OPTIMIZATION AND PREDICTION ON MECHANICAL PROPERTIES OF CARBON-KENAF REINFORCED EXPOY HYBRID COMPOSITES USING FULL EXPERIMENTAL AND FACTORIAL APPROACH

BY

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ABSTRACT

The development of hybrid composites from the combination of synthetic and natural fibers have been extensively studied due to their excellent in both mechanical and physical properties. However, the absence of a robust statistical model in predicting and optimizing the optimum mechanical properties based on several parameters, especially fiber content, thickness, and stacking sequences, has caused a problem in designing and producing the hybrid composites. Therefore, the main objective of the current research is to predict and optimize the mechanical properties of fabricated hybrid composites based on these three parameters. Hybrid composite was fabricated by utilizing kenaf fiber (K) and carbon fiber (C) with epoxy matrices. These hybrid composites were fabricated based on three parameters: fiber content (30, 40, and 50 vol.%), thickness (3mm and 5mm), and stacking sequences (CKCKC, CCKCC, CKCK, and KCKCK) using vacuum infusion method in which the ratio of carbon-to-kenaf was fixed to 1:1. The mechanical and physical properties of fabricated carbon-kenaf hybrid composites were investigated. The optimization on mechanical properties of the hybrid composite was then conducted via the multilevel categoric factorial design of experiment (DEO) method. Experimentally, the addition of 30 vol.% to 40 vol.% of fibers has increased the values of tensile, flexural, and impact properties of hybrid composites due to formation of good interaction between fibers and matrix that observed by SEM morphology. Meanwhile, the addition of 50 vol.% fibers has reduced the mechanical properties of carbon-kenaf hybrid composites due to poor interfacial bonding between layers of fibers and epoxy matrix. Besides, the highest tensile and flexural properties were obtained when hybrid composites were fabricated at 3 mm thickness. This is corroborated with the effectiveness of matrix to distribute evenly along the surface of fibers compared to the one with 5 mm thickness of hybrid samples. In terms of stacking sequences, the assignation of carbon fibers as the outer layers exhibit the highest tensile strength, flexural strength, and impact strength with the value of 210.49 MPa, 329.59 MPa, 1143 J/m, respectively as compared to kenaf fiber at 40 vol.% fiber content. Moreover, it can be perceived that the density of carbon-kenaf hybrid composites decreases with an increase in the fiber content and thickness due to the formation of voids and it can be detected by optical microscope (OM) fractography. Additionally, the utilization of kenaf fiber as the outer layer tends to increase the rate of water absorption of hybrid composites in comparison to the carbon fiber as the outer layer due to the hydrophilic nature of kenaf fiber. From the overall findings, ANOVA analysis showed a significant interaction in the developed DOE model in which the result shows that the optimum parameters achieved at 40 vol.% fiber content, 3 mm thickness, and CCKCC stacking sequence. These parameters validated by the fabrication and the obtained values are in the range of predicted values. Therefore, this statistical model offers the great potential of the utilization of carbon-kenaf hybrid composite in structural applications, specifically the automotive industry.

