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CHARACTERISATION OF KENAF FIBRE COMPOSITE TRAPEZOID SANDWICH STRUCTURE BASED ON CORRUGATED CORE

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Thesis submitted in fulfillment of the requirements
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Author,

Ahmad Fahmy Jusoh

ABSTRAK

Komposit diperkukuh gentian semulajadi telah digunakan secara meluas sejak dahulu lagi. Gentian semulajadi termasuk semua bentuk gentian dari rumput, biji, tumbuhan berkayu, buah-buahan, tumbuhan liar, tanaman pertanian, tumbuhan air, tumbuhan palma, daun, bulu haiwan dan kulitnya. Beberapa kelebihan gentian semulajadi adalah sangat mesra alam, boleh terbiodegradasi sepenuhnya, tidak toksik dan menjadi sumber pendapatan bagi masyarakat luar bandar dan pertanian. Secara perbandingan, gentian kenaf mempunyai prestasi mekanikal yang baik dan sama seperti gentian semulajadi yang lain. Sementara itu, panel sandwic semakin berubah menjadi bahan penting kerana pelbagai gunanya ke pelbagai sektor perindustrian. Salah satu ciri terbaiknya ialah nisbah kekakuan tinggi kepada berat, terutamanya di bawah keadaan lenturan. Dalam eksperimen ini, penulis dikehendaki untuk menghasilkan teras beralun trapezoid dengan menggunakan gentian kenaf pendek untuk mengkaji kesan rawatan kimia pada gentian kenaf kepada prestasi kenaf / epoksi bergelombang komposit dan untuk mengkaji kesan perubahan parameter dan sifat kenaf / teras epoxy beralun struktur sandwic. Inti beralur disediakan menggunakan gentian semula jadi kenaf dan resin epoksi cair sebagai bahan matriks bersama dengan pengeras (2 epoksi: 1 pengeras dengan berat%). Ketebalan gentian ditetapkan dari 4mm, 6mm dan 12mm dengan peratusan berat gentian 5%, 10% dan 15%. Untuk sampel 12mm, proses mercerisasi tambahan telah dilakukan. Acuan yang digunakan untuk bahan komposit bergelombang diperbuat daripada blok keluli dengan panjang 290mm, lebar 210mm dan ketebalan 24mm untuk kedua-dua acuan atas dan bawah. Acuan itu sengaja disediakan untuk membina cerun dengan sudut 45° untuk menghasilkan produk beralun. Sampel yang telah siap sepenuhnya dipotong ke unit tunggal dengan 50mm x 25mm dalam dimensi dan ujian ketegangan statik dan ujian mampatan dilakukan. Untuk sampel 12mm, gentian kenaf dirawat dengan nisbah 5% larutan alkali (NaOH) dalam nisbah berat 1 gentian: 20 NaOH. Hasilnya dari ujian tegangan dan mampatan meningkat dengan ketara. Nilai tegasan tertinggi untuk gentian kenaf dirawat pada 5.88 MPa, iaitu 18% lebih tinggi daripada gentian kenaf yang tidak dirawat. Hasil tingkah laku yang sama didapati pada ujian mampatan dimana nilai tegasan tertinggi yang dicatat untuk gentian kenaf dirawat ialah 6.96 MPa; di mana tegasan tertinggi yang dicatatkan untuk gentian kenaf tidak dirawat hanya 5.30 MPa. Ia menunjukkan bahawa rawatan kimia menggunakan larutan 5% telah mempengaruhi prestasi mekanikal komposit gentian kenaf. Dalam ujian tegangan 4mm, nilai tegasan yang lebih rendah dicatatkan pada 2.07 MPa (dari sampel KEU.4.5) dan tegasan meningkat kepada 3.49 MPa untuk sampel 6mm (KEU.6.15) kerana kandungan gentian juga meningkat dari 5% hingga 15% mengikut berat. Sementara untuk ujian mampatan, sampel 12mm dengan nilai tegasan gentian 15% (5.30 MPa) adalah lebih tinggi daripada sampel 6mm dengan pemuatan gentian yang sama (3.72 MPa). Ia jelas menunjukkan bahawa kenaikan ketebalan sampel dan pemuatan gentian menghasilkan peningkatan nilai tegasan untuk kedua-dua ujian tegangan dan mampatan.

