# DEVELOPMENT AND CHARACTERIZATION OF FLAX/CARBON/KEVLAR-REINFORCED BIO-PHENOLIC/EPOXY BLENDS HYBRID COMPOSITES FOR BALLISTIC HELMET

By

**AHMAD SAFWAN BIN ISMAIL**

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

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

Nowadays, the needs of high-performance materials have led the researcher to study various method in producing new material through modification or synthesis of polymers. Polymer blends is one of the methods in polymer modification which can be used to improve the overall performance of polymer. The first stage of this study is to investigate the effect of different bio-phenolic loading, which is 5(P-5), 10(P-10), 15(P-15), 20(P-20) and 25(P-25) wt% on the physical, structural, mechanical, morphological, dynamic mechanical and thermal properties of epoxy matrix. The polymer blends have a void content of less than 5% and water absorption of less than 1%. P-20 showed the highest tensile strength, flexural strength and impact resistance while P-25 showed the highest tensile and flexural modulus. The addition of bio-phenolic to epoxy matrix has improve the dynamic mechanical analysis (DMA) and thermal stability of polymer blends. Based on the analysis it was revealed that polymer blend with 20wt% bio-phenolic show optimum formulation. This formulation will be used in second and third stage of this study. The second stage of the study was designed to evaluate the physical, mechanical, morphological, dynamic mechanical and thermal properties of bio-phenolic/epoxy polymer blends with incorporation of flax fabric as reinforcement. Flax reinforced bio-phenolic/epoxy composites was fabricated with different fibre loading, which is 30(F-30), 40(F-40) and 50(F-50) wt%. The obtained results showed that addition of flax fabric has increase the water absorption and density of the composites while the void content of the composite was reported less than 3%. F-50 showed the highest tensile properties and impact strength while F-40 has the highest flexural properties. The addition of flax fabric improved the DMA of the composite but decreased its thermal stability. The analysis reveals the optimum fibre loading is 50wt% and it will be used in the third stage of the study. Flax/carbon/Kevlar reinforced bio-phenolic/epoxy hybrid composites were fabricated with different ratio of Flax fabric and carbon/Kevlar fabric (F/CK) which is 100/0 (F), 75/25/ (75F25CK), 50/50 (50F50CK). 25/75 (25F75CK) and 0/100 (CK). The hybrid composites were analysed based on physical, mechanical, morphological, dynamic mechanical, high velocity impact and thermal properties. The density of the composite increase while water absorption decreases with addition of carbon/Kevlar fabrics. The void content of the composite was reported to be less than 2%. The hybrid composite, 25F75CK have tensile and flexural strengths that are about 70% and 82%, respectively, of those of the CK composites. In addition, tensile modulus, flexural modulus and impact strength of hybrid composite, 25F75CK is better compared to CK composite. Moreover, the DMA and thermal stability of the composite increase with addition of carbon/Kevlar fabrics. In addition, the high velocity impact test of hybrid composite 25F75CK showed there is no significant different in energy absorption and ballistic limit compared to carbon/Kevlar composite where the different is 5.50% and 2.79%, respectively. The study found that the hybrid composite 25F75CK has the best overall mechanical properties and comparable ballistic properties to carbon/Kevlar composites. This suggests that 25F75CK hybrid composites have potential for use in ballistic helmet applications.

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

**PEMBANGUNAN DAN PENCIRIAN KOMPOSIT HIBRID BIO-FENOLIK/EPOKSI DIPERKUKUH FLAX/KARBON/KEVLAR UNTUK TOPI KELEDAR BALISTIK**

