
# *EVALUATION OF THERMAL PROPERTIES OF BAMBOO/KENAF FIBER REINFORCED EPOXY HYBRID COMPOSITES AND NANOCOMPOSITES*

**CHEE SIEW SAND**

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# EVALUATION OF THERMAL PROPERTIES OF BAMBOO/KENAF FIBER REINFORCED EPOXY HYBRID COMPOSITES AND NANOCOMPOSITES

By

CHEE SIEW SAND

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2020

**DEDICATION**

I wish to dedicate this thesis to my family members, especially:

To my late mother:
Yong Lee Fong for her encouragement and advise in pursuing further my study

To my late grandmother:
Yong Yen Yin for her endless loves

To my beloved husband, son and daughter:
Tan Wei Chee, Lucas Tam, Hayley Tan

For their continuous love, understanding and support that enabled me to complete the work of this thesis.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

# EVALUATION OF THERMAL PROPERTIES OF BAMBOO/KENAF FIBER REINFORCED EPOXY HYBRID COMPOSITES AND NANOCOMPOSITES

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**May 2020**

**Chairman : Mohammad Jawaid, PhD**
**Institute : Tropical Forestry and Forest Product**

The awareness of environmental concerns has increased the need to produce high-performance engineering materials with natural fiber-based materials. Hybridizing natural fibers with nanofiller modified polymeric composites is a potential alternative material that displays better mechanical and thermal properties for advanced applications. This research work focussed on the evaluation of the hybridization effects between non-woven bamboo mat (B) and woven kenaf mat (K) reinforced epoxy hybrid composites with further enhancement on the thermal properties by adding nanoclay. The hybrid composites were prepared by hand lay-up techniques. The epoxy/nanoclay mixture was prepared by in-situ polymerization by using a high shear speed homogenizer. Optimum fiber mixing ratio (B/K:30/70, B/K:50/50; B/K:70/30) were examine in terms of their thermal properties and resistance against environmental effects. The results reveal that increasing the bamboo fiber loading improved the thermal stability of the hybrid composites. The initial decomposition temperature of B/K:70/30 is about 10 ℃ higher than kenaf/epoxy composite. B/K:50/50 hybrid composites exhibit the highest dimensional stability and viscoelastic behaviour. It recorded the lowest thermal expansion percentage (1.14%) while B/Epoxy and K/Epoxy recorded the total thermal expansion at 2.33% and 1.47%, respectively. Besides, the durability of the hybrid composites against environmental effects was also studied by accelerated weathering test and soil burial test. B/K:50/50 hybrid composites presents a balance of resistance to environmental effects while maintaining the biodegradability characteristic. The organoclay loading (0.5, 1.0, 2.0, 4.0wt.%) epoxy nanocomposites were fabricated. The morphological, thermal, dynamic mechanical and tensile properties of the nanocomposites show optimum performance at 1wt.% loading. Further study was carried out by fabricating B/K/Nanoclay/Epoxy hybrid nanocomposites with bamboo and kenaf fiber ratio was fixed at 50:50 and nanoclay loading was fixed at 1wt.%. The effects on adding 3 different types of nanoclays: halloysite nanotube (HNT), montmorillonite (MMT) and organically modified MMT (OMMT) were compared. The morphological, thermal