ABSTRACT

Natural fibre reinforced composites have been widely used since ancient times. Natural fibre includes all form of fibre from grass, seeds, woody plants, fruits, wild plants, agricultural crop, aquatic plants, palm plants, leaves, animal hair, and its bark. Some of the advantages of natural fibre are very environmentally friendly, can be completely biodegradable, non-toxic and a source of income for rural and agricultural communities. Kenaf is a natural fibre that a promising mechanical performance in comparison with other natural fibres. Sandwich panels are becoming increasingly important materials because of their multipurpose uses in various industrial sectors. One of their best features is their high-stiffness-to-mass ratio, particularly under bending conditions. In this experiment, trapezoidal corrugated cores using short kenaf fibre were manufactured in order to investigate the effect of chemical treatment on kenaf fibre to the performance of kenaf/epoxy corrugated composites and to study the effect of varying the parameters and properties of kenaf/epoxy corrugated cores sandwich structure. The corrugated core was prepared using kenaf natural fibre and liquid epoxy resin as its matrix material along with a hardener (2 epoxy:1 hardener by weight %). The fibre thickness was set at 4 mm, 6 mm and 12 mm with 5%, 10% and 15% fibre weight percentage, respectively. For the 12 mm sample, an additional mercerisation process was done. The mould used for the corrugation of the composite material was fabricated from a steel block of 290 mm in length, 210 mm in width and 24 mm in thickness for both male and female moulds. The mould was intentionally prepared to have a corrugated slope with a 45° angle to produce corrugated-end products. The fully cured sample was cut into single units of 50 mm x 25 mm dimensions and static tension and compression tests were carried out. For the 12 mm samples, the kenaf fibres were treated with a 5% alkaline solution (NaOH) in a weight ratio of 1 fibre:20 NaOH. As a result the tensile and compression tests significantly increased in value. The highest stress value for treated kenaf fibre was recorded at 5.88 MPa, which was 18% higher than the untreated kenaf fibre. The same behavioural results were found in the compression test where the highest recorded stress value for treated kenaf fibre was 6.96 MPa; whereas the highest recorded stress for untreated kenaf fibre was only 5.30 MPa. It shows that the chemical treatment using a 5% solution did affect the mechanical performance of the kenaf fibre composite. In the 4 mm tensile test, a lower stress value was recorded at 2.07 MPa (from sample KEU.4.5) and the stress increased to 3.49 MPa for the 6 mm samples (KEU.6.15) as the fibre content also increased from 5% to 15% by weight. Meanwhile, for the compression test, the 12 mm samples with 15% fibre had a stress value of 5.30 MPa which was higher than the 6 mm samples with the same fibre loading (3.72 MPa). It clearly shows that the increment in sample thickness and fibre loading resulted in the increment of stress limits for both tensile and compression tests.

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LIST OF SYMBOLS

A_0	Area
^{o}	Degree
^oC	Degree Celsius
ρ	Density
ΔL	Difference in length
ε	Engineering Strain
σ	Engineering Stress
L_f	Final length
m	Mass
L_o	Original Length
P	Pressure
T_{Room}	Room temperature
V	Volume
w_c	Weight of composite
w_f	Weight of fibre
w_m	Weigh of matrix