Oleh

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Pada masa kini, keperluan akan bahan berkualiti tinggi telah mendorong penyelidik untuk mengkaji pelbagai kaedah dalam penghasilan bahan baru melalui pengubahsuaian atau sintesis polimer. Campuran polimer adalah salah satu kaedah dalam pengubahsuaian polimer yang boleh digunakan untuk meningkatkan prestasi keseluruhan polimer. Peringkat pertama kajian ini adalah untuk menyiasat kesan pemuatan bio-fenolik yang berbeza, iaitu 5(P-5), 10(P-10), 15(P-15), 20(P-20) dan 25(P-25) wt% pada sifat fizikal, struktur, mekanikal, morfologi, mekanikal dan haba matriks epoksi. Campuran polimer mempunyai kandungan rongga kurang daripada 5% dan penyerapan air kurang daripada 1%. P-20 menunjukkan kekuatan tegangan, kekuatan lenturan dan rintangan hentaman tertinggi manakala P-25 menunjukkan modulus tegangan dan lentur yang paling tinggi. Penambahan bio-fenolik kepada matriks epoksi telah meningkatkan analisis mekanikal dinamik (DMA) dan kestabilan terma campuran polimer. Berdasarkan analisis didapati bahawa campuran polimer dengan 20wt% bio-fenolik menunjukkan formulasi optimum. Formulasi ini akan digunakan dalam peringkat kedua dan ketiga kajian ini. Peringkat kedua kajian telah direka untuk menilai sifat fizikal, mekanikal, morfologi, mekanikal dinamik dan terma campuran polimer bio-fenolik/epoksi dengan penggabungan fabrik flax sebagai pengukuh. Komposit bio-fenolik/epoksi bertetulang flax telah direka dengan kandungan serat berbeza, iaitu 30(F-30), 40(F-40) dan 50(F-50) wt%. Keputusan yang diperolehi menunjukkan penambahan fabrik flax telah meningkatkan penyerapan air dan ketumpatan komposit manakala kandungan rongga komposit dilaporkan kurang daripada 3%. F-50 menunjukkan sifat tegangan dan kekuatan hentaman tertinggi manakala F-40 mempunyai sifat lenturan yang paling tinggi. Penambahan fabrik flax meningkatkan DMA komposit tetapi mengurangkan kestabilan termanya. Analisis menunjukkan kandungan serat yang optimum adalah 50wt% dan ia akan digunakan dalam peringkat ketiga kajian ini. Komposit hibrid bio-fenolik/epoksi diperkukuh flax/karbon/Kevlar telah difabrikasi dengan nisbah berbeza fabrik Flax dan fabrik

karbon/Kevlar (F/CK) iaitu 100/0 (F), 75/25/ (75F25CK), 50/ 50 (50F50CK). 25/75 (25F75CK) dan 0/100 (CK). Komposit hibrid dianalisis berdasarkan sifat fizikal, mekanikal, morfologi, mekanikal dinamik, kesan halaju tinggi dan sifat terma. Ketumpatan komposit meningkat manakala penyerapan air berkurangan dengan penambahan fabrik karbon/Kevlar. Kandungan rongga komposit dilaporkan kurang daripada 2%. Komposit hybrid, 25F75CK mempunyai kekuatan tegangan dan lenturan yang masing-masing 70% dan 82%, daripada komposit CK. Selain itu, modulus tegangan, modulus lenturan dan kekuatan hentaman hybrid komposit 25F75CK adalah lebih baik berbanding komposit CK. Selain itu, DMA dan kestabilan terma komposit meningkat dengan penambahan fabrik karbon/Kevlar. Selain itu, ujian hentaman halaju tinggi komposit hibrid 25F75CK menunjukkan tiada perbezaan yang signifikan dalam penyerapan tenaga dan had balistik berbanding komposit karbon/Kevlar di mana perbezaannya masing-masing adalah 5.50% dan 2.79%. Kajian mendapati komposit hibrid 25F75CK mempunyai sifat mekanikal keseluruhan terbaik dan sifat balistik setanding dengan komposit karbon/Kevlar. Ini menunjukkan bahawa komposit hibrid 25F75CK mempunyai potensi untuk digunakan dalam aplikasi topi keledar balistik.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AFRP | Aramid reinforced polymer composites |
| ASTM | American Society for Testing and Materials |
| B | Basalt |
| BMC | Bulk Moulding Compound |
| C | Carbon |
| CDN | cardanol/ formaldehyde |
| CF | Carbon fibre |
| CFRP | Carbon fibre-reinforced polymer |
| CK | Carbon/Kevlar |
| CS | Cocos nucifer sheath |
| DMA | Dynamic mechanical analysis |
| DNA | Deoxyribonucleic acid |
| DSC | Differential scanning calorimetry |
| DTG | first derivative curve of thermogravimetric |
| ECO | Epoxidized corn oil |
| EMI | Electromagnetic interference |
| EP | Epoxy |
| EPN | Epoxidized phenolic novolacs |
| Eq | Equation |
| F | Flax |
| FFRP | Flax fibre reinforced polymer |
| FRPC | Fibre reinforced polymer composite |
| FTIR | Fourier transform infrared spectroscopy |
| G | Glass |