and flammability of the B/K/Nanoclay/Epoxy hybrid nanocomposites were characterized. The morphological study reveals that MMT/Epoxy and HNT/Epoxy are highly agglomerated while OMMT/Epoxy reveals a more uniform distribution morphology. The oxidative decomposition behaviour of the hybrid composites was studied with a thermogravimetry analyzer (TGA) under an oxygen atmosphere. The flammability properties were evaluated through Underwriters Laboratories 94 horizontal burning test (UL-94HB), limiting oxygen index (LOI), cone calorimetry and smoke density tester. The final decomposition temperature of B/K/OMMT recorded at 495 °C and it is 60 °C higher compare to B/K/Epoxy. The residue value of the hybrid nanocomposites at 800 ℃ is significantly increased by 196%, 175%, 269% with the addition of MMT, HNT and OMMT nanoclay, respectively. All hybrid nanocomposites achieved an HB40 rating in the UL-94HB test. With the addition of nanoclay, the LOI value increased from 20 to 28%. A significant reduction of total heat release and peak heat release rate between 36 – 43% was observed on nanoclay filled hybrid composites. Improvement of other fire indicators such as FIGRA (fire growth rate index), MARHE (maximum average rate of heat emission) and SMOGRA (smoke growth rate index) were noticed in all hybrid nanocomposites with excel performance observed on B/K/OMMT. The findings from this work can be utilized in preparing high-performance natural fibers reinforced epoxy hybrid composites with improvement in their dimensional stability and fire performance for automotive and building applications.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENILAIAN SIFAT TERMA KOMPOSIT DAN NANOKOMPOSIT HIBRID BULUH/KENAF DIPERKUKUHKAN DENGAN EPOKSI**

Oleh

**CHEE SIEW SAND**

**Mei 2020**

**Pengerusi : Mohammad Jawaid, PhD**
**Institut : Perhutanan Tropika dan Produk Hutan**

Perhatian terhadap masaalah alam sekitar yang semakin meningkat telah menginspirasikan untuk menghasilkan bahan kejuruteraan yang berprestasi tinggi dengan sumber alam semulajadi. Hibridisasi serat semulajadi dengan komposit polimer yang diubahsuai dengan nanofiller adalah bahan alternatif yang berpotensi dan mempamerkan sifat unggul untuk aplikasi berprestasi tinggi. Kajian ini menumpukan penilaian terhadap kesan hibridisasi antara serat buluh bukan tenunan buluh (B) dan serat tenunam kenaf (K) sebagai ejen pengukuh dalam komposit hibrid epoksi dan penambahan nanoclay untuk meningkatkan sifat terma. Komposit hibrid disediakan dengan teknik belaian tangan. Pengubahsuaian epoksi menggunakan cara pempolimeran in situ. Nanoclay ditambahkan dengan epoksi melalui kaedah pencampuran daya ricih tinggi. Nisbah pencampuran serat yang optimum (B/K:30/70, B/K:50/50; B/K:70:30) telah dinilai dari segi sifat terma dan rintangan terhadap kesan persekitaran. Sifat terma komposit hibrid bertambah baik dengan penambahan serat buluh ke atas komposit kenaf. Suhu penguraian awal komposit hibrid B/K:70/30 adalah 10 ℃ lebih tinggi berbanding dengan komposit K/Epoksi. B/K:50/50 menunjukkan keunggulan dari segi kestabilan dimensi dan sifat likat-elastik. Ia mencatatkan peratusan pengembangan terma paling rendah (1.14%) manakala peratusan pegembangan terma komposit B/Epoksi dan K/Epoksi adalah sebanyak 2.33% dan 1.47% masing-masing. Di samping itu, rintangan komposit hibrid terhadap kesan persekitaran juga dikaji dengan ujian luluhawa dipercepat dan ujian timbusan tanah. B/K:50/50 menunjukan rintangan terhadap kesan persekitaran, sambil mengekalkan ciri-ciri biodegradasi. Penambahan nanoclay (0.5, 1.0, 2.0, 4.0wt.%) untuk menyediakan nanokomposit epoksi telah dikaji. Penambahan nanoclay 1wt.% menunjukkan prestasi optimum dari segi morfologi, terma, kekuatan dinamik dan kekuatan tegangan. Kajian selanjutnya dilakukan dengan menyediakan hibrid komposit B/K/Nanoclay/Epoksi dengan nisbah buluh and kenaf ditetapkan pada 50:50 dan penambahna nanoclay sebanyak 1wt.%. Kesan penambahan 3 jenis nanoclays: '*halloysite nanotube'* (HNT), '*montmorillonite'* (MMT) dan organik MMT (OMMT)