LIST OF ABBREVIATIONS

CNC	Computer Numerical Control
DI	De-ionized
FE	Finite Element
KET.12.10	Treated kenaf and epoxy with 12mm thickness and 10% fibre
KET.12.15	Treated kenaf and epoxy with 12mm thickness and 15% fibre
KET.12.5	Treated kenaf and epoxy with 12mm thickness and 5% fibre
KEU.12.10	Untreated kenaf and epoxy with 12mm thickness and 10% fibre
KEU.12.15	Untreated kenaf and epoxy with 12mm thickness and 15% fibre
KEU.12.5	Untreated kenaf and epoxy with 12mm thickness and 5% fibre
KEU.4.10	Untreated kenaf and epoxy with 4mm thickness and 10% fibre
KEU.4.15	Untreated kenaf and epoxy with 4mm thickness and 15% fibre
KEU.4.5	Untreated kenaf and epoxy with 4mm thickness and 5% fibre
KEU.6.10	Untreated kenaf and epoxy with 6mm thickness and 10% fibre
KEU.6.15	Untreated kenaf and epoxy with 6mm thickness and 15% fibre
KEU.6.5	Untreated kenaf and epoxy with 6mm thickness and 5% fibre
mm	Milimeter
MPa	Megapascal
NaOH	Sodium Hydroxide
ROM	Rule of Mixture
SI	System Internationale

CHAPTER 1

INTRODUCTION

1.1 Natural Fibre

Natural fibre reinforced composites have been widely used since ancient times. Historical records show that humans used organic materials from nature as textiles or ropes (Akil et al., 2011). Then, civilisation learned to harvest crops and managed to process them accordingly. Natural fibre has the benefits of being ecologically friendly, is a non-harmful material and as a source of income for the rural and horticultural community.

1.2 Corrugated Core Sandwich Structure

Nowadays, sandwich panels are becoming increasingly important materials because of their multipurpose uses in various industrial sectors. One of their best features is their high stiffness-to-mass ratio, particularly under bending conditions (Bartolozzi, Baldanzini, & Pierini, 2014). The sandwich structure may be developed in various types; the most popular lay-up consists of a stiff core, face sheets, and laminated with a polymer. The core is fabricated from foams or moulded in a corrugated pattern using different materials. This kind of structure may deliver different types of damages including manufacturing damages (delamination, uneven thickness of core, etc.) and damages during operation (crack of core, delamination, impact damages, etc.) which will seriously impact the structure's reliability and safety (Katunin, 2014).

1.3 Applications of Corrugated Core Sandwich Structure

The corrugated core sandwich structure has been used in many industrial sectors such as in product packaging applications, transportation/vehicle parts, civil construction, and others. The following part will cover the application of corrugated core sandwich structures.

1.3.1 Product Packaging

The proper packaging of fruits such as apples is essential for the long, multiple stage journey from farmers to consumers. During transportation, handling and storage, the product and its packaging encounter multiple loading conditions which may be dynamic, static or even both (Lewis, Yoxall, Marshall, & Canty, 2008). Despite the different packaging designs used in the market, handling conditions may lead to mechanical damage (Lewis et al., 2008). However, due to its efficient material characteristics and economical nature, the corrugated board is used in shipping containers (Fadiji, Coetzee, & Opara, 2016).

1.3.2 Transportation/Vehicle Parts

Sandwich panels with multiple cores are commonly utilised in aviation products, high-speed trains, shipbuilding, and other transportation or vehicle parts. For example, researchers studied the ratio of stiffness over mass using different panels with reference to stiffened panels used in shipbuilding (Buannic, Cartraud, & Quesnel, 2003). An excellent material used in shipbuilding for walls, structural decks, bulkheads and ramp is composed of two stiffened face sheets with a low-density core in the middle and considered as a sandwich structure (P. Zhang et al., 2015). Many researchers focused on the mechanical behaviour of the sandwich structure in past decades. These include a structure with a different core along with honeycombs, stochastic foams, prismatic topologies, and lattice topologies in order to improve their blast/impact resistance.

1.4 Significance of study

Natural fibre as a composite reinforcement material has been widely used in many applications. In recent years, researchers from all over the world have carried out studies in the fields of natural fibres and their composites. In Malaysia, the production of kenaf is fully supported by the government in order to replace tobacco plantations. The rural agricultural community has been given a lot of opportunities and support to plant kenaf yearly. Kenaf grows widely in many tropical countries such as Malaysia, Philippines, India, and Indonesia. Kenaf has been found to have promising mechanical performance comparable to other natural fibres. Even though most corrugated core sandwich structures are constructed with metals and/or other advanced composites, the use of kenaf in corrugated core sandwich structures may be part of the global race that aims for green technology and a better future. Therefore, this study aims to substitute the usage of metal or other advanced composites with kenaf fibres in order to produced corrugated core samples.