| | |
|---|---|
| GFRP | Glass reinforced polymer composites |
| H | Hybrid |
| HCL | Hybrid composite laminate |
| HFRP | Hybrid fibre reinforced polymer |
| K | Kevlar |
| KFE | Kevlar/flax/epoxy |
| Lig-F | lignin-based flame-retardant additive |
| MAPP | Maleic anhydride polypropylene |
| NFRC | Natural fibre reinforced composites |
| NIJ | National institute of justice |
| NMT | Natural fibre mat thermoplastic |
| NP-C/C | Needle-punched carbon-carbon |
| PAN | Polyacrylonitrile |
| PE | Polyethylene |
| PLA | Polylactic |
| PMCs | Polymer matrix composites |
| PN | Phenolic phenol/formaldehyde |
| PP | Polypropylene |
| PSF | Polysulfone |
| PSR | Polysulfide rubber |
| PTTA | Poly(p-phenylenetrephthalamide) |
| RTM | Resin transfer method |
| SCRIMP | Seemann Composite Resin Infusion Moulding Process |
| SEM | Scanning electron microscopy |
| SMC | Sheet moulding compound |

| | |
|---|---|
| SRIM | Structural reaction injection moulding |
| Tg | Glass transition temperature |
| TGA | Thermogravimetric analysis |
| UD | Unidirectional |
| UPR | Unsaturated polyester |
| UV | Ultraviolet |
| VARI | Vacuum-assisted resin infusion |
| VARTM | Vacuum assisted resin transfer moulding |
| VE | Vinyl ester |

## LIST OF SYMBOLS

| | |
|---|---|
| $V_{50}$ | Ballistic limit |
| cm | Centimeter |
| $cm^3$ | Centimeter cube |
| °C | Degree Celsius |
| $d_{CK}$ | Density of carbon/Kevlar fabric |
| $d_F$ | Density of flax fabric |
| d | Density of reinforcement |
| D | Density of resin |
| de | Depth of beam |
| $E_{(abs)}$ | Energy absorption |
| $F_L$ | Flexural in longitudinal direction |
| $F_T$ | Flexural in transverse direction |
| $FM_L$ | Flexural modulus in longitudinal direction |
| $FM_T$ | Flexural modulus in transverse direction |
| GPa | Gigapascal |
| g | Gram |
| g/cm3 | Gram per cubic centimeter |
| gsm | Grams per square meter |
| Hz | Hertz |
| h | Hour |
| $v_i$ | Impact velocity |
| $W_d$ | Initial weight before immersing in distilled water |
| J | Joule |
| E” | Loss modulus |

| | |
|---|---|
| *m* | Mass |
| $D_E$ | Measured density |
| MPa | Megapascal |
| m | Meter |
| m/s | Meter per second |
| mg | Milligram |
| mm | Millimeter |
| mL | Milliliter |
| min | Minutes |
| cm-1 | Per centimeter |
| % | Percentage |
| Ra | Rate of crosshead motion |
| $v_r$ | Residual velocity |
| s | Second |
| E’ | Storage modulus |
| L | Support span |
| $T_L$ | Tensile in longitudinal direction |
| $T_T$ | Tensile in transverse direction |
| $TM_L$ | Tensile modulus in longitudinal direction |
| $TM_T$ | Tensile modulus in transverse direction |
| $D_T$ | Theoretical density |
| *v* | Volume |
| $W_n$ | Weight of the sample after immersing in distilled water |
| $r_{CK}$ | Weight percent of carbon/Kevlar fabric |
| $r_F$ | Weight percent of flax fabric |

| | |
|---|---|
| r | Weight percent of reinforcement |
| R | Weight percent of the resin |
| wt % | Weight percentage. |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Fibre reinforced polymer composite (FRPC) has been used in wide range of application such as automotive, defense marine, aerospace and structural (Mishra et al., 2020; Ramesh, 2016; K. Venkatesan & Bhaskar, 2020; Yahaya et al., 2014a). The performance of FRPC varies depending on the combination of polymer matrix and reinforcement. The selection of polymer matrix and reinforcement depending on its application. Polymer matrix is divided into two types which are thermoplastic and thermoset. Polyviny butraly, polypropylene, polycarbonate and acrylonitrile butadiene styrene are example of thermoplastic. While some of thermoset polymers are epoxy, polyester, polyvinyl ester and phenolic. Polymer blends are a mixture of two or more polymer matrix. This combination gives benefits in terms of economic and material properties. There a lot of study has been done on polymer blends. Cabo et al. (2023) investigated the effect of epoxidized corn oil content on the properties of a polymer blend of vinyl ester and epoxidized corn oil(ECO). It was found that optimum ECO content is 15%. Lee et al. (2023) investigated the effect of polymer blending of epoxy/polyimide on the thermal and mechanical properties and found that blending epoxy with polyimide improved the mechanical properties. Another study conducted by Unnikrishnan and Thachil (2006b) on the properties of phenolic/epoxy polymer blends. Different loading of phenolic were used (2.5,5 10,15 and 20 wt%). There is improvement in the properties of blends containing 10-15 wt% of phenolic resin. Further increase in loading of phenolic resin gives the negative effect on the properties of polymer blends.

