Analysis and Optimization of Mechanical Properties of Biocomposites Reinforced with Kenaf Fibers/Graphene in the Presence of Compatibilizers

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ABSTRACT

This article examines the mechanical properties of bio-composites reinforced with kenaf fibers and nano-graphene within a polypropylene matrix by adding a compatibilizer. The response surface methodology with the Box-Behnken approach was used to investigate and present a mathematical model for the behavior of the bio-composite considering the parameters of fiber weight percentage, nano-graphene weight percentage, and compatibilizer weight percentage. The behavior of the samples was analyzed under tensile, bending, and impact tests, and the results were justified using FE-SEM. The fracture surface of the samples indicated that the main mechanism in improving the introduced bio-composite behavior is fiber fracture and fiber pull-out. Multi-objective optimization was carried out using two meta-heuristic methods and the desirability function. The optimization aimed to increase the flexural, impact, and tensile strength while simultaneously reducing the weight of the samples, with the weight percentages of the fibers, nanoparticles, and compatibilizer defined as the problem variables. The results showed that the bio-composite sample with the optimal design parameters has three mechanical properties, including tensile strength, impact strength, and flexural strength, equal to 28.5MPa, 92.29J/m, and 50MPa, respectively. Finally, the optimal state showed that the weight of the bio-composite sample could be reduced by up to 32%.

KEYWORDS

Mechanical Properties, Optimization, Design of experiment, Compatibilizer, Natural fibers

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1. Introduction

In recent years, the use of natural fibers in the production of environmentally friendly composite materials has gained attention in various industries due to their inherent properties such as high strength-to-weight ratio, good thermal properties, water impermeability, and biodegradability [1]. Several studies have explored these aspects. Shokrieh et al. [2], studied graphene/polypropylene nanocomposites, finding that adding 0.5% by weight of graphene increased impact strength by 30%, with the maximum impact strength observed at 0.5%, while higher percentages reduced impact properties. Aghnia Qasemi et al. [3], analyzed polypropylene/graphene/glass fiber/EPDM nanocomposites, finding that low percentages of graphene improved tensile strength and elongation, but higher percentages reduced these properties.

This study focuses on the mechanical properties of bio-composites reinforced with kenaf fibers and nano-graphene in a polypropylene matrix with a compatibilizer. Using the response surface methodology (RSM) with the Box-Behnken design (BBD), a mathematical model was developed to predict the behavior of the bio-composite based on the weight percentages of kenaf fibers, nano-graphene, and compatibilizer. The accuracy of regression equations was enhanced by using power functions and removing less impactful factors. Optimization methods calculated optimal parameter values, and field emission scanning electron microscope images examined damage mechanisms. The multi-objective optimization aimed to increase strength while minimizing the composite's weight, with the optimal values determined through the desirability function and shown on the Pareto front.

2. Materials and Methods

In this research, polypropylene (PP) produced by the Arak Petrochemical Company was used as the matrix material for composite samples. Kenaf fibers, with a diameter of 50 microns and a density of 750 kg/m³, entirely made of natural materials, were used as the reinforcing phase. According to the manufacturer, these fibers have a tensile strength of 240-930 MPa, a Young's modulus of 14-53 GPa, and an elongation at break of 1.6-2.9%. The compatibilizer, PP-g-MA, branded as PPG6060, was procured from Arya Polymer Pishgam Company (Iran). This compatibilizer is a polymeric material where "PP" refers to polypropylene and "g-MA" denotes grafted coupling with maleic anhydride. Maleic anhydride (MA) is a chemical compound used in polymer grafting processes to enhance polymer properties such as adhesion. According to the manufacturer, this compatibilizer has a melt flow index of 18 g/10 min. Graphene powder from XG Sciences (USA) was used as the nanoparticles in this study. Based on the product's technical data sheet, these nanoparticles have an average diameter of less than 5 microns, a thickness of 2 nanometers, a surface area of 750 m²/g, and a density of 2200 kg/m³.

3. Sample Fabrication

The composite samples were fabricated using the melt blending method with an internal mixer from HAAKE (USA) at a speed of 60 rpm and a temperature of 180°C. First, polypropylene was melted in the internal mixer. The compatibilizer was then added and mixed for 5 minutes. Next, graphene nanoparticles were gradually added, and the mixture was stirred at a lower speed of 20 rpm for 5 minutes, followed by mixing at 60 rpm for an additional 3 minutes. Finally, kenaf fibers were incrementally added at 20 rpm according to the specified weight percentage for each sample. After adding the fibers, the mixture was mixed at high speed for 5 minutes. The total mixing time for all samples was 18 minutes. Figure 1 schematically illustrates the sample fabrication process.