1.5 Problem Statement

There are many types of corrugated core sandwich structures built up with different kinds of topology. The trapezoidal shape is one of most investigated geometry cores (Zhang, J. Liu, et al., 2015). Sinusoidal corrugation has also been studied in previous research (Bartolozzi, Pierini, Orrenius, & Baldanzini, 2013; Magnucka-Blandzi, Magnucki, & Wittenbeck, 2015). Few of the reviewed and cited experiments fabricated a sandwich structure with corrugated core using natural fibres in either trapezoidal or sinusoidal topology. While some researchers have used synthetic fibres to create sandwich structures with corrugated cores, it is conceivable to build this structure utilising natural fibres such as kenaf, jute, and others. Analysts may run a few tests to consider the characteristic of a sandwich structure with corrugated core using natural fibres. This is the gap in the research field that requires more experimental work to be conducted to discover the benefits of corrugated cores such as high stiffness/strength to weight ratios and their attractiveness for energy absorption applications (Yan et al., 2014).

In addition, different kinds of matrix materials utilised from various natural fibres affect the tensile and compression test results. By selecting an appropriate chemical treatment, matrix material and fabrication method, the tensile and compression tests will provide different results.

1.6 The objectives of the study

The objectives of this research are:

1. To investigate the effect of chemical treatment on kenaf fibre to the performance of a kenaf/epoxy trapezoidal corrugated composite.
2. To determine the effect of varying the parameters and mechanical properties of a kenaf/epoxy trapezoidal corrugated core sandwich structure.

1.7 Scopes and limitations of study

This thesis attempts to design and develop new natural composites of kenaf fibre as specified below:

1. Development of a lightweight trapezoidal sandwich structure based on a corrugated core.
2. Using natural fibre (kenaf) as the investigated materials for the sandwich structure.
3. Carrying out fibre surface treatment using an alkaline solution (5% NaOH)
4. Static tension and compression tests using an in-house Instron Universal Testing Machine.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of recent research works on the corrugated core sandwich structure and kenaf natural fibre; based on its characteristics, usage of such product as well as its mechanical performance. An overview of corrugated core design structures and manufacturing process are given. Furthermore, examples of studies related to the corrugated-core sandwich structure and relevant published work are discussed.

2.2 Design and manufacture of sandwich cores

Corrugated cores are a subset of two-dimensional periodic cores and the most essential element is the folding (corrugated) shape that can be shifted for a manufactured design of the components (Bartolozzi et al., 2014). A considerable measure of hypothetical, numerical, and exploratory investigations have been run to discover its failure mode, properties of the design and the behavioural of corrugated core sandwich structure.

In Figure 2.1, Buannic et al. reported that the corrugated core sandwich structure can be categorised into four different conventional geometries; straight, hat-type, triangular, and curvilinear (Buannic et al., 2003). The authors correlated the properties of these four geometries to a reference stiffened panel. The motivation behind this correlation is to decide the pure bending characteristics of periodic plates and equivalent membranes.