telah dibandingkan. Morfologi, terma dan sifat mudah terbakar hibrid nanokomposit dicirikan. Kajian morfologi menunjukkan bahawa HNT/Epoksi dan MMT/Epoksi memaparkan aglomerasi manakala OMMT/Epoksi memaparkan morfologi taburan yang seragam. Instrumentasi termogravimetri (TGA) digunakan untuk mengkaji suhu penguraian nanokomposit hibrid dengan gas oksigen. Ciri-ciri mudah terbakar ditaksirkan melalui ujian *'Underwriters Laboratories 94'* (UL-94), *'limiting oxygen index'* (LOI), kon calorimetri dan penguji ketumpatan asap. Suhu penguraian akhir B/K/OMMT direkodkan pada suhu 495 ℃, iaitu sebanyak 60 ℃ lebih tinggi berbanding dengan B/K/Epoksi. Sisa penguraian yang direkodkan pada suhu 800 ℃ meningkat sebanyak 196%, 175%, 269% dengan penambahan MMT, HNT dan OMMT. Semua nanokomposit hibrid mencapai pengadaran HB40 dalam ujian UL-94. LOI juga meningkat dari 20% ke 28% dengan penambahan nanoclay. Penurunan kadar pelepasan haba puncak (pHRR) sebanyak 36 – 43% juga direkodkan pada nanokomposit hibrid. Peningkatan indeks api, FIGRA (indeks kadar pertumbuhan api), MARHE (kadar purata maksimum pelepasan haba) dan SMOGRA (indeks kadar pertumbuhan asap) telah dijumpai dalam semua nanokomposit hibrid dengan B/K/OMMT menunjukkan prestasi yang unggul. Hasil dari kerja ini boleh digunakan dalam menyediakan komposit hibrid epoksi yang memaparkan sifat kestabilan dimensi dan tahan api untuk aplikasi automotif dan bangunan.

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Last but not least, I would like to thank my parents, husband, son and daughter for supporting me spiritually throughout writing this thesis.

**Chee Siew Sand**

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

**Mohammad Jawaid, PhD**
Research Fellow
Institute of Tropical Forestry and Forest Product
Universiti Putra Malaysia
(Chairman)

**Mohamed Thariq bin Hameed Sultan, PhD**
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Member)

**Luqman Chuah bin Abdullah, PhD**
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

**Othman Y Alothman, PhD**
Professor
College of Engineering
King Saud University
Saudi Arabia
(Member)

**ZALILAH MOHD SHARIFF, PhD**
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:16 July 2020

**Declaration by graduate student**

I hereby confirm that:

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Name and Matric No: Chee Siew Sand (GS47197)

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This is to confirm that:

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Signature: _____
Name of Chairman of Supervisory Committee: Dr. Mohammad Jawaid

Signature: _____
Name of Member of Supervisory Committee: Professor Ir. Dr. Mohamed Thariq Bin Hameed Sultan

Signature: _____
Name of Member of Supervisory Committee: Professor Dr. Luqman Chuah Bin Abdullah

Signature: _____
Name of Member of Supervisory Committee: Professor Dr. Othman Y. Alothman

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| APTES | 3-aminopropyltriethoxy silane |
| Bamboo | B |
| BMC | Bulk moulding compound |
| CAGR | Compound annual growth rate |
| CTE | Coefficient of thermal expansion |
| DGEBA | Diglycidyl ether of bisphenol A |
| DMA | Dynamic mechanical analysis |
| DSC | Differential scanning calorimetry |
| FESEM | Field Emission Scanning Electron Microscope |
| FIGRA | Fire growth rate index |
| FR | Fire retardant |
| HNT | Halloysite nanotube |
| Kenaf | K |
| LDH | Layered double hydroxide |
| LOI | Limiting oxygen index |
| MARHE | Maximum average rate of heat emission |
| MMT | Montmorillonite |
| NFPC | Natural fiber polymer composites |
| ODA | Octadecylamine |
| OIT | Oxidation induction time |
| OMMT | Organo-modified montmorillonite |
| OOT | Oxidation onset temperature |
| pHRR | Peak heat release rate |
| RoHS | Restriction of hazardous substances |

| | |
|---|---|
| SMOGRA | Smoke growth rate index |
| TGA | Thermogravimetric analysis |
| TMA | Thermomechanical analysis |
| TOD | Thermo-oxidative |
| UV | Ultraviolet |
| WAXS | Wide angle x-ray scattering |
| WEEE | Waste electrical and electronics equipment |

