

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

BY

MOHAMAD IKHWAN BIN YUSUFF

A thesis submitted in fulfilment of the requirement for the
degree of Master of Science (Materials Engineering)

Kulliyyah of Engineering

International Islamic University Malaysia

NOVEMBER 2020

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 إستناداً إلى العديد من المعلومات، 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 الكفاف (K) وألياف الكربون (C) في مصفوفات الإيبوكسي. تم تصنيع المركبات الهجينة بناءً على ثلاث معلومات، وهي محتوى الألياف (30 و 40 و 50 ٪)، وسمك (3 ملم و 5 ملم)، وتتابعات التراص (CKCK، CCKCC، CKCKC)، و (KCKCK) باستخدام طريقة ضخ الفراغ في حيث تم تحديد نسبة الكربون إلى الكفاف 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 الكفاف. بسبب ضعف الروابط البينية بين طبقات الألياف ومصفوفة الإيبوكسي. إلى جانب ذلك، تم الحصول على أعلى خصائص الشد والانشاء عندما تم تصنيع المركبات الهجينة بسمك 3 ملم. يتم تأكيد ذلك مع فعالية المصفوفة للتوزيع بالتساوي على طول سطح الألياف مقارنة بالسمك 5 ملم من العينات الهجينة. من حيث تسلسل التراص، فإن تعيين ألياف الكربون كطبقات خارجية تظهر أعلى قوة شد وقوة إنشاء وقوة تأثير بقيمة 210.49 ميغا باسكال، 329.59 ميغا باسكال، 1143 جول / م، على التوالي مقارنة بألياف الكفاف 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). بالإضافة إلى ذلك، فإن استخدام ألياف الكيناف كما تميل الطبقة الخارجية إلى زيادة معدل إمتصاص الماء للمركبات الهجينة مقارنة بألياف الكربون كطبقة خارجية بسبب الطبيعة المحبة للماء لألياف الكيناف. من النتائج الإجمالية، أظهر تحليل ANOVA تفاعلاً كبيراً 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 الإمكانيات 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)

.....
Norshahida Sarifuddin
Supervisor

.....
Afifah Mohd Ali
Co-Supervisor

I certify that I have 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)

.....
Noorasikin Samat
Internal Examiner

.....
Mariatti Jaafar
External Examiner

This thesis was submitted to the Department of Manufacturing and Materials Engineering and is acceptable as a fulfilment of the requirement for the degree of Master of Science (Materials Engineering)

.....
Erry Yulian T. Adesta
Head, Department of
Manufacturing and Materials
Engineering

This thesis was submitted to the Kulliyyah Engineering and is acceptable as a fulfilment of the requirement for the degree of Master of Science (Materials Engineering)