Besides that, properties of polymer can be improved by incorporate the polymer matrix with reinforcement. Usually, fibre was used as reinforcement in polymer such as E-glass, carbon and aramid. Combination of fibre as reinforcement in polymer matrix can produce a composite with unique properties. There are two types of fibre which are natural fibre and synthetic fibre. Synthetic fibre is usually used for advanced applications such aerospace, structural and ballistic application. This is because synthetic fibre has higher strength compared to natural fibre. However, synthetic fibre is expensive, abrasive to environment and used high energy for production compared to natural fibre. Natural fibre can produce a composite which has good mechanical properties, cost effective, eco-friendly, and renewable material (Ain Umaira et al., 2016; Biswas et al., 2015; Tang & Yan, 2017). This has made researcher to study the effect of hybridizing synthetic fibre with natural fibre in order to produce a composite with suitable properties for targeted application, more environmentally friendly and low cost compared to polymer composite with synthetic fibre only.

Wang et al. (2023) investigated the mechanical properties of unidirectional flax/carbon fibre reinforced epoxy composites. They found that the tensile properties of the hybrid composites were enhanced compared to those of the flax and carbon composites alone. Audibert et al. (2018) has investigate the mechanical properties and damage mechanism of flax/Kevlar reinforced epoxy composites. It can be concluded that from this study, hybrid composites have intermediate mechanical properties compared to flax composite and Kevlar composite. Zhao et al. (2017) has studied the flexural behavior of jute/glass mat hybrid reinforced unsaturated polyester. In this study different ratio of jute/glass were used which is 1:0, 1:1, 1:2 and 2:1. It was found that hybrid jute/glass with ratio 1:1 and 2:1 exhibit the highest flexural strength. Naveen et al. (2019) study on mechanical properties of Kevlar (K)/cocos nucifer sheath (CS) reinforced epoxy composites. Different weight ratios of Kevlar and cocos nucifer sheath (K/CS) were used which is 100/0, 75/25, 50/50, 25/75 and 0/100. It was found that the highest tensile, flexural and impact properties among the hybrid composites is 75/25. However, compared to Kevlar composite tensile strength decreases about 19% while tensile modulus declines about 27%. Different with tensile properties, compared to Kevlar composite hybrid composites with ratio 75/25 show improvement in flexural strength and modulus. In addition, the impact strength of hybrid composite 75/25 is comparable to the Kevlar composites.

Study conducted by Naveen et al. (2018) on ballistic performance of Kevlar/cocas nucifer sheath show that energy absorption of cocos nucifer sheath composite and  hybrid composite exhibit the energy absorption of Kevlar composites. A study by Meliande et al. (2023) on hybrid composites of Carua and aramid for military helmet application found that the composite with 15% Carua and 52% aramid provided the highest level of ballistic protection. The high velocity impact performance of Kevlar/basalt has been studied by Amirian et al. (2022) by varies the layering sequence of the Kevlar and basalt fibre. The finding reveals hybridization of Kevlar and basalt improve the energy absorption of the composites. The effect of layering sequence of Kevlar (K), carbon (C) and glass(G) fibre in a composite on ballistic performance were studied by Randjbaran et al. (2014) . Five different sequences were used which is K/C/G/K/G/C, G/C/K/C/K/G, K/G/C/G/C/K, G/K/C/C/G/K and K/C/G/G/C/K. It was found that ballistic energy absorption (J) for the composite range from 94.36 J to 95.17 J and final velocity from 4.47 m/s to 14.36 m/s. The study found that the stacking sequence of fibres in a composite material can affect its ballistic properties. When glass fibre is in the first layer, the material has better ballistic properties than when Kevlar is in the first layer. Hybrid composite G/C/K/C/K/G has the highest ballistic energy absorption and lowest final velocity which is 95.17 J and 4.47 m/s respectively.