## LIST OF SYMBOLS

| | |
|---|---|
| E* | Complex modulus |
| $\nu_e$ | Cross link density |
| $C$ | Effective coefficient |
| $T_E$ | Endset of degradation |
| $T_g$ | Glass transition temperature |
| $L_0$ | Initial sample length |
| E" | Loss modulus |
| $\bar{\alpha}$ | Mean coefficient of linear thermal expansion |
| D | Moisture diffusion coefficient |
| $T_o$ | Onset of degradation |
| E' | Storage modulus |
| È | Storage modulus in rubbery region |
| Tan $\delta$ | Tan delta |
| $T_M$ | Temperature of maximum rate of mass loss |
| $\Delta E$ | Total colour changes |
| $W_{loss}$ | Weight loss |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Natural fiber polymer composites (NFPCs) are a class of composite material comprising a polymer matrix reinforced with high-strength natural fibers, such as jute, oil palm, sisal, kenaf, bamboo, or flax (Atiqah et al., 2019). The NFPCs are garnering much attention from the research and industrial community due to the increase in environmental awareness, new environmental regulations, and the depletion of unsustainable petroleum products. The market for end products made with natural fibers is expected to reach an estimated $12.2 billion by 2023 ("Bio-Composites Market by end use industry, process, resin, fiber, and region 2018-2023| Lucintel,"). The key driver for the rise of this market is the growth in demand for lightweight and environmentally sustainable composite materials for various applications, such as automotive, building, construction, and others (Al-Oqla & Sapuan, 2014; Dai & Fan, 2013; Fan & Fu, 2016).

Natural fibers are renewable resources and exhibit several advantages such as low weight, high specific stiffness and strength, biodegradable, readily available from natural sources, and more importantly inexpensive as compared to synthetic fibers (Sen et al., 2016). Natural fibers from the plant can be extracted from the plants' stem (bast fibers), leaf, seed, wood, fruit, grass, and stalk. Bast fibers such as kenaf, jute, hemp and ramie exhibit attractive mechanical properties providing a replacement to glass fibers as reinforcing components in polymer composites (Faruk et al., 2012; Jawaid & Khalil, 2011).

Hybrid composites are advanced engineering material that consists of two or more different constituent at the molecular or nanometer level leading to a distinctive property composite that cannot be delivered by single constituent based composite (Saba et al., 2016c). One of the common approaches is the hybrid composites were reinforced with natural and synthetic fibers and these composites display enhanced mechanical and thermal stability performance (Khalil et al., 2009; Hariharan & Khalil, 2005; Thiruchitrambalam et al., 2010). Hybrid composite reinforced solely by natural fibers is rare, but they are possible to develop into useful materials with regards to environmental concerns (Shanmugam & Thiruchitrambalam, 2013). Natural fibers can be incorporated into a polymer composite in different forms, such as continuous, randomly oriented, and as woven or non-woven mat form. The latter form is found to be more attractive reinforcement as they provide excellent integrity and conformability for advanced structural applications (Singh et al., 2015). Researchers report that the woven fabric composites show excel performance on tensile, flexural and impact properties as compare to those of unidirectional and randomly oriented composites (Arifuzzaman et al., 2016).