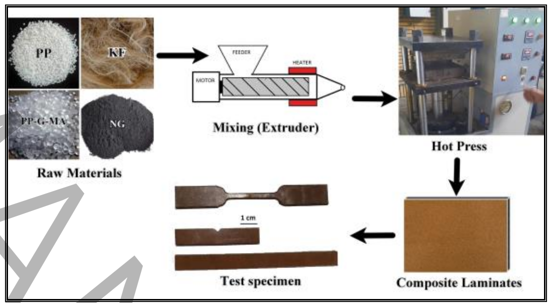


Figure 1. The process of making test samples

4. Discussion and Conclusion

Based on the experimental test results, the statistical analysis method is employed to analyze and examine the parameters and their effects on tensile, flexural, and impact strength.

5. Morphological Studies

Figure 3 clearly demonstrates the effect of the presence of a compatibilizer on the adhesion of fibers to the matrix material. In Figure 3-a, the sample without a compatibilizer shows that the low adhesion of fibers to the matrix material causes the fibers to pull out from the matrix, and the separation of fibers from the polymer is clearly visible. Additionally, the uniform dispersion of nanoparticles is apparent in this figure.

In contrast, Figure 3-b shows that in the sample with a compatibilizer, the adhesion of fibers to the matrix material is significantly improved, with the main mechanism for increased strength being the fracture of fibers and the matrix material. In this sample, the phenomenon of fiber pull-out from the matrix is not observed.

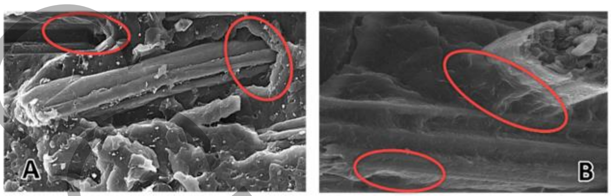
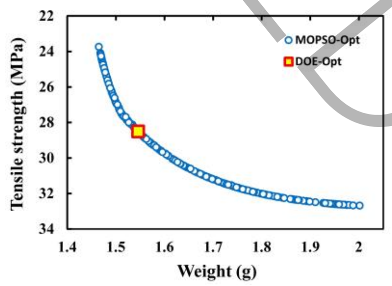


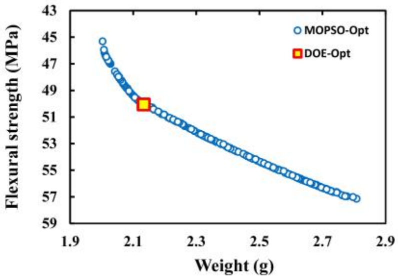
Figure 3. FE-SEM image taken from a) sample without compatibilizer and b) sample with compatibilizer presence

6. Optimization Results

Based on the optimization performed using Design Expert software and the MOPSO optimization algorithm, Pareto front charts obtained from the multi-objective optimization for tensile strength, flexural strength, and impact strength are presented. The optimal points for all three cases are shown in Figure 4.



a)



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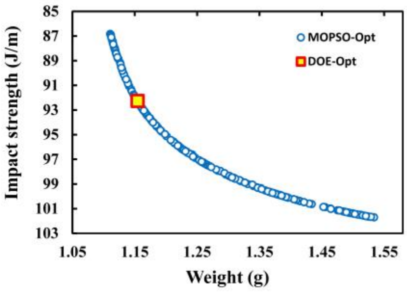

c)

Figure 4: Diagram of Pareto front optimal points obtained using MOPSO for; (a) Tensile strength (b) Elastic modulus (c) Impact strength

7. Conclusion

In this study, the effect of the weight percentage of hemp fibers and graphene nanoparticles in the presence of a compatibilizer on the mechanical properties of the biocomposite was introduced. The tensile, flexural, and impact strengths of the introduced biocomposite were evaluated using the design of experiments with a response surface approach and the BBD method. Multi-objective optimization was conducted using the MOPSO method to improve mechanical properties and reduce weight. The overall results are as follows:

The presence of 0.88% by weight of graphene increased tensile strength by 16%, while the presence of 1.5% by weight of graphene decreased tensile strength compared to the sample with 0.88% by weight of graphene. An increase of 15% by weight of hemp fibers increased tensile strength by 24%. An increase of 6% by weight of the compatibilizer increased tensile strength by 18%.

The presence of 1.5% by weight of graphene nanoparticles resulted in a 70% increase in elastic modulus. An increase of 15% by weight of hemp fibers increased the elastic modulus by 84%. An increase of 15% by weight of the compatibilizer increased the elastic modulus by 75%.

The highest mechanical strength was observed in sample number 12, with 15% by weight of hemp fibers, 6% by weight of compatibilizer, and 0.75% by weight of graphene (tensile strength of 32 MPa, elastic modulus of 3.8 GPa, impact strength of 100 J/m, and flexural strength of 57.63 MPa).

Optimization results showed that the highest impact strength, with the sample having the lowest weight, was achieved in a sample containing 0.88% graphene nanoparticles, 4.55% hemp fibers, and 2.57% compatibilizer, with an impact strength of 92.29 J/m.

8. References

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