.....
Sany Izan Ihsan
Dean, Kulliyyah of Engineering

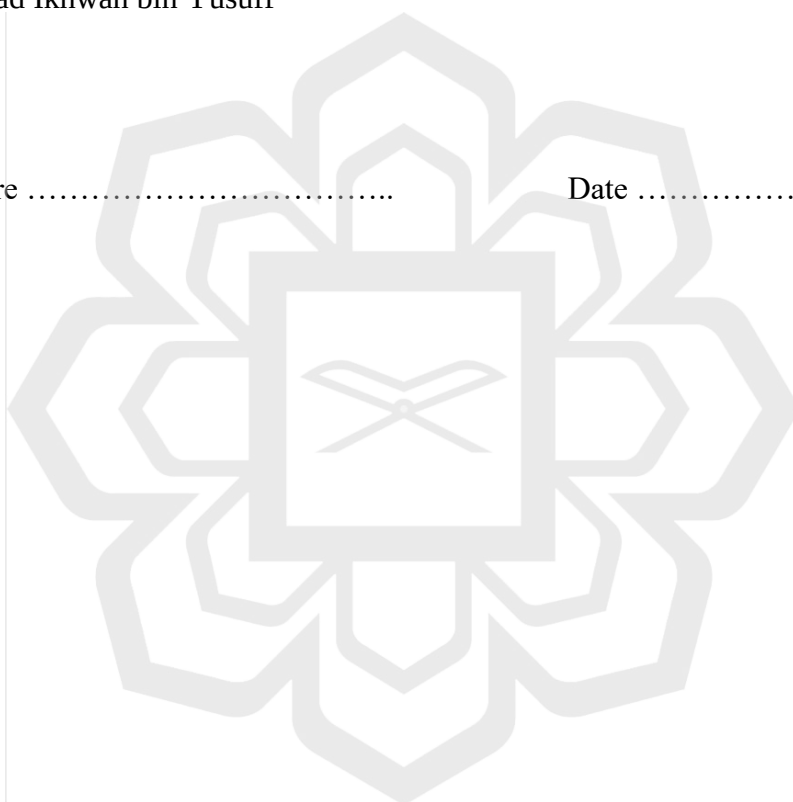
DECLARATION

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.

Mohamad Ikhwan bin Yusuff

Signature

Date



INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

**DECLARATION OF COPYRIGHT AND AFFIRMATION OF
FAIR USE OF UNPUBLISHED RESEARCH**

**OPTIMIZATION AND PREDICTION ON MECHANICAL
PROPERTIES OF CARBON-KENAF HYBRID COMPOSITE
USING FULL FACTORIAL APPROACH**

I declare that the copyright holder of this thesis is jointly owned by the student and IIUM.

Copyright © 2020 Mohamad Ikhwan bin Yusuff and International Islamic University Malaysia. All rights reserved.

No part of this unpolished research may be reproduced. Stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder expect as provided below

1. Any material contained in or derived from this research may be used by others in the writing with due acknowledgement.
2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institution and academic purposes.
3. The IIUM library will have the right to make, store in a retrieved system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Mohamad Ikhwan bin Yusuff

.....

Signature

.....

Date

ACKNOWLEDGEMENTS

The success and final outcome of this research work required a lot of guidance and assistance from many people and I am extremely privileged to have got this all to the completion of my project. All that I have done is only due to such supervision and assistance. First and foremost, this thesis is dedicated to my beloved parents and siblings, Mr. Yusuff bin Ibrahim and Mrs. Farizah bin Yahya, Nur Kharimah Yusuff, and Fatin Najawa Yusuff for their love and endless support throughout my master's degree.

I would not forget to thank them respect and thank my supervisors Dr. Norshahida binti Sarifuddin for providing an opportunity to accept me as supervisee and giving all support and guidance which made me complete the project. I am extremely thankful to her for providing such a nice support and guidance, although she had a busy schedule. Also, I want to thank my co-supervisors Dr. Afifah Mohd Ali and my field supervisor Prof. Dr. Hanafi Ismail for their help in completing this project. I owe my deep gratitude to my friends, Kak Siti Norbahiyah and Br. Muhammad Hilmi, who took keen supervise on the project and guided me all along, till the completion of the master period.

I believe this thesis would not have been completed without a close collaboration with few laboratories. I am thankful to Mr. Mohd Hamri Rahmat (Sand Testing Lab), Mr. Tarmizi (Materials Testing Lab), Mr. Ibrahim Razali (Metallography Lab) for and fortunate enough to get constant guidance during my experimentation in those laboratories. Besides, I would like to thank administrative and technical staff members of CPS and PG KOE, IIUM who have been kind enough to advise and help in their respective role. Last but not least, I would like to extend my sincere esteems to all parties which are involved directly or indirectly in completing this research work.

TABLE OF CONTENTS

Abstract	i
Arabic Abstract	ii
Approval Page.....	iv
Declaration	v
Copyright	vi
Acknowledgements.....	vii
Table of Contents	viii
List of Tables	xi
Lis of Figures	xii
List of Abbreviations	xvi
List of Symbols	xvii

CHAPTER 1: INTRODUCTION

1.1 Research Background	1
1.2 Problem Statement	3
1.3 Research Objectives	6
1.4 Project Scope	6
1.5 Structure of Report.....	8