ملخص البحث

تمت دراسة تطوير المركبات الهجينة من مزيج الألياف الاصطناعية والطبيعية على نطاق واسع بسبب خصائصها الممتازة في كل من الخصائص الميكانيكية والفيزيائية. ومع ذلك، فإن عدم وجود نموذج إحصائي قوي في التنبؤ بالخصائص الميكانيكية المثلي وتحسينها إستنادًا إلى العديد من المعلمات، وخاصة محتوى الألياف، وسمك، وتسلسل التراص، تسبب مشكلة في تصميم وإنتاج المركبات الهجينة. لذلك، فإن الجهود الحالية الجارية في إنتاج مثل هذه المركبات باستخدام ألياف الكناف (K) وألياف الكربون (C) في مصفوفات الإيبوكسي. تم تصنيع المركبات الهجينة بناءً على ثلاث معلمات، وهي محتوى الألياف (30 و 40 و.50 ٪)، وسمك (3ملم و 5 ملم)، وتتابعات التراص (CKCKC ، CCKCC ، CKCK ، وKCKCK) باستخدام طريقة ضخ الفراغ في حيث تم تحديد نسبة الكربون إلى الكناف إلى 1:1. تم فحص الخواص الميكانيكية والفيزيائية للمركبات الهجينة الكربونية المصنعة. تم بعد ذلك إجراء التحسين على الخواص الميكانيكية للمركب الهجين من خلال التصميم العاملي الفئوي متعدد المستويات لطريقة التجربة (DEO) . من الناحية التجريبية، أدت إضافة 30٪ إلى 40 ٪ من الألياف إلى زيادة قيم خصائص الشد والمرونة والتأثير للمركبات المختلطة وقد تم إثباتها من خلال التفاعل الجيد بين الألياف والمصفوفة التي اكتشفها مورفولوجيا SEM.إضافة إضافية للألياف إلى 50 ٪ خفضت الخواص الميكانيكية للمركبات الهجينة الكربونية الكيناف. بسبب ضعف الروابط البينية بين طبقات الألياف ومصفوفة الإيبوكسي. إلى جانب ذلك، تم الحصول على أعلى خصائص الشد والانثناء عندما تم تصنيع المركبات الهجينة بسمك 3 ملم. يتم تأكيد ذلك مع فعالية المصفوفة للتوزيع بالتساوي على طول سطح الألياف مقارنة بالسمك 5 مام من العينات الهجينة. من حيث تسلسل التراص، فإن تعيين ألياف الكربون كطبقات خارجية تظهر أعلى قوة شد وقوة إنثناء وقوة تأثير بقيمة 210.49 ميجا باسكال، 329.59 ميجا باسكال، 1143 جول / م، على التوالي مقارنة بألياف الكناف عند المجلد 40 ٪ محتوى الألياف. علاوة على ذلك، يمكن إدراك أن كثافة المركبات

الهجينة الكربونية الكيناف تتناقص مع زيادة محتوى الألياف وسمكها بسبب تكوين الفراغات ويمكن الكشف عنها بواسطة المجهر الضوئي (OM). باالإضافة إلى ذلك، فإن استخدام ألياف الكناف كما تميل الطبقة الخارجية إلى زيادة معدل إمتصاص الماء للمركبات الهجينة مقارنة بألياف الكربون كطبقة خارجية بسبب الطبيعة المحبة للماء لألياف الكناف. من النتائج الإجمالية، أظهر تحليل ANOVA تفاعلًا كبيرًا في النموذج المطور حيث أظهرت النتيجة أن المعلمات المثلي تم تحقيقها في محتوى الألياف بحجم 40 ٪ ، وسمك 3 ملم، وتسلسل تكديس CCKCC. هذه المعلمات التي تم التحقق منها من قبل التصنيع والقيم التي تم الحصول عليها تقع في نطاق القيم المتوقعة. لذلك، يقدم هذا النموذج الإحصائي الإمكانات الكبيرة لاستخدام مركب الكربون الهجين المركب في التطبيقات الهيكلية، وخاصة صناعة السيارات.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Materials Engineering)

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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institution.

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LIST OF ABREVIATIONS

ANOVA	Application of Variance
ASTM	American Society for Testing and Materials
C	Carbon fiber
CNT	Carbon Nanotube
DOE	Design of Experiment
FTIR	Fourier Transform Infra-Red
F-value	Ratio of two variance
GMT	Glass Mat Thermoplastic
K	Kenaf fiber
MLC	Multilevel Categoric
MP	Mesophase Pitch
OM	Optical Microscope
PAN	Polyacrylonitrile
Pd	Palladium
P-value	Probability value
R^2	Variability of Mean
SEM	Scanning Electron Microscopy
SMC	Sheet Moulding Compression
UTM	Universal Testing Machine

LIST OF SYMBOLS

%	Percentage
℃	Degree Celsius
GPa	GigaPascal
g	Gram
g/cm^3	Gram per centimetre cube
gsm	Gram square meter
J/mm	Joule per milimeter
kN	Kilo newton
mm	Milimeter
MPa	MegaPascal
vol.%	Volume percent
wt.%	Weight percent