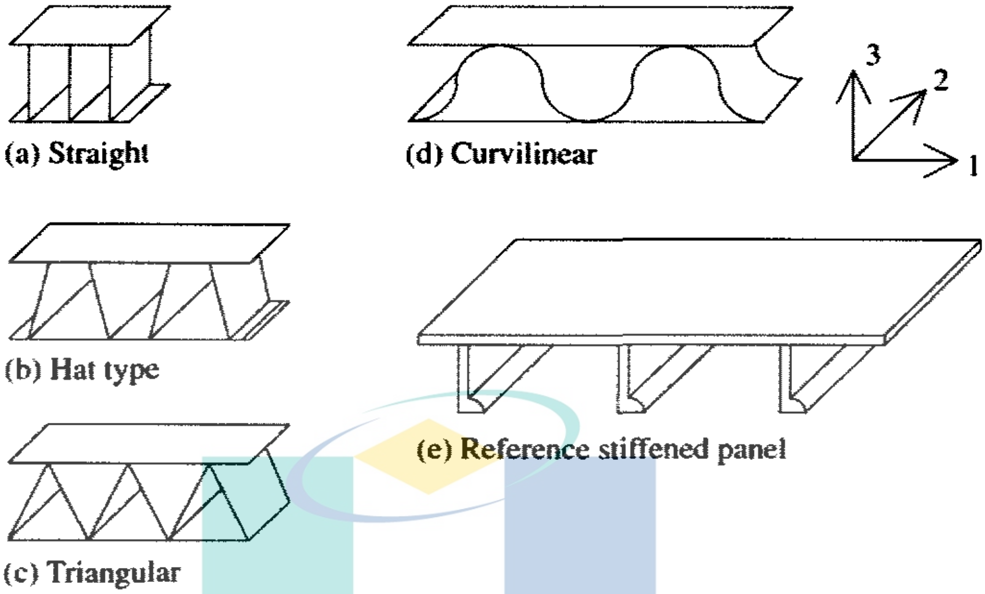

Figure 2.1 Traditional corrugated core sandwich structures. Source: Buannic et al (2003).

Sandwich structures with different core types are generally utilised as part of aviation technology, in high-speed trains, building structures, and so on. These structures have become very recognisable and popular in manufacturing these days because of their lightweight and high firmness/stiffness properties (Wu, Li, & Wang, 2013). Numerous researchers have concentrated on the dynamic mechanical conduct of sandwich structures with corrugated cores. An assortment of such structures with various metallic cores including stochastic foams, honeycombs, prismatic topologies, and lattice topologies have been explored experimentally and numerically (P. Zhang et al., 2015).

Of all the sandwich structures, corrugated cores are the most desired arrangement. The characteristics of corrugated cores are good structural performance with an extremely limited thickness and little thickness contrasted to overall measurement which adversely influences their modelling (Bartolozzi et al., 2014). Most researchers utilised metallic cores, stochastic foams, honeycombs, lightweight ceramic and polymeric foams to study the characteristics and the impact of sandwich panels with corrugated cores (Lim & Bart-Smith, 2014; Wei et al., 2014; Yan et al., 2014; Zhang, J. Liu, et al., 2015; Zhang, Supernak, Mueller-Alander, & Wang, 2013).

In order to obtain a repeatable and uniform corrugated cores, a glass fiber reinforced plastic (GFRP) were prepared using a 45° triangular profile with a planar surface dimension of 210mm by 240mm (Rejab & Cantwell, 2013). The steel mould used to produce corrugations with a nominal cell height of 10mm and a unit cell length of 20mm as in Figure 2.2. A hot press was used to produce the corrugated core sheets for the sandwich panel. Then, the composite prepreg was placed between the upper and lower moulds, and cured according to manufacturer's processing cycle. Once the hot press had cooled to a temperature below 60°C, the sheet was removed from the mould and visually inpected for defects.