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction.....	10
2.2 Polymer Composites in Automotive Application.....	11
2.3 Synthetic Fiber Reinforced Polymer Composites.....	12
2.3.1 Carbon Fiber	14
2.3.2 Developments of Carbon Fiber Composites	17
2.3.3 Challenges in Developing Carbon Fiber Composites.....	20
2.4 Introduction of Natural Fibers	21
2.4.1 Natural Fibers For Composite Materials.....	22
2.4.2 Kenaf Fibers.....	27
2.4.3 Kenaf and Its Composites	29
2.4.4 Barrier in Developing Natural Fiber Composites	31
2.5 Hybrid Composites	33
2.5.1 Kenaf Hybrid Composites.....	36
2.5.2 Polymer Resins in Hybrid Composites	42
2.5.3 Epoxy Resin	43

2.5.4	Fabrication Method	45
2.5.5	Vacuum Infusion Method	48
2.5.6	Factors Affecting Performances of Composites	51
2.5.6.1	Effect of Fiber Content	51
2.5.6.2	Effect of Stacking Sequences	53
2.5.6.3	Effect of Thickness	54
2.6	Formulation of Statistical Model for Composites.....	57
2.8.1	Full Factorial Design	57
2.7	Summary	60

CHAPTER 3: METHODOLOGY

3.1	Introduction.....	61
3.2	Raw Materials	61
3.2.1	Carbon Fiber and Kenaf Fiber	61
3.2.2	Epoxy Resin	62
3.3.	Experimental Design.....	63
3.4	Fabrication of Carbon-Kenaf Hybrid Composites Using Vacuum Infusion Method.....	67
3.4.1	Rule of Mixture Concept	67
3.4.2	Designation of Hybrid Composites.....	69
3.4.3	Fabrication of Hybrid Composites Via Vacuum Infusion Method	71
3.5	Testing of Raw Materials and Hybrid Composites.....	72
3.5.1	Fourier Transform Infra-red (FTIR) Analysis.....	72
3.5.2	Scanning Electron Microscope (SEM)	73
3.5.3	Optical Microscope	73
3.5.4	Density	73
3.5.5	Water Absorption.....	74
3.5.6	Tensile Test.....	74
3.5.7	Flexural Test	75
3.5.8	Impact Test.....	76
3.7	Full Factorial Analysis	76
3.8	Summary	78

CHAPTER 4: RESULTS AND DISCUSSION

4.1	Introduction.....	79
4.2	Characterization of Raw Materials	79

4.2.1	Morphological Properties.....	79
4.2.2	Fourier Transform Infra-red (FTIR) Analysis.....	82
4.3	Effects of Fiber Loadings and Stacking Sequences on The Properties of Carbon-Kenaf Hybrid Composites	86
4.3.1	Tensile Properties.....	86
4.3.2	Morphological Properties.....	94
4.3.3	Flexural Properties	102
4.3.4	Impact Properties.....	116
4.4	Effect of Thickness on The Properties of Carbon-Kenaf Hybrid Composites.....	126
4.4.1	Tensile Properties.....	126
4.4.2	Morphological Properties.....	132
4.4.3	Flexural Properties	137
4.4.3	Impact Properties.....	144
4.5	Physical Properties of Hybrid Composites	153
4.5.1	Density of Hybrid Composites.....	153
4.5.2	Water Absorption.....	160
4.6	Optimization on Mechanical Properties of Carbon-Kenaf Hybrid Composites Via DOE Method	163
4.6.1	Half-Normal Plot of Effects.....	170
4.6.2	ANOVA Analysis on Developing Models	173
4.6.3	Optimization Model and Validation	183
4.7	Summary	188
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS		
5.1	Conclusion	189
5.2	Recommendation for Future Works.....	191
REFERENCES.....		193
APPENDIX I: LIST OF CONFERENCES		207
APPENDIX II: LIST OF PUBLICATIONS		208