The technology advances in the field of nanotechnology and nanomaterials have brought interesting new possibilities into the materials field with the development of polymer nanocomposite where nano-size fillers (nanoclay, graphene, carbon nanotube, etc.) dispersed in a polymer matrix. In particular, many researchers have reported that polymer nanocomposites (PNCs) which filled with small amount of nanoclay (< 5% by weight) show enhanced properties in several perspectives such as improvement of mechanical properties, enhanced barrier properties, good solvent and heat resistance and improved fire performance (Suoware et al., 2017; Zabihi et al., 2018). Hybridizing natural fibers together with nanoclay shown great promising properties that can overcome the limitations of traditional composites such as hydrophilic nature of natural fibers, low heat and fire-resistant. Few research works have been reported on nanoclay/natural fiber hybrid nanocomposites such as bamboo/organoclay/polyester (Patel et al., 2018) madar/organoclay/polyester (Ramakrishnan et al., 2019), banana/nanoclay/epoxy (Mohan & Kanny, 2019) and kenaf/oil palm empty fruit bunch/epoxy (Saba et al., 2019). All these natural fibers/ nanoclay hybrid composites revealed improved mechanical, physical and thermal properties compared to un-hybridized composites.

In this research, the potential of hybridizing non-woven bamboo mat and woven kenaf mat with epoxy matrix was explored. This research focussed on finding the optimum mixing ratio between bamboo and kenaf fibers and fabrication of bamboo/kenaf/nanoclay/epoxy hybrid composites through hand lay-up technique. The effect of adding nanoclay on bamboo/kenaf/epoxy hybrid composite was evaluated on the morphological, thermal and flammability properties.

## 1.2 Problem of statement

Synthetic fiber such as glass, Kevlar, carbon, etc. was commonly used as reinforcing fibers in polymer composites due to its excellent mechanical performance, long fatigue life, and versatile functionality. Despite the excel properties possess by synthetic fiber reinforced polymer composites, they have got some severe problems such as high cost, high density (as compared to polymers), poor recyclability, and non-biodegradable properties. Synthetic fiber is difficult to dispose of due to its poor recyclability and non-biodegradable properties, meaning at the end is long-term pollution contributing to an overwhelming amount of chemicals, waste, and carbon emission. To turn synthetic fiber into ash, the special incinerator is required but these equipment are expensive (Frederick & Weston, 2004). High manufacturing cost, safe and healthier working environment is another major concern on the usage of synthetic fiber. NFPCs is the alternative material replacing synthetic fiber polymer composites in automotive and building applications (Davoodi et al., 2011; Mounika et al., 2012; Pozo et al., 2017; Preda eta l., 2019). However, their applications may limit to only non-structural and indoor applications. The inherent properties of natural fiber polymer composites such as low thermal stability, high flammability, and release of toxic gasses during the combustion of both polymer matrix and natural fiber have greatly hindered their versatility for different applications.

Temperature plays an influential role in changing a material property; thus, it is important to understand the thermal behavior of a material. For instance, composite material intended for outdoor applications required better durability against UV, moisture, and heat as compared to indoor applications. Besides that, the material used for automotive and outdoor building materials applications is preferred with high dimensional stability, thermal stability, and flammability.

Kenaf fiber is well known for its high strength and high initial modulus characteristic. Another interesting property of kenaf fiber is its long aligned and continuous fiber to manufacture into a woven mat form. On the other hand, bamboo fiber are well known for strong, stiff, inferior microfibrillar angle with the fiber axis and thicker cell wall and is considered as ‘‘nature’s glass fiber’ (Li et al., 1995). The high lignin content in bamboo fiber also renders high thermal stability performance. However, the bamboo fiber in the woven mat form is hardly available due to its stiff fiber and brittle characteristic.

Kenaf and bamboo fiber have been reported to hybridize with different natural fiber such as oil palm empty fruit bunch, jute, hemp, pineapple leaf, coir, etc. Most of these findings show that hybrid composites exhibit improved mechanical properties (Asim et al., 2017; Hanan et al., 2018; Safwan et al., 2019), thermal properties (Saw & Datta, 2009), moisture absorption behavior (Maslinda et al., 2017) which cannot be achieved by single fiber-based composites. Besides, a study carried out by Safwan et al., (2019) on a bamboo/kenaf hybrid composites show improvement on the void content, tensile, vibration, and acoustic properties. They suggested the resultant hybrid composites may be used for non-load bearing structure applications.