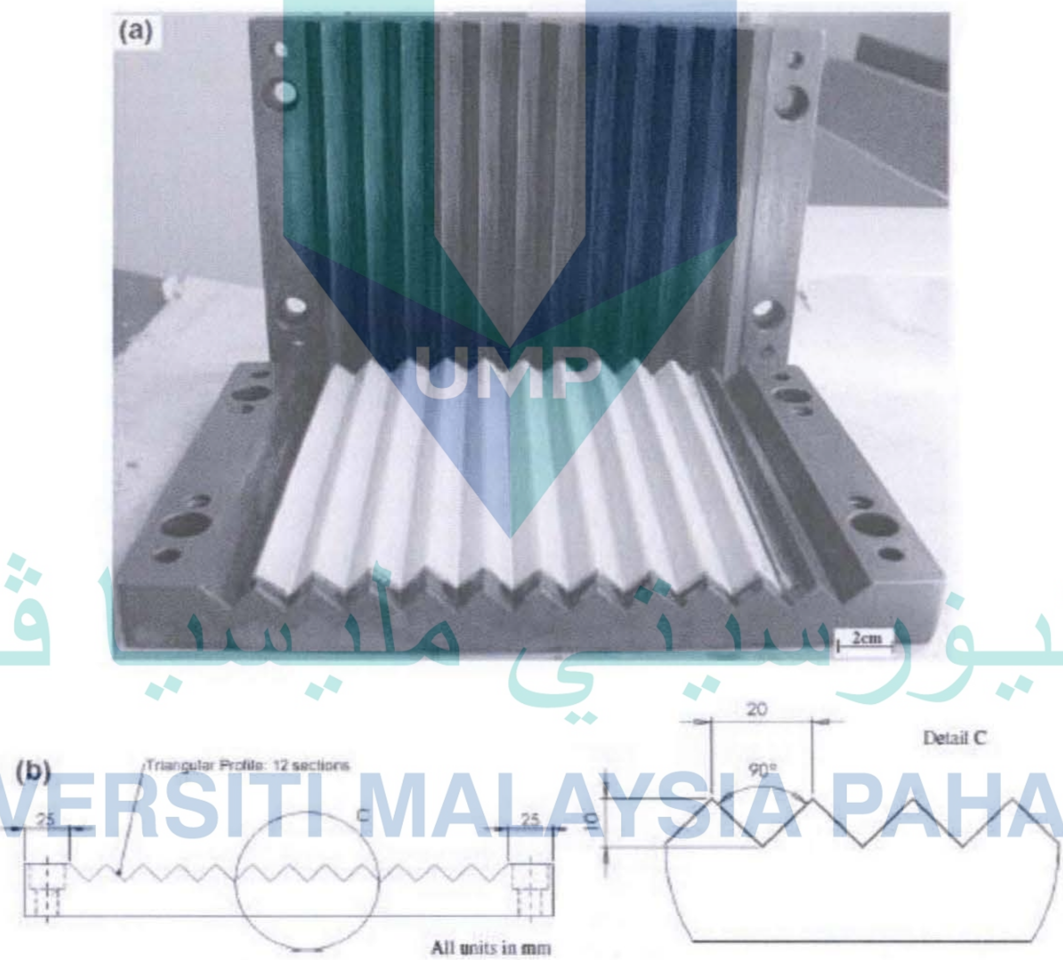

Figure 2.2 (a) Corrugated mold is made from steel and (b) the profile angle of the mould. Source: Rejab & Cantwell (2013)

2.3 Natural Fibre

Natural fibre consists of all forms of fibre from grasses, seeds, woody plants, fruits, wild plants, agricultural crops, water plants, palms, leaves, animal feathers and their skins. By-products of bananas, pineapples, sugarcane, sugar palm, rice, cotton, coconut, kenaf, hemp, abaca, sisal, oil palm, jute and bamboo are very popular materials in the production of composites (Salit, 2014). Natural fibres have several advantages such as being very environmentally friendly, fully biodegradable, non-toxic and as sources of income for the rural and agricultural community.

Malaysia is situated close to the equator resulting in a tropical climate. Being warm and moist all year long, it is well suited for growing and maintaining cash crops, which include kenaf, oil palm, sugar cane, betel nut and coconut trees. Timber is also abundant in the country. These types of plants are vital because they possess tremendous potential as renewable sources of alternative components or utilised as reinforcement for commercial products and applications. This opportunity has not been completely taken advantage of. According to the Malaysia Timber Industry Board, as far as timber wastes are concerned, there are approximately 10 million m^3 of timber residues and 46 million m^3 of agricultural residues produced every year in Malaysia (Nirmal, Hashim, & Megat Ahmad, 2015). The abundant supply of natural residues signifies that there is an excellent possibility of modifying many of these natural sources into commercial products along with reinforcement products for industrial applications. Appropriate marketing promotions and rewards will catalyse research works and development of natural sources into commercial products.