Aisyah et al. (2019) study on thermal and dynamic properties of woven kenaf/carbon fibre reinforced epoxy hybrid composites. Carbon composites have the highest thermal stability. Hybridization of carbon fibre with kenaf fibre improves the thermal stability of composites. Among the hybrid composites, the highest content of kenaf fibre has the highest thermal stability. The investigation on the performance of Kevlar/ cocos nucifer sheath reinforced epoxy hybrid composites based on thermogravimetric analysis(TGA), differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) has been conducted by Naveen et al. (2019). Five different weight ratios of K/CS were used which is 100/0, 75/25, 50/50, 25/75 and 0/100. The finding shows that, thermal stability based on char residue of hybrid composites 75/25 is higher compared to others hybrid composites and it is comparable to Kevlar/epoxy composite. Moreover, DSC result reveals that hybrid composite 75/25 offers a good resistance or stability toward heat in epoxy composites. In addition, 75/25 hybrid composite has the highest storage modulus (E') and loss modulus (E") compared to others hybrid composites. Besides that, damping of 75/25 hybrid composites is comparable to Kevlar/epoxy composite.

This research work has focused on identifying the optimum bio-phenolic/epoxy polymer blends and developing flax/carbon/Kevlar reinforced bio-phenolic/epoxy hybrid composites for ballistic helmet application. Hand lay-up method was employed to fabricate the hybrid composites at different ratio of flax fibre and carbon/Kevlar fibre. Dimension stability, structural, mechanical, morphological, high velocity impact, thermal and dynamic mechanical, properties of hybrid composites will be investigated. Based on the results optimal ratio of flax to carbon/Kevlar will be selected for development of ballistic helmet.

## 1.2 Problem Statement

Synthetic fibre reinforced polymeric composites offer many advantages such as higher specific strength and stiffness, corrosion resistance and enhanced fatigue properties compared to conventional metallic materials. Kevlar and carbon fibre based polymeric composites are widely used in ballistic applications due to its ability to resist high kinetic energy projectiles. Even though this high-performance fibre reinforced polymeric composites possess higher specific strength, impact strength and corrosion resistance, they are manufactured from petroleum-based resources. Depletion of petroleum-based resources urges the researchers to find a sustainable replacement. Moreover, disposal of Kevlar and carbon fibre releases enormous amount of carbon dioxide which pollutes the environment. Hence, it is imperative to find an alternative material to man-made Kevlar and carbon fabric. In addition, usage of Kevlar and carbon fabric increases the overall fabrication and product cost. Also, disposal of Kevlar and carbon fibre is hard and expensive. Because it cannot be dumped at land fill due to degradation issues. To dispose these type of materials, special type of incinerator is required to turn this fibre into ash (Okubo et al., 2004).

Natural fibre has been used as a reinforcement in polymeric composites for many applications such as automotive, packaging insulation, sound absorption panel and construction. Besides that, researcher has been studying the potential of natural fibre as reinforcement material in high performance application such as ballistic application. Flax fibre is one of the strongest natural fibres with tensile strength of 1400 MPa. Even tough flax fibre is non-native to Malaysia, it is easy to be procured and it can be obtained in fabric form. Braga et al. (2018) has studied the ballistic performance of multilayer armor system with ramie/epoxy composites and Kevlar/epoxy composites. It was found that both MAS met the standard requirement. Another researcher (Hani et al., 2016) has studied the ballistic impact respond of coir/Kevlar laminated composites. The result showed that ballistic performance of coir/Kevlar epoxy successfully achieved the national institute of justice (NIJ) standard level IIA. The composites achieved partially penetration when Kevlar was place on the front face. Based on the finding, natural fibre can be used as an alternative to synthetic fibre in the polymeric composites for ballistic application.

Epoxy is a polymer with excellent mechanical properties, making it a popular choice for many high-performance applications. However, it has relatively poor fire resistance and thermal properties. This can be improved by blending epoxy with another polymer, such as phenolic, which has better fire resistance and thermal properties. In addition, polymer blending can also improve the mechanical properties of the polymer, as shown in a study conducted by Unnikrishnan and Thachil (2006b). It was found that addition of 10-15 wt% of phenolic improved the mechanical properties. Blends of phenolic/epoxy resin will be able to produce a composite with better overall performance compared to neat epoxy and phenolic resin. The most important thing is the polymer blend can improve the mechanical properties of the polymer and it is the important properties for the application in this study. Increase in the mechanical properties with addition of phenolic is due to increase in network formation and crosslinking.

