for enhancing the elastic modulus at higher fiber content.

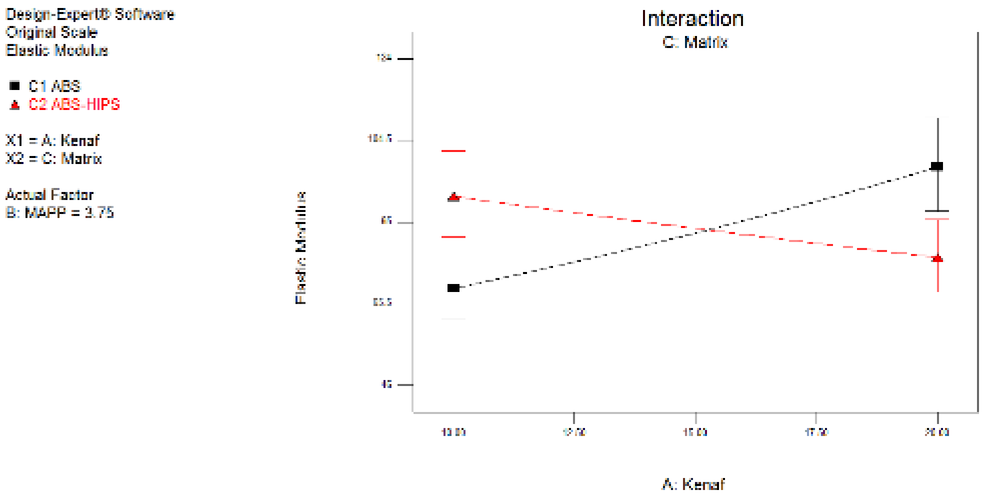

Figure 5: Interaction plot of AC

Those not significant factor is eliminated from the model. Thus, for maximum composite’s elastic modulus, the optimum parameters are the interaction between kenaf and MAPP; and kenaf and matrix only.

3.2 Elongation at break

Elongation at break is a critical mechanical property that measures a material's ductility, indicating how much it can stretch or deform before fracturing under tensile stress. It is particularly important in applications where flexibility, toughness, and the ability to absorb energy without breaking are essential. A higher elongation at break suggests that the material can undergo more significant deformation before failure, which is advantageous in impact-resistant and flexible applications.

The full factorial design aims to investigate the impact of various parameters on the mechanical property, specifically elongation at break. This is evaluated by examining the half-normal plot in Figure 6. The plot with the highest half-normal probability value indicates the factor with the greatest effect on elongation at break. Based on this analysis, factor C exhibits the largest influence, followed by the interaction factor BC, main factor A, interaction factor AC, main factor B, and finally, interaction factor BC. The green plots represent the error derived from replicate measurements.

