MECHANICAL PROPERTIES OF SINGLE KENAF FIBRE WITH OPTIMISATION AND INDENTATION BEHAVIOUR OF KENAF FIBRE REINFORCED EPOXY COMPOSITE

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DEDICATION

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ABSTRACT

The development of eco-friendly materials has attracted a lot of researchers' interest to avoid environmental imbalance and prevent depletion of the ozone layer. Hence, the reinforcement of polymer composite using natural fibre called composites is interesting to develop. Inconsistency of morphology structure of single kenaf fibres, an optimum of bonding parameters between fibres-epoxy matrices interaction and low resistance to localised loading during composites' impact response is fascinating to discover. Therefore, this study aims to determine the kenaf fibre's monotonic tensile properties, optimising the blending composition and examining the indentation behaviour of kenaf fibre composites. Initially, the effect of chemical treatment and fibre length of single kenaf fibres were evaluated using a Weibull statistical approach. Next, the mixing parameter between the kenaf fibre and epoxy resin, including alkaline treatment, fibre loading and fibre length, was then elucidated using central composite design (CCD) of response surface methodology (RSM). The contact stiffness and indentation parameter of the kenaf epoxy composite were subsequently calculated using Mayer indentation law. The finding highlights that the Weibull modulus (m) of single kenaf fibre varied between two and four. Moreover, the highest absolute value of tensile strength for fibre length and chemical treatment were yielded at 30 mm and 6 wt.% of alkaline concentration, respectively. The surface morphology showed that the surface was rough and no impurities were obtained from the treated fibre. Furthermore, through the CCD analysis, the optimum configuration of the biocomposites (alkaline concentration, fibre loading and fibre length) were obtained at 6.03 wt.%, 26.02 wt.% and 7.39 mm. Lastly, the value of the indentation parameter laid between 1.4 and 1.8. It was also found that the contact stiffness increased with increasing density of composites, indenter diameter and velocity impact. This optimises kenaf reinforced epoxy composite which is suitable to be used for consumer product with short life cycles ranging between three and four years, where the mechanical properties of structures are of paramount importance.

ABSTRAK

Pembangunan bahan mesra alam telah menarik minat penyelidik untuk mengelakkan ketidakseimbangan persekitaran dan mencegah penipisan lapisan ozon. Oleh itu, pengukuhan komposit polimer menggunakan serat semula jadi amat sesuai untuk dibangunkan. Ketidakselarasan struktur morfologi gentian tunggal, parameter ikatan optimum interaksi antara gentian dengan matrik epoksi dan rintangan rendah terhadap muatan setempat semasa tindak balas hentaman adalah antara bidang yang amat menarik untuk dikaji. Sehubungan dengan itu, kajian ini bertujuan untuk menentukan sifat tegangan ekanada gentian kenaf, mengoptimumkan komposisi pencampuran dan memeriksa tingkah laku lekukan komposit serat kenaf. Pada peringkat awal, kesan rawatan kimia dan panjang serat kenaf tunggal dinilai menggunakan pendekatan statistik Weibull. Seterusnya, parameter pencampuran antara serat kenaf dan resin epoksi, termasuk rawatan alkali, pemuatan serat dan panjang serat, kemudiannya dijelaskan dengan menggunakan reka bentuk komposit pusat (CCD) bagi metodologi tindak balas permukaan (RSM). Parameter kekakuan dan lekukan kontak komposit epoksi kenaf akhirnya dikira menggunakan hukum lekukan Mayer. Hasil kajian mendapati bahawa modulus Weibull (m) serat kenaf tunggal berbeza antara dua dan empat. Selain itu, nilai mutlak kekuatan tegangan tertinggi untuk panjang serat dan rawatan kimia masing-masing dihasilkan pada kepekatan alkali 30 mm dengan berat 6%. Morfologi permukaan menunjukkan bahawa permukaannya kasar dan tiada kekotoran dari serat yang terawat. Seterusnya, melalui analisis CCD, konfigurasi optimum biokomposit (kepekatan alkali, pemuatan serat dan panjang serat) diperolehi pada berat 6.03%, berat 26.02% dan 7.39 mm. Akhir sekali, nilai parameter lekukan adalah di antara nilai 1.4 dan 1.8. Kekakuan sentuhan juga didapati meningkat dengan peningkatan kepadatan komposit, diameter pelekuk dan halaju lekukan. Komposisi optimum komposit bertetulang gentian kenaf bersama epoksi ini adalah sesuai digunakan sebagai produk pengguna dengan jangka hayat pendek antara tiga hingga empat tahun, di mana sifat mekanik struktur bahannya memainkan peranan yang sangat penting.