Modern ballistic helmets were introduced during the first world war due to increase in the usage of artillery and machine gun. It was made from steel and was design to protect the user from the shrapnel and small arm fire. The ballistic helmet evolves to offer more protection. It was made by increase the thickness of the steel ballistic helmet and more rounded shape which made it more effective at deflecting shrapnel. Ballistic helmets continue to improve and after the World War II a new material was introduce in production of ballistic helmet. Kevlar and Spectra have been used to make it lighter and stronger. The ballistic helmet continues to evolve to improve the protection. Many studies reported that natural fibre has potential to improve the ballistic properties of the composite by hybridization of natural fibre with synthetic fibre. In addition, there is also reported work claim that some natural fibre has better ballistic performance than synthetic fibre (Naveen et al., 2018).

In this research work, polymer blends of bio-phenolic/epoxy will be utilized. Hand lay-up method followed by hot-press was utilize in this study. Hand lay-up was used to prepare the material and hot press was used to cure the sample. Hot press can reduce the time for the sample to cure, reduce the voids and produce material with better properties when right parameter was used. While woven flax fabric and woven carbon/Kevlar fabric will be used as reinforcement. Hybridization of flax, carbon and Kevlar can reduce the utilization of synthetic fibre in polymeric composites for ballistic application. It was expected that hybridization of flax with carbon/kevlar will produce a hybrid composite which has comparable properties with carbon/kevlar composites. The purpose of this study is to evaluate the dimensional stability, structural, mechanical, morphological, dynamic mechanical, thermal, and high velocity impact of the hybrid composites for ballistic helmet applications.

## 1.3 Research Objectives

1. To investigate the effect of bio-phenolic/epoxy polymer blend on the physical, structural, morphological, mechanical, dynamic mechanical and thermal properties.

2. To evaluate the effect of flax fibre loading on the physical, mechanical and morphological properties of flax reinforced bio-phenolic/epoxy polymeric composites.

3. To analyze the influence of flax fibre loading on the thermal, and dynamic mechanical properties of flax fibre reinforced bio-phenolic/epoxy polymeric composites.

4. To determine the effect of carbon/Kevlar fibre loading on dimension stability, mechanical and thermal properties of flax fibre reinforced bio-phenolic/epoxy polymeric composites.

5. To examine the effect of carbon/Kevlar fibre loading on flexural properties, dynamic mechanical properties and high velocity impact of flax fibre reinforced bio-phenolic/epoxy polymeric composites.

## 1.4 Significant of Study

Nowadays, the application of natural fibres as reinforcement has increased due to environmental concern and regulation set up by the government. The main purpose of using natural fibres as reinforcement is to reduce the usage of petroleum-based materials. The aim of this study is to explore the potential of natural fibre as reinforcement in ballistic applications where the important properties need to focus is mechanical and ballistic properties. It is well known that synthetic fibre such as Kevlar was widely used as reinforcement in ballistic application. In addition, polymer blend of bio-phenolic/epoxy will be used in this study as polymer matrix where there is no existing literature reported on flax/carbon/Kevlar reinforced polymer blend composite. Although there have been studies on phenolic/epoxy polymer blends, the formulation used in this study will be different because different types of epoxy and bio-phenolic resins are being used. Additionally, this study will use powder form and commercially available bio-phenolic resin, while the existing studies used a few different types of phenolic resins that were synthesized in the lab. This study will focus on the potential of hybrid composite consisting of flax fabric and carbon/Kevlar as reinforcement and bio-phenolic/epoxy polymer blends as the matrix with the objective to develop a ballistic helmet with this material.