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

For many years, synthetic fibers have extensively adopted in most of the structural engineering applications such as marine, aerospace, construction, and automotive sectors (Koumoulos et al., 2019; Petersson et al., 2013). Synthetic fibers such as carbon and glass fibers are commonly utilized as a reinforcement to produce fiber-reinforced composite materials. The utilization of these fibers due to their outstanding mechanical properties and good durability behaviour (Elahi et al., 2014; Huang, 2009). Nevertheless, researchers start to explore other potential materials to reduce the use and dependency on the synthetic fibers. This is due to the high cost of synthetic fibers and the realization to maintain the sustainability of a green environment (Nagalakshmaiah et al., 2019). In fact, most synthetic fibers are non-biodegradable materials that difficult to be recycled, where improper recycling processes may contribute to the environmental issue (Nagalakshmaiah et al., 2019).

Therefore, the selection of reinforcements from agricultural resources has raised great attention among researchers in developing products based on green-composite materials. Many attempts that focused on the employment of natural fibers as a reinforcing agent in fiber-reinforced composites to replace synthetic fibers has been established. The adoptions of natural fibers are due to its advantages in terms of renewable resources, biodegradability, low density, non-abrasiveness, and low cost (Hajiha and Sain, 2014; Ticoalu et al., 2010). The utilization of kenaf fiber extracted from a plant known as *Hibiscus Cannabinus* to produce fiber-reinforced composite materials gain tremendous attention among researchers. The adoption of kenaf fiber in various scale of composite productions because of its excellent specific strength concurrently with the availability of this natural fiber which can rapidly grow within 4 to 5 months (Ramesh et al., 2018). Traditionally, kenaf fiber was used for non-structural applications such as fish lines, rope, feed for cattle, filters, and bags (Zuhri et al., 2009). The prospect of kenaf fiber in automotive, aerospace, and other structural applications has been widely studied by many researchers. Hassan et al. (2017) and Shubhra et al. (2011) have discussed that the selection of kenaf fiber in composites due to its robust specific tensile strength of about 930 MPa. Furthermore, the demonstration of a low density that can reduce the weight of automotive components is another driving force in the utilization of kenaf fiber in most of the automotive industries (Holbery & Houston, 2009).

Researchers have invented a new composite known as a hybrid composite to obtain the benefits from both synthetic and natural fibers. The combination of two or more different types of fibers with a polymer matrix tend to produce superior mechanical and physical properties of fabricated fiber-reinforced composites. Therefore, the use of synthetic fibers can be an interesting way to enhance the overall mechanical performances, while natural fibers able to impart the biodegradable properties in a hybrid composite. The hybridization of natural-synthetic fibers has made a remarkable impact on structural industrial applications. One of the positive findings by Davoodi et al. (2010) has proved that kenaf-glass fiber hybrid composites demonstrate excellent tensile and flexural properties which were found to be suitable for a car bumper application.

The mechanical properties assessment of synthetic-natural hybrid composites, especially kenaf hybrid composites based on different parameters has been widely evaluated by many researchers. The question of whether all the mechanical evaluations which are currently proposed in the literature are sufficient towards identifying the optimal mechanical properties of this hybrid composite; since, the research on optimizing the mechanical properties of kenaf hybrid composites is limited because of the development of a comprehensive statistical model is required. Therefore, the current study aims to develop hybrid composites by utilizing woven carbon fiber and kenaf fiber as reinforcing agents with a polymer resin (epoxy) that acts as a matrix using vacuum infusion technique. Moreover, further investigations on the mechanical, physical, and morphological properties of resultant hybrid composites were conducted. The development of statistical model based on the Design of Experiment (DOE) approach that predict and optimize the mechanical properties of fabricated hybrid composites was established by considering parameters of fiber content, stacking sequence, and laminate thickness of this hybrid composite. This newly developed model may become a guideline for future research to explore the potential of kenaf hybrid composite in many structural engineering applications.

1.2 PROBLEM STATEMENT

Composite is a potential material to replace the use of traditional materials like steel, aluminium, wood, and granite (Nagavally, 2017). They have grown tremendously in many industries due to their excellent mechanical properties (Gupta et al., 2016). Moreover, composite materials have been well-developed owing to their high strength-to-weight ratio, durability, easily produce, and open to new design options (Mahajan and Aher, 2012; Visal, 2016).