Table 2.1 Types of plant and fibre groups. Source: Azwa et al (2013) and Holbery et al (2006)

Wood fibre	Stalk fibre	Fruit fibre	Seed fibre	Leaf fibre	Bast fibre
Hardwood	Bamboo	Coconut	Cotton	Sisal	Hemp
Softwood	Wheat	Betelnut	Oil palm	Banana	Jute
Sawdust	Rice		Kapok	Mengkuang	Ramic
	Grass Barley		Alfalfa	Date palm	Sugarcane
	Corn			Pineapple	Kenaf
				Abaca	Roselle

Natural fibres have some disadvantages such as having poor compatibility with a hydrophobic polymer matrix. This drawback needs several treatments to enhance the compatibility, such as alkali treatment and coupling agent (Goulart, Oliveira, Teixeira, Miléo, & Mulinari, 2011). Alkali treatment also expands the mechanical properties of the composite itself, resulting in an enhanced surface wettability of the fibre against the matrix (Fiore, Di Bella, & Valenza, 2015; Nirmal et al., 2015).

In spite of their particularly low environmental effect, the primary benefits of choosing natural fibres over artificial fibres are because of the fact that natural fibres happen to be lightweight, renewable, non-abrasive to process equipment, lower in price, versatile in its consumption, display high certain mechanical properties, have greater impact absorbance and great sound padding properties, and are naturally recyclable and biodegradable (Joshi, Drzal, Mohanty, & Arora, 2004; Yousif & Ku, 2012). Natural fibres have become widely used as reinforcements instead of artificial fibres in different varieties of polymeric composites. Utilising natural fibres provides the advantages of being less expensive and environmentally beneficial (Brahmakumar, Pavithran, & Pillai, 2005). It had been calculated that 3.07 million tons of CO_2 emissions and 1.19 million m^3 of crude oil could be preserved simply by replacing 50% of artificial fibres with natural fibre composites in automotive applications of North America exclusively (Rahman & Khan, 2007).

Companies and researchers involved in composites development globally are currently switching their focus towards using natural fibres. Because of their social responsibility and environmental determination, they are able to decrease carbon dioxide (CO_2) emissions significantly through replacing non-renewable artificial fibres with natural fibres as reinforcements in polymeric composites [36]. Natural fibres are very well recognised. However, they have some disadvantages including variations in chemical compositions due to their diverse sources geographically. The level of growth once harvested also impacts the fibre maturity and durability. Therefore, variations in quality and level of processing are inevitable as a result of the influence of geographical locations and weather conditions. Natural fibres easily absorb moisture because of their hydroxyl groups (Pervaiz & Sain, 2003). Additional significant drawbacks of natural fibres are poor handling temperature (< 200°C) (Lilholt & Lawther, 2000), low thermal stability (easily combustible), poor wrinkle resistance, brittleness, fibre shedding and yellowing in the event the fibre is exposed consistently to sunlight (Khalil, Ismail, Rozman, & Ahmad, 2001).

2.4 Kenaf fibre composite

Kenaf has been observed to be comparable in characteristics to other types of fibres, highly accessible and least expensive amongst different types of natural fibre reinforced materials. Kenaf is also labelled as industrial kenaf due to its great returns in the manufacturing of industrial raw materials.

Kenaf fibre comes from the *Hibiscus cannabinus* species where its subdivision is *Hibiscus* and family *Malvaceae* obtained from the plant's stems (Salleh et al., 2012) which also includes cotton (*Gossypium spp.*) and okra (*Abelmoschus esculentus L. Moench*). The word kenaf itself comes from Persian which portrays the plant having grown in a place with a warm season and short days, and is an annually herbaceous plant with the fibre diameter being 67.6 μm on average (Mahjoub, Yatim, Mohd Sam, & Hashemi, 2014). Kenaf is an extremely solid and tough plant with a stringy stalk, resistant to bugs and needs relatively little or no pesticides in general (Elsaid, Dawood, Seracino, & Bobko, 2011). The kenaf fibre comprises cellulose, hemicellulose, and lignin with values of 56 – 64, 21 – 35, and 8 – 14 by weight percentage (Wt. %) (Davoodi et al., 2010b; Mazuki, Akil, Safiee, Ishak, & Bakar, 2011).