LIST OF TABLES

Table 2.1	Tensile properties and density of common types of synthetic fibers in fiber reinforced composites	14
Table 2.2	Carbon fiber weave designs and its advantages (Adapted from Elevated Materials)	17
Table 2.3	Development of carbon fiber composites	18
Table 2.4	Chemical compositions of various natural fibers	22
Table 2.5	Chronological developments of natural fiber composites	25
Table 2.6	Developments of kenaf hybrid composites based on previous studies	39
Table 2.7	Various fabrication methods of fiber reinforced composites	44
Table 2.8	Developments of composite materials from various fabrication methods	46
Table 2.9	Factors and levels in full factorial design	58
Table 3.1	Properties of carbon fiber and kenaf fiber	62
Table 3.2	Product information	62
Table 3.3	Details of experiment by phases	66
Table 3.4	Parameters and designation of carbon-kenaf hybrid composites	70
Table 3.5	Generating factors and level in the full factorial analysis	76
Table 4.1	Analyzation and results of screening process for fiber-reinforced polymer composites from previous studies	87
Table 4.2	Surface morphology of hybrid composite at 3mm thickness, different fiber loadings and stacking sequences	160
Table 4.3	Surface morphology of hybrid composite at 5mm thickness and different fiber loadings and stacking sequences	161
Table 4.4	Analyzation and results of the screening process for fiber-reinforced polymer composites from previous studies	158
Table 4.5	Multilevel categoric factorial design for 24 runs of experiments	162
Table 4.6	ANOVA for the selected factorial model (Tensile strength response)	166
Table 4.7	ANOVA analysis of factorial model for flexural strength response	169
Table 4.8	ANOVA analysis of the factorial model for impact strength response	172
Table 4.9	Optimization criteria for factors and responses	176
Table 4.10	Solutions for 24 combinations of three factors with the desirability value	177
Table 4.11	Summary and comparison of predicted vs experimental results	180
Table 4.12	Mechanical properties of fabricated carbon-kenaf hybrid composite (current study) versus synthetic-natural hybrid composites from previous studies	

LIST OF FIGURES

Figure 2.1	Carbon fibers, (a) Strands, (b) woven, and (c) non-woven	16
Figure 2.2	Categories of natural fibers	21
Figure 2.3	Mechanical properties of natural fibers	23
Figure 2.4	Core region and bast region from kenaf stem	27
Figure 2.5	Kenaf fibers, (a) non-woven, (b) unidirectional, and (c) woven	28
Figure 2.6	Types of fiber hybrid laminated, (a) xiinterplay hybrid, (b) intraply hybrid, and (c) intermingled mixed hybrid	34
Figure 2.7	(a) Tensile properties and (b) Flexural properties of GMT and kenaf hybrid composites	37
Figure 2.8	Micrograph images of (a) surface of treated kenaf fiber and (b) surface of untreated kenaf fiber	38
Figure 2.9	Impact strength of glass-kenaf hybrid composite for treated and untreated condition at various fiber loadings	39
Figure 2.10	The chemical structure of epoxy resin	44
Figure 2.11	Schematic diagram of vacuum infusion method	49
Figure 2.12	Tensile strength of hybrid composites at various kenaf loadings	52
Figure 2.13	Illustration of hybrid composites stacking configuration (a) A/K/A, (b) K/A/K, and (c) A/K/A/K	53
Figure 2.14	Flexural properties of Kevlar-kenaf hybrid composite under various stacking sequences	54
Figure 2.15	Tensile properties of hybrid composite at thickness of 2 mm and 3 mm	55
Figure 2.16	Tensile properties of glass composites at 2 mm and 3 mm thickness	56
Figure 3.1	Experimental flow chart	62
Figure 3.2	Schematic diagram for stacking sequence (a) CCCCC, (b) CKCKC, (c) KCKCK, (d) KCKC, © CCKCC, and (f) KKKK	69
Figure 3.3	(a) Schematic diagram and (b) experimental setup of vacuum infusion method	71
Figure 3.4	Schematic diagram for the tensile test sample	75
Figure 3.5	Schematic diagram for the flexural sample	75
Figure 3.6	Steps involved in full factorial analysis	77
Figure 4.1	SEM surface morphology of carbon fiber at (a) $\times 25$ and (b) $\times 35$ magnification	79
Figure 4.2	SEM surface morphology of Kenaf fiber at (a) $\times 25$ and (b) $\times 35$ magnification	80
Figure 4.3	Representative FTIR spectra of carbon fiber and kenaf fiber	82
Figure 4.4	Representative FTIR spectra of epoxy resin	84
Figure 4.5	(a) Chemical structure of cellulose component in kenaf fiber and (b) chemical reaction between epoxides and hydroxyl groups in carbon and kenaf fibers	85
Figure 4.6	Tensile strength of hybrid composites at different fiber loadings and stacking sequences	86
Figure 4.7	Lamination of fabricated carbon-kenaf hybrid composites at (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.%	88
Figure 4.8	Tensile modulus of hybrid composites at different fiber loadings and stacking sequences	91