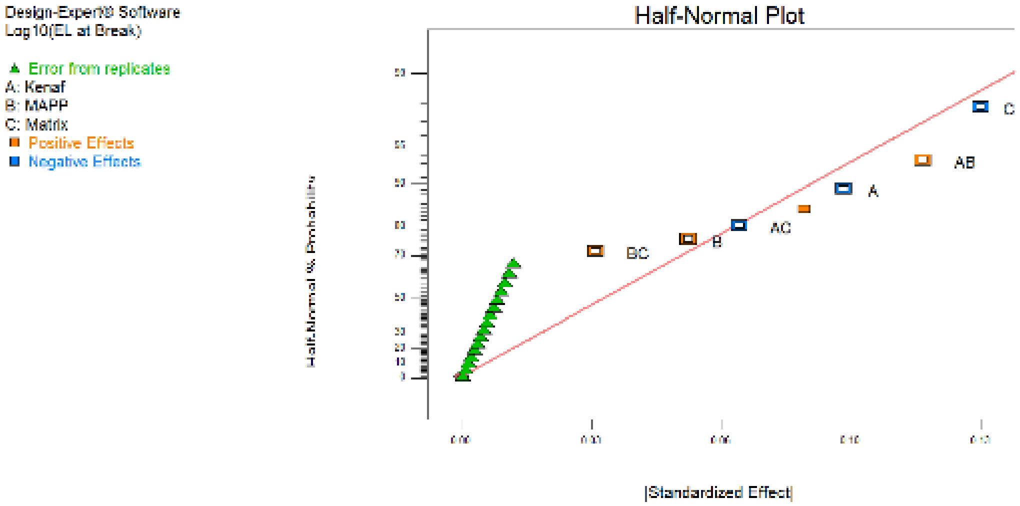

Figure 6: Half-normal plot against standardized effect

The normal plot of residuals in a full factorial design is a crucial diagnostic tool used to assess the validity of the model's assumptions, particularly to present the differences between observed and predicted values are normally distributed. This assumption is important for the reliability of statistical tests such as ANOVA and for the overall accuracy of the model.

Normal plot for ABS-HIPS-Kenaf composite’s elongation at break response is in Figure 7. All the 24 residuals are normally distributed, they are align closely with a straight reference line. There is no significant deviations from this reference line indicate that the residuals suggesting the model is accepted with no non-linearity, outliers, or incorrect factor levels.

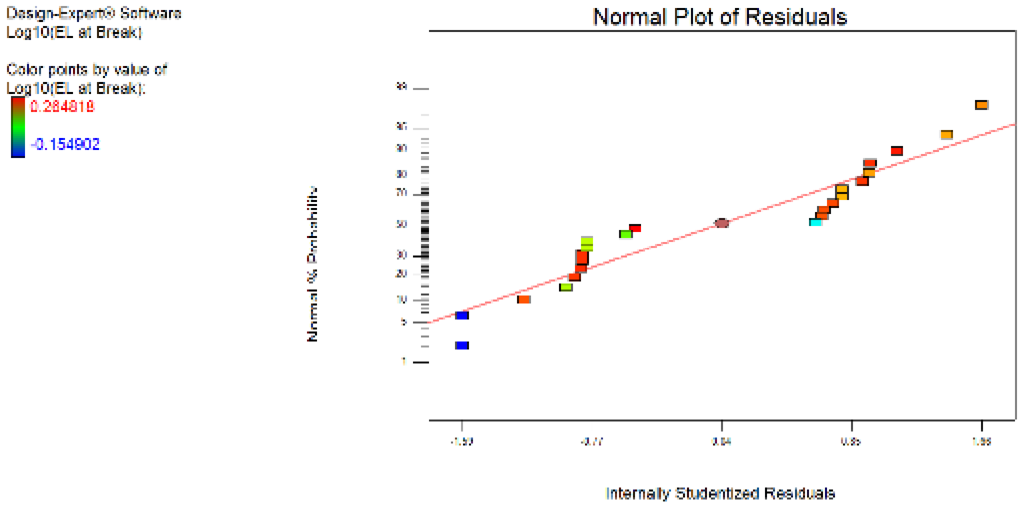

Figure 7: Normal probability plot of residuals

Another tool to measure the effect of parameters on composite's elongation at break is the pareto chart as shown in Figure 8. As seen in the chart the first rank that give the highest effect is main factor C (Matrix) followed by interaction factor AB, then main factor A (Kenaf), next in 5th ranked is interaction factor AC, then main factor B (MAPP) and lastly interaction factor BC. Do note that factor main factor C, A and interaction factor AC are all giving negative effect to the elongation at break. This means adding more C, or A or AC will reduce elongation at break of the composite even though they have high effect on this property.