This research aims to prepare a more environmentally friendly composite by reducing the utilization of petroleum-based materials. Hence, bamboo fibers, kenaf fibers, and nanoclay are used as reinforcement to prepare a novel bamboo/kenaf/nanoclay/epoxy hybrid composites by evaluating the thermal expansion, dynamic mechanical, thermal stability, morphological and flammability properties. Besides, the resistance to environmental effects such as UV irradiation, moisture and microorganism activities are also explored. Hence, hybridizing woven kenaf mat fibers and non-woven bamboo mat fibers in a nanoclay modified epoxy matrix will provide enhanced properties that cannot be achieved from either natural fiber composites or nanoclay/polymer nanocomposites. Also, the bamboo/kenaf/nanoclay hybrid composites may pave as a new alternative material to conventional synthetic fiber composites for automotive and civil engineering applications which demand high dimensional and thermal stability.

## 1.3 Objective

The primary aim of this current study is to fabricate a natural fibers base hybrid composite system by using a non-woven bamboo mat and woven kenaf mat as reinforcing fiber and nanoclay modified epoxy as the matrix. The bamboo/kenaf hybrid composites, epoxy nanocomposites, and bamboo/kenaf/epoxy nanocomposites are characterized. The specific research objectives are as follows:

1. To explore the effect of hybridizing bamboo and kenaf fibers on the thermal properties of bamboo/kenaf fibers reinforced epoxy hybrid composites.
2. To analyze the environmental and biodegradation effect on the thermal properties of kenaf/bamboo reinforced epoxy hybrid composites.
3. To evaluate the morphological, thermal stability, viscous elastic behaviour and tensile properties of nanoclay modified epoxy nanocomposites.
4. To investigate the effect of nanoclay on the morphological, thermo-oxidative stability and flammability properties of the bamboo/kenaf fibers reinforced epoxy hybrid composites.

## 1.4 Significance of this study

Growing environmental concerns, new environmental regulations, and the unsustainable consumption of petroleum have sparked interest in the development of natural fibers composites, which could be the new bio-friendly alternative to synthetic fibers reinforced composites. According to the environmental legislation, the REACH ACT (Registration, Evaluation, Authorization and Restriction of Chemical Substances) ("REACH - Chemicals - Environment - European Commission") alternative material with comparable properties to synthetic fibers, green attribution, and low cost shall replace the traditional material.

Hybrid composites reinforced solely with natural fibers are infrequent, but they could be a highly potential alternative material. Currently, the studies on the thermal properties such as thermal expansion/ shrinkage behavior, thermal/ thermo-oxidative stability, dynamic mechanical properties of hybrid composites reinforced solely by natural fibers remained scared. Besides, only limited study has been carried out on natural fibers composites reinforcing with mat form natural fibers.

The findings from the current study are expected to enhance the knowledge of the thermal properties of a non-woven bamboo/woven kenaf hybrid composites. It is anticipated that the woven kenaf mat would render better dimensional stability to the composite due to the longitudinal fiber arrangement on both horizontal and vertical directions. Also, it is anticipated to improve the thermal stability of kenaf fiber by incorporation of bamboo fibers due to the higher thermal stability possess by bamboo fiber compare to kenaf fiber.

The high susceptibility of fibers and polymers to flames has limited their applications especially in areas where fire threat is imminent. Nanoclay is an attractive material because the addition of a small quantity of nanoclay can improve mechanical, thermal, and electrical properties of plastics without changing processability. Hence, hybridizing bamboo and kenaf fibers in the nanoclay modified epoxy composites will improve the performance of the composites by overcoming the intrinsic properties of NFCs. It is expected that this research will open new avenues in the NFCs materials research for automotive and building material applications.