Figure 4.9	Stress-strain curve at (a) 30 vol.% fiber loadings, (b) 40 vol.% fiber loadings, and (c) 50 vol.% fiber loading	93
Figure 4.10	Resin rich and resin starve region in 30 vol.% hybrid composites, (a) CKCK and (b) KCKCK	95
Figure 4.11	Tensile fracture surface of 30 vol.% carbon-kenaf hybrid composites with (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK stacking sequences at $\times 25$ magnification	96
Figure 4.12	Tensile fracture surface of 40 vol.% carbon-kenaf hybrid composites with (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK stacking sequences at $\times 25$ magnification	98
Figure 4.13	Micrograph of (a) CKCK and (b) KCKCK 40 vol.% carbon-kenaf hybrid composites at $\times 250$ magnification	99
Figure 4.14	Tensile fracture surface of 50 vol.% carbon-kenaf hybrid composites with (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK stacking sequences at $\times 25$ magnification	101
Figure 4.15	Flexural strength of carbon-kenaf hybrid composites at different fiber loadings and stacking sequence	102
Figure 4.16	Flexural modulus of carbon-kenaf hybrid composites at different fiber loadings and stacking sequences	106
Figure 4.17	Surface morphology of KCKCK hybrid composites at (a) 40 vol.% and (b) 50 vol.% fiber loadings	107
Figure 4.18	Flexural stress-strain curves of carbon-kenaf hybrid composite with various stacking sequences at (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.% fiber loadings	109
Figure 4.19	(a) Flexural modulus, (b) stress-strain curve, and (c) resilience for CCKCC hybrid composites at different fiber contents (30, 40, and 50 vol.%)	111
Figure 4.20	Modes of failure of 30 vol.% carbon-kenaf hybrid composites with stacking sequences (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK subjected to flexural testing	114
Figure 4.21	Modes of failure of 40 vol.% carbon-kenaf hybrid composites with stacking sequences (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK subjected to flexural testing	114
Figure 4.22	Modes of failure of 50 vol.% carbon-kenaf hybrid composites with stacking sequences (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK subjected to flexural testing	115
Figure 4.23	Impact energy of fabricated hybrid composites at various fiber loadings and stacking sequences	117
Figure 4.24	Impact strength of fabricated hybrid composites at different fiber loadings and stacking sequences	118
Figure 4.25	Carbon-kenaf hybrid composites with 30 vol.% fiber loading after impact testing at different stacking sequences, (a) CCCCC, (b) CKCKC, (c) CKCK, (d) CCKCC, (e) KCKCK, and (f) KKKKK	123
Figure 4.26	Carbon-kenaf hybrid composites with 40 vol.% fiber loading after impact testing at different stacking sequences, (a) CCCCC, (b) CKCKC, (c) CKCK, (d) CCKCC, (e) KCKCK, and (f) KKKKK	124