In general, polymer composites based on synthetic fibers extensively used in most of the structural applications such as automotive and aerospace industries due to outstanding properties of these fibers such as high mechanical strength, relatively low density, excellent corrosion resistance, and durability (Yao et al., 2018). Apart from these noteworthy points, high production cost remains dominant barriers to the wide-range adoption of this material for the structural applications. Life cycle assessment of synthetic fibers after end-of-service also becomes an issue, where synthetic products are difficult to be recycled due to high cost as well as require advancement in a waste management system. Thus, poor waste management of synthetic materials leads to environmental problems (Robert, 2015).

In these regards, it has prompted an idea to develop new composite materials based on natural resources. Many attempts have been performed from previous studies that utilize jute, kenaf, sisal, empty fruit bunch (EFB), and hemp fibers as a reinforcing agent in polymer composites (Ticoalu et al., 2010). The employment of natural fibers in polymer composites seems promising because they can naturally biodegrade without contributing serious problems toward the environment, they are abundantly available, inexpensive, non-abrasive, and exhibit low density (Mishra & Biswas, 2013; Mohammed et al., 2015; Pickering et al., 2016). Therefore, the utilization of these materials able to reduce the dependency on petroleum-based synthetic fiber such as carbon fiber. Among the available natural fibers, kenaf fiber was proposed as a potential material to replace synthetic fibers owing to its excellent properties such as high specific strength, high stiffness, cost-effectiveness, and low density (Tong et al., 2017; Hajiha & Sain, 2014; Bagum and Islam, 2013).

Despite the advantages of kenaf fiber, the high moisture absorption of this fiber resulted in poor mechanical performances which might limit its usage (Kalia et al., 2009). Another concern in developing kenaf fiber based composites is the incompatibility with the polymer resin may lead to weak interfacial bonding between kenaf fibers and polymer matrix (Khan et al., 2015). It is because kenaf fiber is known to be hydrophilic, whereas the polymer matrix is hydrophobic. Different in polarity tends to promote poor adhesion between natural fibers and matrix resin that consequently reduce the mechanical strength of fabricated composites.

At present, considering the better mechanical performances without sacrificing the environmental concern, the idea of developing a hybrid composite from the combination of natural and synthetic fibers with one phase of the matrix has been established. The deployment of two different types of fibers is expected to compensate for the drawback of one another. Therefore, many pieces of research have discussed the combination of natural and synthetic fibers with a polymer resin in a fiber-reinforced composite system. Researchers have found that the combination of two fibers able to boost the mechanical strength of fabricated hybrid composites (Fauzi et al., 2016; Sapiai et al., 2015).

It should be noted that, several parameters such as fiber-matrix ratio, stacking sequence of fibers, and thickness of laminate need to be taken into consideration in fabricating hybrid composites. Even though there are many attempts have been performed to investigate the effects of fiber contents, stacking sequences, and thickness of laminate on mechanical behaviours of hybrid composites (as Table 2.6 in Section 2.5.1), the absence of robust statistical model in predicting and optimizing the optimum mechanical properties of hybrid composites based on these parameters is the primary constraint towards the design of hybrid composites. Besides, there is a limited report available regarding the optimization analysis of these three parameters toward prediction on the mechanical properties of carbon-kenaf hybrid composites. Indeed, these data are essential in continuing the investigation on the prospect of kenaf hybrid composites in various structural applications.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to predict and optimize the mechanical behaviour of hybrid composites by utilizing woven carbon and woven kenaf fabric reinforced epoxy matrix fabricated using vacuum infusion technique. To achieve this prime objective, several explicit objectives need to be executed as follows:

1. To screen the parameters for the fabrication of carbon-kenaf reinforced epoxy matrix hybrid composites.

2. To evaluate the mechanical, morphological, and physical (water absorption and density) properties of the fabricated hybrid composites based on fiber content, stacking sequence, and thickness.

3. To formulate and validate a statistical analysis model in predicting and optimizing the optimal tensile, flexural, and impact properties of fabricated hybrid composites using design of experiments (DOE) approach via Design-Expert software by considering fiber content, thickness, and stacking sequence parameters.