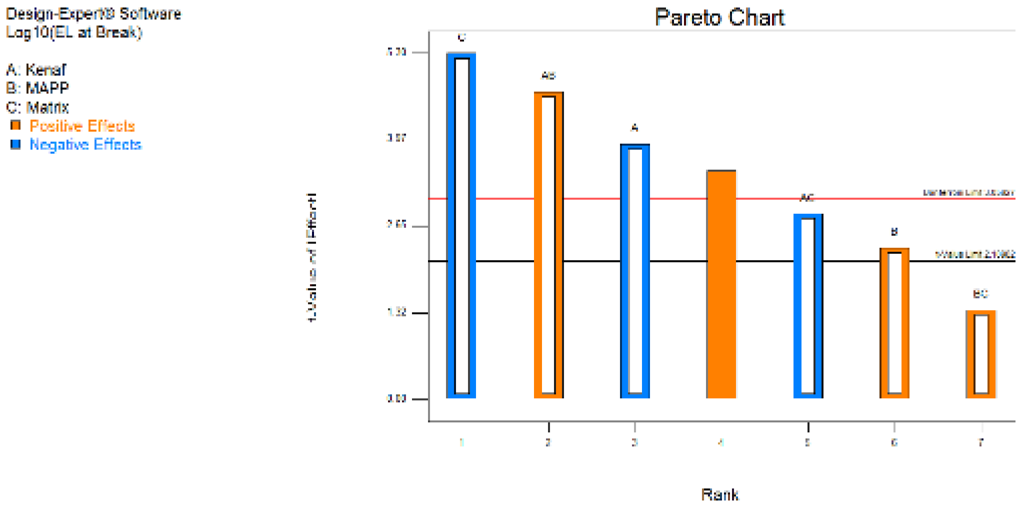

Figure 8: Pareto chart for elongation at break response

ANOVA statistical analysis for identifying which factors and interactions significantly influence the response variable and for optimizing experimental conditions. Table 5 is the ANOVA analysis for elongation at break of the composite. It shows that the model is significant with p-value <0.0001. All the main factors A (Kenaf), B (MAPP) and C (Matrix) are significant where these parameters give significant influence on the composite's ductility. As for the interaction factors, only interaction factor AB and AC are significant as the p-values of these interaction factors are less than 0.05. The lack of fit is significant relative to the pure error, suggesting that the model fits require further refinement that might be due to replication data.

Table 5: ANOVA analysis of elongation at break response

Source	Sum of Squares	df	Mean Square	F Value	p-Value Prob>F	
Model	0.28	6	0.046	13.47	<0.0001	significant
A-Kenaf	0.053	1	0.053	15.26	0.0011	
B-MAPP	0.018	1	0.018	5.36	0.0333	
C-Matrix	0.097	1	0.097	28.08	<0.0001	
AB	0.076	1	0.076	22.20	0.0002	
AC	0.028	1	0.028	8.05	0.0114	
BC	6.50E-003	1	6.50E-003	1.89	0.1871	
Residual	0.059	17	3.44E-003			
Lack of fit	0.042	1	0.042	41.20	0<.0001	significant
Pure Error	0.016	16	1.023E-003			
Cor Total	0.34	23				

The interaction factor AB is a positive significant factor. Figure 9 show the interaction plot between factor A (Kenaf) and factor B (MAPP). The plot indicates that at lower fiber loading, lower MAPP loading give higher ductility. On the other hand, at higher fiber loading, higher MAPP loading give higher ductility. This means that fiber and MAPP loading is directly proportional to the composite elongation at break.