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LIST OF ABBREVIATIONS

ABS	-	Acrylonitrile Butadiene Styrene
ANOVA	-	Analysis of Variance
ASTM	-	American Society for Testing and Materials
BFRP	-	Basalt Fibre Reinforced Epoxy
BVID	-	Barely Visible Impact Damage
CAGR	-	Compound Annual Growth Rate
CCD	-	Central Composite Design
CO_2	-	Carbon Dioxide
COP	-	Conference of Parties
CT	-	Computer Tomography
DOE	-	Design of Experiment
EFB	-	Empty Fruit Bunch
FESEM	-	Field Emission Scanning Electron Microscope
GLUEs	-	Good Linear Unbiased Estimators
KF	-	Kenaf Fibre
K-PP	-	Kenaf-Polypropylene
LKTN	-	Lembaga Kenaf and Tembakau Negara
LR	-	Least Square Regression
LSE	-	Least-Squares Estimation
LSM	-	Least Squares Method
MC	-	Moisture Content
MEKP	-	Methyl Ethyl Ketone Peroxide
MLE	-	Maximum Likelihood Estimator

MOM	-	Method of Moments
MSE	-	Mean Square Error
$NaClO_2$	-	Sodium Chlorite
NaOH	-	Sodium Hydroxide
NFC	-	Natural Fibre Composite
NFRP	-	Natural Fibre Reinforced Polymer
NO_2	-	Nitrogen Dioxide
PDF	-	Probability Distribution Function
PE	-	Polyethylene
PMMA	-	Polymethyl Methacrylate
PP	-	Polypropylene
PU	-	Polyurethane
PVA	-	Polyvinyl Alcohol
QSI	-	Quasi-Static Indentation
RSM	-	Response Surface Methodology
SE-SMA	-	Superelastic Shape Memory Alloy
SEM	-	Scanning Electron Microscope
UF	-	Urea Formaldehyde
UNFCCC	-	United Nations Framework Convention on Climate Change
UPE	-	Unsaturated Polyester
USD	-	United States Dollar
UTM	-	Universal Testing Machine
WLR	-	Weighted Least Squares Regression
WPC	-	Wood-Polymer Composite
WVTR	-	Water Vapour Transmission Rate
YG	-	Yucca Gloriosa
3D	-	3 Dimensional

LIST OF SYMBOLS

σ	-	Tensile strength
σ_o	-	Tensile strength applied / characteristic strength
A	-	Contact indent
E	-	Young modulus
E_o	-	Weibull Young modulus
CV	-	Coefficient of variation
CV_d	-	Coefficient of variation of the data
C	-	Contact of stiffness
F	-	Force
$F(\sigma)$	-	The probability of survival
i	-	Imaginary number
k	-	Number of independent variables
kgm^{-3}	-	Unit of density
m	-	Weibull modulus
m_o	-	Weibull modulus for tensile strength
m_E	-	Weibull modulus for Young modulus
N	-	Total number
n	-	Indentation coefficient
P	-	Load applied
$P(\sigma)$	-	Failure probability
V	-	Fibre volume
wt.%	-	Weight percentage
X	-	Displacement / indentation depth
$\overline{x}$	-	Mean of data

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The introduction of new regulations, such as carbon emission tax and waste recycling policy has forced consumers to use recycled materials as everyday products (Zampaloni et al., 2007; Suddell, 2008). To comply with these regulations, the need to utilise environmentally friendly and green materials in different applications has significantly increased (Zampaloni et al., 2007). A massive promotion to use biodegradable materials began during the 17th session of the Conference of Parties to the UNFCCC hosted by South Africa to combat this specific environmental challenge.

In the polymer industry, the growing application of synthetic plastics and elastomers, and the demand for certain adhesives are predicted to increase due to urbanisation. Famous synthetic thermoplastic materials, such as polypropylene, polyethene and polyvinyl-chloride are practical materials with numerous household, commercial, and fashion applications. On the other hand, thermosetting polymers as non-recycled materials including epoxy, fibreglass, polyester, and polyurethane, are used in a protective coating, lightweight structures, and civil engineering construction grouts.