## 1.5 Scope of Study

In this study hybrid composite consist of natural and synthetic fibre was fabricated to investigate it potential for ballistic helmet application. Flax fibre was chosen among others natural fibre is due to its properties which better compared to other natural fibres. In addition, it can be purchase easily and in fabric form which can tailored the area density to specific needed. Despite of expensive price of carbon/kevlar, it was chosen to be used in this study due to its superior properties which cannot be offered by other synthetic fibre such as glass fibre. It was needed for high performance application such as ballistic helmet. In addition, in term of weight carbon/kevlar is lighter compared to glass fibre and this can reduce the overall weight of the product. This study used polymer blends of bio-phenolic/epoxy as the matrix. This is because blending of bio-phenolic with epoxy can improve the properties of the matrix especially mechanical properties. Addition of phenolic resin can increase the cross-linking and network formation which resulted in better mechanical properties. Furthermore, bio-phenolic can improve the thermal stability of the composite.

The study was divided into three stages. The first stage of this study is to find the optimum ratio of the bio-phenolic/epoxy polymer blends where the physical, structural, mechanical, thermal, morphological and dynamic mechanical properties of the polymer blends was evaluated. The optimum ratio of the bio-phenolic/epoxy polymer blends decided in the first stage was used as polymer matrix in the second stage of the study to investigate the effect of fibre loading on the physical, mechanical, thermal, morphological and dynamic mechanical properties of the composites. The optimum fibre loading will be used in the last stage where the effect of hybridization of carbon/Kevlar fabric with flax fabric reinforced bio-phenolic/epoxy polymer composites on the physical, mechanical, thermal, morphological, ballistic and dynamic mechanical properties.

## 1.6 Thesis Outline

This thesis has been structured into 10 chapters according to alternative thesis format of Universiti Putra Malaysia (UPM) based on the publications on which each chapter (4-9) contains its introduction, materials, methods, results, discussions and conclusions. A brief description of each chapter has been addressed in the following section.

Chapter 1

This chapter highlighted the background of this research, problem statements, research objectives, significance and scope of the study with thesis outline.

Chapter 2

Chapter 2 is an overview of the literature review on natural fibre, synthetic fibre, natural fibre-based polymer composites, synthetic fibre-based polymer composites, hybrid composite, manufacturing techniques and the application of polymer composites.

Chapter 3

Chapter 3 provides detailed information of materials as well as the fabrication method of the composites for each stage of the study. The testing method used in this study is elaborated in this chapter.

Chapter 4 (Objective 1: Article 1)

This chapter cover a part of the first objective which publish as first research article entitled of "Mechanical and Morphological Properties of Bio-Phenolic/Epoxy Polymer Blends". This work focusing the effect of bio-phenolic loading on the mechanical and morphological properties of epoxy.

Chapter 5 (Objective 1: Article 2)

This chapter addresses the second part of the first objective which publish as second article entitle "Physical, Structural and Thermal Properties of Bio-Phenolic/Epoxy Polymers Blends". This study investigates the effect of bio-phenolic loading on the physical, structural and thermal properties of the epoxy.

Chapter 6 (Objective 2: Article 3)

This chapter present the second objective of the study and publish as the third research article entitled "Dimensional Stability, Density, Void and Mechanical Properties of Flax Fabrics Reinforced Bio-Phenolic/Epoxy Composites". This research evaluated the effect of flax fibre loading on the dimensional stability, density, void and mechanical properties of bio-phenolic/epoxy polymer blends.

Chapter 7 (Objective 3: Article 4)

This chapter present the third objective of the research and publish as fourth research article entitled "The Effect of Different Loading of Flax Fabric on The Dynamic Mechanical and Thermal Properties of Bio-Phenolic/Epoxy Reinforced Composites." The study dealt with the effect of flax fibre loading on the dynamic mechanical and thermal properties of the bio-phenolic/epoxy polymer blends.

Chapter 8 (Objective 4: Article 5)

This chapter addressed the fourth objective “Physical, Mechanical and Thermal Properties of Flax/Carbon/Kevlar Reinforced Bio-Phenolic/Epoxy Composites.”. This study investigates the effect of flax and carbon/Kevlar ratio on the physical, tensile and thermal properties of flax/carbon/Kevlar reinforced bio-phenolic/epoxy composites.

Chapter 9 (Objective 5: Article 6)

This chapter cover the fifth objective “Flexural, Dynamic Mechanical and Ballistic Properties of Flax/Carbon/Kevlar Reinforced Bio-Phenolic/Epoxy Composites.”. This study investigates the effect of flax fibre and carbon/Kevlar ratio on the flexural properties, dynamic mechanical properties and ballistic performance of flax/carbon/Kevlar reinforced bio-phenolic/epoxy polymeric composite.

Chapter 10

This chapter presents the overall conclusions from every stage of the study, overall study and future recommendations.

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