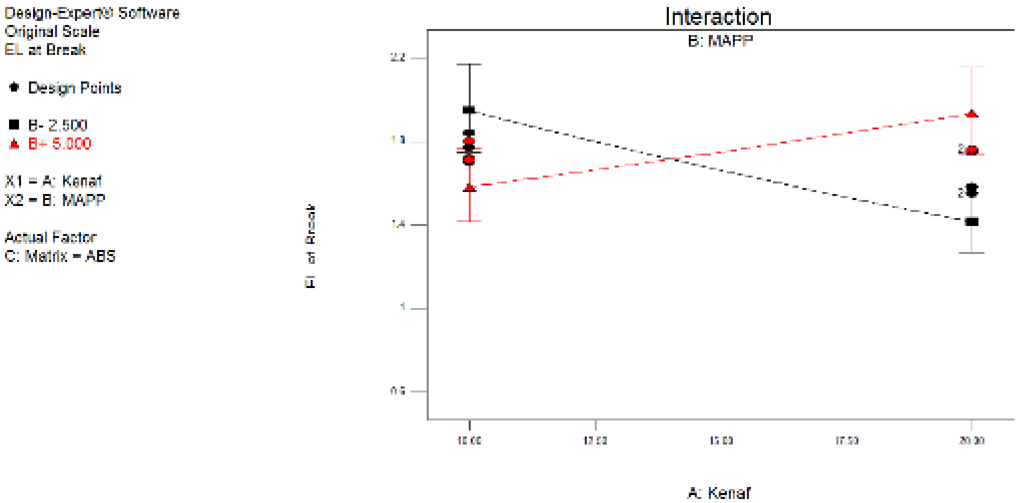

Figure 9: Interaction plot of AB

The interaction factor AC is ranked 5th on the pareto chart and exhibits a significant negative effect. The interaction plot between factors A (Kenaf loading) and C (Matrix) is shown in Figure 10. At both lower and higher kenaf loading levels, the ABS matrix dominates the composite's ductility. This indicates that the ABS matrix is more favorable for enhancing ductility in the composite, regardless of the kenaf content, suggesting that ABS contributes positively to the composite's flexibility.

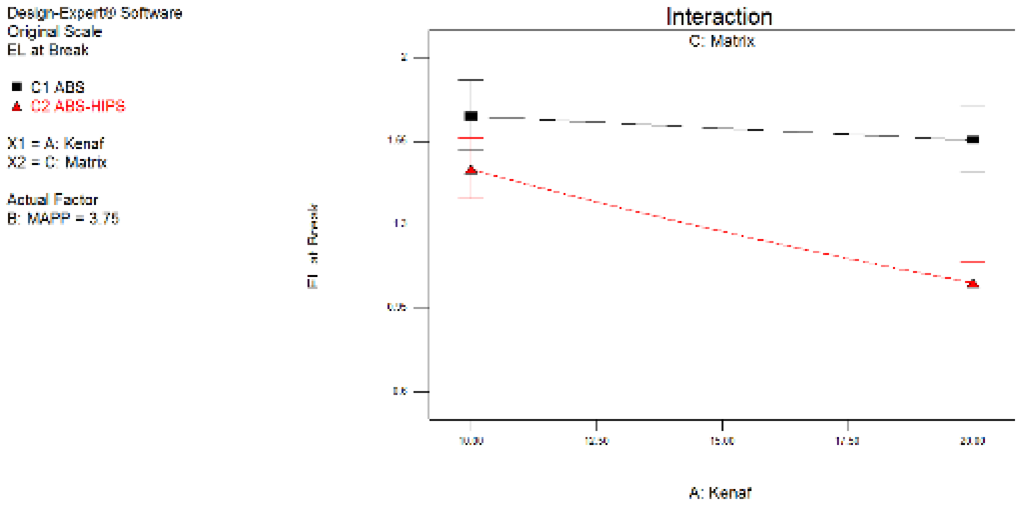

Figure 10: Interaction plot of AC

Those not significant factor is eliminated from the model. Thus, for maximum composite's ductility, the optimum parameters are A (Kenaf) at lower loading, B (MAPP) at higher loading and C (Matrix) at lower loading.

4.0 CONCLUSIONS

Natural fiber-reinforced polymer composites (NFRPCs) offer significant advantages in terms of sustainability and biocompatibility compared to traditional synthetic fiber composites. This study focuses on the mechanical properties of NFRPCs, particularly those reinforced with kenaf fibers in acrylonitrile butadiene styrene (ABS) and high-impact polystyrene (HIPS) matrices.

The results from the full factorial experimental design show that fiber, matrix, and compatibilizer loadings have notable effects on the mechanical properties, specifically the elastic modulus and elongation at break. The key findings include:

1. Elastic Modulus: The interaction between kenaf loading and polymer matrix significantly influences the elastic modulus, with higher fiber content in ABS yielding better stiffness. However, adding HIPS to the matrix tends to reduce stiffness at higher fiber content.
2. Elongation at Break: The ABS matrix enhances ductility, while higher fiber and compatibilizer loadings improve flexibility. Significant interactions between kenaf fiber and MAPP compatibilizer further contribute to increased elongation at break.

In conclusion, optimizing fiber, matrix, and compatibilizer content can tailor the mechanical properties of NFRPCs, providing a pathway to develop environmentally friendly materials with desired performance characteristics.

Author Contribution

N. Irfilzati Ruslan: Conduct experiment; N. Bahiyah Baba: Data analysis and discussion A. Mohd: Investigation and supervision, N. Azinee Said: Methodology, writing and editing; N. Ngah: Methodology, writing and editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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