Therefore, the use of biodegradable materials as substitutes for non-recycled fibres in composite structures has gained great interest amongst researchers for the past two decades (Asumani, 2014). For instance, the use of natural fibres, such as kenaf and hemp in the automotive industries is recommended in the fabrication of interior and door trim parts, which do not require high load-bearing capabilities. These natural fibres are also preferred due to their low production cost and lightweight. Moreover, they finally improve car production cost and vehicle fuel efficiency. Among the natural fibres available in the composite market, kenaf (Hibiscus cannabinus) fibres extracted from the bast have been identified as an attractive option due to their ability to grow in a variety of climatic conditions (Liu and Labuschagne, 2009). They also offer tensile strength that is 81 per cent higher in polypropylene reinforced composite than neat polymer (Suddell, 2008). Kenaf reinforced thermoplastic composite has also shown approximately 20 per cent weight reduction compared to conventional parts. It is also a viable source of raw materials for food packaging and biofuel technology applications (Asumani, 2014). Based on the mentioned factors, kenaf has tremendous potential as a commodity crop that needs to be discovered, especially in emerging and developing countries.

1.2 Problem Statements

The mechanical properties of fibres are closely related to the strength of a single fibre. Uncertainty in the morphological structure, flaw, diameter inconsistency, and changes in the dimensions of the lumen of fibres, when blending it with polymer matrix has varied in the final mechanical behaviour of the composites. It affects the product performance and unpredictable micromechanical damage of the structures. Many attempts have been made to determine the absolute value of the single fibre properties using Weibull analysis as reported by Shaban et al. (2019) and Guo et al. (2014). These investigations mainly concentrated on the factors, such as chemical treatment (Zhang et al., 2018; Shaban et al. 2019; Chen et al., 2020; Ferreira et al., 2017; Shahzad et al., 2013), and gauge length (Sarasini et al., 2017; Guo et al. 2014), however, a limited study on properties of single kenaf fibre is an area of great potential to be explored. In this study, the absolute value of tensile strength for a single kenaf fibre using the Weibull and modified Weibull prediction models are used. The effect of gauge length and chemical treatment of single fibre are examined.

Even though natural fibres can replace synthetic fibres in some specific composite structures applications, however, limitations regarding the mechanical properties and resistance to moisture absorption arise when natural fibres are used. The inadequate interfacial adhesion between fibre and matrix interaction due to the hydrophilic nature of the natural fibre and the hydrophobic effect of polymer matrices is a significant weakness of the biocomposites. To improve biocompatibility and surface adhesion of fibres, Li et al. (2007) listed several surface modification methods, such as alkaline, silane, acetylation, and benzoylation treatments, which are also the best options for treating lignocellulosic fibre. On the other hand, fibre length and fibre loading also affect the mechanical properties of composite structures (Bledzki and Gassan, 1999; Bos, 2004; John and Thomas, 2008). However, there are limited studies on improving the mechanical properties through fibre treatments, fibre loading, and fibre length of kenaf reinforced composites. In this study, the optimum parameter combining alkaline concentration, fibre loading, and fibre length of the kenaf fibre composites that offered the maximum mechanical properties is investigated.

Further, one of the significant drawbacks of using natural fibre composites is low resistance to the localised loading during impact. In this study, the damage of composite panels initiated by high-speed loading dominated by fibre breakage, fibre pull-out, and delamination was obtained (Wisnom, 2012; Fahmi et al., 2016). Tan et al. (1985) reported that the indentation parameter of the synthetic composite plate was equal to 1.5 and closely similar to Hertzian's contact law (Hassan and Cantwell, 2011). However, minimal research has been conducted to evaluate the contact stiffness and indentation parameters of the natural fibre composite panels. These key parameters need to be accurately determined before simulating the natural fibre composites subjected to quasi-static and dynamic loading.

There are several knowledge gaps that need to be highlighted in the field of study. Firstly, most studies in Weibull analysis have only been carried out in a small number of studies, and the insight of this analysis is still lacking. Most of the works of literature on the Weibull analysis were focused mainly on modifying one parameter for a single natural fibre. In addition to these primary data, systematic studies on the Weibull analysis are still needed better to understand two variable parameters altogether, particularly gauge length and alkaline concentration for single kenaf fibre in the Weibull analysis. Furthermore,we were the only researchers who investigated the effect of chemical treatment on the single kenaf fibre using Weibull analysis before 2020.