Figure 4.27	Carbon-kenaf hybrid composites with 30 vol.% fiber loading after impact testing at different stacking sequences, (a) CCCCC, (b) CKCKC, (c) CKCK, (d) CCKCC, (e) KCKCK, and (f) KKKKK	125
Figure 4.28	Tensile strength of carbon-kenaf hybrid composite at 3mm and 5mm thickness (40 vol.% of fiber contents)	127
Figure 4.29	Tensile modulus of carbon-kenaf hybrid composites at 3mm and 5mm thickness (40 vol.% fiber contents)	129
Figure 4.30	Stress-strain curve of carbon-kenaf hybrid composites at 3mm and 5mm thickness (40 vol.% fiber contents)	130
Figure 4.31	Tensile fractured morphology of 30 vol.% carbon-kenaf hybrid composites with 5mm thickness, (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK at $\times 25$ magnification	133
Figure 4.32	Tensile fractured morphology of 30 vol.% carbon-kenaf hybrid composites with 5mm thickness, (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK at $\times 25$ magnification	134
Figure 4.33	Tensile fractured morphology of 50 vol.% carbon-kenaf hybrid composites with 5mm thickness, (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK at $\times 25$ magnification	135
Figure 4.34	Flexural strength of (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.% fiber hybrid composites at 3mm and 5mm thickness	137
Figure 4.35	Morphology of fabricated carbon-kenaf hybrid composite (a) 3mm thickness and (b) 5mm thickness	138
Figure 4.36	Flexural modulus of (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.% carbon-kenaf hybrid composite at 3mm and 5mm thickness	140
Figure 4.37	Flexural modes of failures of 30 vol.% carbon-kenaf hybrid composites (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK (5mm thickness)	142
Figure 4.38	Flexural modes of failures of 40 vol.% carbon-kenaf hybrid composites (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK (5mm thickness)	142
Figure 4.39	Flexural modes of failures of 30 vol.% carbon-kenaf hybrid composites (a) CKCKC, (b) CCKCC, (c) CKCK, and (d) KCKCK (5mm thickness)	143
Figure 4.40	Impact energy of (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.% carbon-kenaf hybrid composite at 3mm and 5mm thickness	144
Figure 4.41	Impact strength of (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.% carbon-kenaf hybrid composite at 3mm and 5mm thickness	146
Figure 4.42	Impact fracture of 5 mm Carbon-kenaf hybrid composites with 30 vol.% fiber loading after impact testing at different stacking sequences, (a) CCCCC, (b) CKCKC, (c) CKCK, (d) CCKCC, (e) KCKCK, and (f) KKKKK	150
Figure 4.43	Impact fracture of 5 mm Carbon-kenaf hybrid composites with 40 vol.% fiber loading after impact testing at different stacking sequences, (a) CCCCC, (b) CKCKC, (c) CKCK, (d) CCKCC, (e) KCKCK, and (f) KKKKK	151
Figure 4.44	Impact fracture of 5 mm Carbon-kenaf hybrid composites with 50 vol.% fiber loading after impact testing at different stacking	153

	sequences, (a) CCCCC, (b) CKCKC, (c) CKCK, (d) CCKCC, (e) KCKCK, and (f) KKKKK	
Figure 4.45	Density of fabricated carbon-kenaf hybrid composites, (a) 3mm thickness and (b) 5mm thickness	155
Figure 4.46	Water absorption behaviour of manufacture hybrid composites at various stacking configurations for (a) 30 vol.%, (b) 40 vol.%, and (c) 50 vol.% fiber loadings	161
Figure 4.47	24 runs (condition) in the MCF DOE from different combinations of factors	169
Figure 4.48	Half-normal plot of effects, (a) tensile strength, (b) flexural strength, and (c) impact strength of carbon-kenaf hybrid composites	172
Figure 4.49	The normal probability plots for residuals for (a) tensile strength, (b) flexural strength, and (c) impact strength of manufactured carbon-kenaf hybrid composites	173
Figure 4.50	Main effects plot for (a) fiber content vs. tensile strength, (b) thickness vs. tensile strength, and (c) stacking sequence vs. tensile strength of manufactured carbon-kenaf hybrid composites	176
Figure 4.51	Main effects plot for (a) fiber content vs. flexural strength, (b) thickness vs. flexural strength, and (c) stacking sequence vs. flexural strength of manufactured carbon-kenaf hybrid composites	179
Figure 4.52	Main effects plot for (a) fiber content vs. impact strength and (b) stacking sequence vs. impact strength of manufactured carbon-kenaf hybrid composites	182
Figure 4.53	Desirability value of factors and responses for the selected hybrid composite	186
Figure 4.54	Selected optimum factors and predicted values of responses from DOE optimization analysis	187

LIST OF ABBREVIATIONS

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 Categorical
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
°C	Degree Celsius
GPa	GigaPascal
g	Gram
g/cm ³	Gram per centimetre cube
gsm	Gram square meter
J/mm	Joule per millimeter
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.