## 1.5 Scope of this study

Scope of current research work focussed on the evaluation of the hybridization effects between bamboo and kenaf fibers reinforced in the epoxy matrix by hand lay-up technique. The optimum nanoclay loading to prepare epoxy modified composite was also studied. The thermal properties and the effects of environmental and biodegradation on the thermal properties of the bamboo/kenaf reinforced epoxy hybrid composites were evaluated. The optimum mixing ratio of bamboo and kenaf fibers with excel thermal properties and optimum nanoclay loading was selected for further fabrication of bamboo/kenaf/nanoclay/epoxy hybrid nanocomposites. The influence of adding three different types of nanoclays (HNT, MMT and OMMT) on morphological, thermal, and flammability properties of the hybrid nanocomposites were studied and compared.

## 1.6 Thesis outline

This thesis has been structured in 10 chapters according to alternative thesis format of Universiti Putra Malaysia (UPM) based on the publication, in which each chapter (4 – 9) represent a separate study that contains its own: 'Introduction', 'Materials and methods', 'Results and discussion' and 'Conclusion'. Brief description of each chapter has been addressed in the following section.

### Chapter 1

The information about the background of this research, problem statements, objectives, significance of the study, scope and thesis outline are explicated within this chapter.

### Chapter 2

This chapter presents a comprehensive literature review on essential area connected to the topics such as natural fiber composites, nanoclay polymeric composites, hybrid composites and applications of nanoclay/natural fibers hybrid composites.

**Chapter 3**

This chapter addresses a details description on the materials, methodology and characterization techniques that employed in this study.

**Chapter 4 (Objective 1: Article 1)**

This chapter presents the first article entitled **"Thermal stability and dynamic mechanical properties of kenaf/bamboo fiber reinforced epoxy composites"**. This research intended to perform a preliminary study on the thermal and dynamic mechanical properties of monolithic composite system (bamboo/epoxy and kenaf/epoxy) and evaluated the feasibility to hybridized both fibers for further studies.

**Chapter 5 (Objective 1: Article 2)**

This chapter deal with the first objective supported by second article entitled **" Thermomechanical and dynamic mechanical properties of bamboo/ woven kenaf mat reinforced epoxy hybrid composites"**. This research study intended to evaluate the hybridizing effects of bamboo and kenaf fibers on the thermomechanical and dynamic mechanical properties of the hybrid composites.

**Chapter 6 (Objective 1: Article 3)**

This chapter deal with the first objective supported by third article entitled **" Evaluation of the hybridization effect on the thermal and thermo-oxidative stability of bamboo/kenaf/epoxy hybrid composites"**. This study evaluated the hybridizing effects of bamboo and kenaf fibers on the thermal and thermo-oxidative stability of the hybrid composites.

**Chapter 7 (Objective 2: Article 4)**

This chapter addresses the second objective supported by the fourth research article entitled **"Accelerated weathering and soil burial effects on colour, biodegradability and thermal properties of bamboo/kenaf/epoxy hybrid composites"**. This study aims to gain insight into the influence of environmental effects on the colour, biodegradability, oxidation stability, thermal stability, and complex modulus of bamboo/kenaf/epoxy hybrid composites.

**Chapter 8 (Objective 3: Article 5)**

This chapter presents the third objective supported by the fifth research article entitled **"Effect of bi-functionalized MMT on morphology, thermal stability, dynamic mechanical and tensile properties of epoxy/organoclay nanocomposites"**. The nanoclay loading (0.5, 1.0, 2.0, 4.0 wt.%) to prepare nanoclay/epoxy nanocomposites

was studied. The effect on morphology, thermal, dynamic mechanical and tensile properties of the nanoclay/epoxy nanocomposites were studied in this work.

**Chapter 9 (Objective 4: Article 6)**

This chapter addresses the fourth objective supported by the sixth research article entitled **"Thermo-oxidative stability and flammability properties of bamboo/ kenaf/ nanoclay reinforced epoxy hybrid nanocomposites"**. This research evaluated the effect of adding nanoclay on the morphological, thermo-oxidative and flammability properties of bamboo/kenaf/nanoclay reinforced epoxy hybrid nanocomposites.

**Chapter 10**

This chapter addresses the conclusions from the individual articles and overall conclusions and future recommendations.

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