Moreover, it appears from the aforementioned investigations that numerous investigations have been conducted on the effects of fibre length, fibre loading, and chemical treatment on the kenaf fibre reinforced epoxy composites. This concept has recently been challenged by only focusing on varies one parameter only and the other parameter being fixed to access the potential relationships between parameters. Therefore, a response surface methodology (RSM) tool is recommended for predicting the connections between changing parameters. However, limited works were made to investigate the simultaneous effect of these three parameters by using response surface methodology (RSM), specifically composite centre design (CCD). The optimization that combining of three input variables including fibre length, fibre loading and chemical treatment of kenaf fibre reinforced epoxy using composite centre design (CCD) has never been explored. The optimum combination of this fibre-matrix blending is novel.

Although indentation by quasi-static and dynamic loading has been widely subjected on the composites, the research to date has tended to focus on synthetic fibre, metal and ceramic composites, and there has been limited use on natural fibre composites. Besides, the indentation parameter such as contact parameter and indentation exponent for kenaf reinforced epoxy composite remains unexplored to the author best knowledge. In summary, these are the knowledge gap extracted from the prior studies, which motivated the present study.

1.3 Objectives

This study aims to enhance the mechanical performance by determining the optimum blending parameter of kenaf fibre reinforced epoxy composites. Therefore, the objectives outlined to achieve the aim are as follows:

a) To identify the absolute value of tensile properties of single kenaf fibre due to inconsistency surface morphology, flaw, diameter and lumen dimensions of the fibre by using Weibull statistical analysis.

b) To determine the optimum parameter combining alkaline concentration, fibre loading, and fibre length of kenaf fibre reinforced epoxy composites using central composite design (CCD).
c) To measure the contact stiffness and indentation exponent of the kenaf fibre reinforced epoxy composites following quasi-static and low-velocity impact.

1.4 Hypothesis

The hypotheses of this study are as follows:

a) The mechanical properties of a single kenaf fibre are influenced by chemical treatment and gauge length. Inconsistencies of these tensile properties can be determined using the Weibull statistical approach.
b) Enhancement of bonding between natural fibres and synthetic polymers comprising alkaline concentration, fibre loading, and fibre length can be achieved using the response surface method (RSM).
c) The indentation parameter of the kenaf reinforced epoxy composites lies between 0.8 to 1.5.

1.5 Scope of a Study

This study focused on determining the absolute value of tensile properties of a single kenaf fibre using the Weibull statistical approach. The effect of the gauge length and chemical treatment were discussed. The modified Weibull parameters, such as scale parameter, least square method, maximum likelihood estimation, and method of moments were discovered. Optimisation of kenaf reinforced epoxy was conducted using the CCD method. It consisted of three variables and three levels of the parameter that consolidated with alkaline concentration, fibre loading, and fibre length of kenaf fibre reinforced composite. This branch of the RSM approach was verified using the analysis of variance (ANOVA) quadratic model. In this study, the Design-Expert software version 11 was used. The indentation behaviour of the kenaf biocomposite was evaluated following quasi-static and low-velocity impact. The uppermost of the biocomposite was loaded at different speeds, indenters, and densities.

1.6 Limitation of Study

The limitation of this study was the different fibre morphology which affected the precision of the data result. Fibre morphology cannot be fully controlled even the fibres were taken from the same plant. Lack of previous research studies on the evaluation of the contact stiffness and indentation parameters of the natural fibre composite panels. The research of indentation was more on metal, foam and polymer matrix.

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LIST OF PUBLICATIONS

Web of Science Index

1. **Ibrahim, I.,** Hassan, M.Z., Abd Aziz, S., Muhamad, S., Fatah, A.Y. and Samsuddin, N. (2020). The effect of chemical treatment on the tensile behavior of kenaf fiber using Box-Behnken design. *Proceedings of Mechanical Engineering Research Day*, 2020, 84-85. **(Indexed by Web of Science)**

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Non-Index

1. **Ibrahim, I.,** Dolah, R., Zuhri, M.Y.M., Sharif, S. and Hassan, M.Z. (2017) Chemical Treatment Evaluation of Tensile Properties for Single Kenaf Fiber. *Journal of Advanced Research in Applied Mechanics*, 32, 9-14.