Kenaf has a long history of cultivation in a few regions of the world such as in Malaysia, Thailand, Bangladesh, India, parts of Africa and Europe. The fibre has been for the most part utilised in paper, fabric, coarse twine, and rope. However, there is a present market enthusiasm for kenaf reinforcement in polymers. As encouraged by the government of Malaysia, the planting, cultivation and harvesting of the kenaf plant has been developed widely in rural areas in order to supplant the tobacco plant and in addition to help nearby markets in creating high-density fibreboards for shipment around the world. In 2016, the cultivation of kenaf for fibre and core production increased from 4090 tons (2012) to 10,339 tons, covering more than 2052 hectares (LKTN, 2016). Kenaf fibres have received a lot of attention to support multi-applications including car parts, bundling and furniture as well as in sports and leisure equipment (Meon, Othman, Husain, Remeli, & Syawal, 2012).

2.5 Mechanical properties of kenaf fibre composite

Many research has been conducted on kenaf fibres including on the mechanical properties of kenaf fibre-reinforced polymer composites. Compared to other natural fibres, the kenaf fibre shows superior properties for reinforcement in different polymeric matrices under different compression loading conditions. Table 2.2 is a list of recent works done by different researchers on kenaf fibre-reinforced polymeric (thermoset or thermoplastic resin or biodegradable) composites and hybrid composites. The researchers showed that the mechanical properties of kenaf fibre-reinforced composites change because of the differing testing methodologies utilised and samples tested (Rassiah & Ahmad, 2013). Table 2.2 illustrates some of the research work related to kenaf fibre-based composites which includes their reinforcement and matrix materials while Table 2.3 shows the mechanical properties of kenaf fibres.

Table 2.2 Previous research work on kenaf fibre composites

Reinforcement	Matrix	References
Kenaf sheets	PLLA	(Nishino, Hirao, Kotera, Nakamae, & Inagaki, 2003)
Kenaf fibre	Polypropylene	(Shibata, Cao, & Fukumoto, 2006)
Kenaf	Poly (lactic acid)	(Ochi, 2008)
Kenaf fibres	Polylactide	(Lee, Kim, Lee, Kim, & Dorgan, 2009)
Kenaf fibre	Polypropylene	(John, Bellmann, & Anandjiwala, 2010)
Kenaf/glass	Epoxy	(Davoodi et al., 2010a)
Kenaf bast fibre	(PP) with (TPNR) and (PP/EPDM	(Anuar & Zuraida, 2011)
Kenaf/glass	Epoxy	(M. M. Davoodi et al., 2012)
Chemically treated kenaf	Epoxy	(El-Shekeil, Sapuan, Abdan, & Zainudin, 2012)
Kenaf fibre	Waste polypropylene	(Suharty, Almanar, Sudirman, Dihardjo, & Astasari, 2012)
Short fibre non-woven kenaf	Polypropylene	(Asumani, Reid, & Paskaramoorthy, 2012)
Treated and untreated kenaf	Epoxy	(Yousif, Shalwan, Chin, & Ming, 2012)
Kenaf/fibre glass	Polyester	(Ghani et al., 2012)
Long kenaf/woven glass	Unsaturated polyester	(Salleh et al., 2012)
Nonwoven kenaf	Polypropylene	(Hao, Zhao, & Chen, 2013)
Kenaf fibre	Polybioresin	(Deka, Misra, & Mohanty, 2013)
Kenaf fibre	Cassava starch	(Zainuddin, Ahmad, Kargarzadeh, Abdullah, & Dufresne, 2013)
Kenaf fibre	Thermoplastic polyurethane	(Sapuan, Pua, El-Shekeil, & Al-Oqla, 2013)
Kenaf fibre	HDPE	(Salleh, Hassan, Yahya, & Azzahari, 2014)
Kenaf fibre	Polyurethane	(Batouli, Zhu, Nar, & D'Souza, 2014)
Kenaf–glass	Unsaturated polyester	(Atiqah, Maleque, Jawaid, & Iqbal, 2014)
Kenaf fibre and corn husk flour	Poly (lactic acid)	(Kwon et al., 2014)
Alkali treated kenaf fibre	Poly (lactic acid)	(Shukor, Hassan, Saiful Islam, Mokhtar, & Hasan, 2014)
Kenaf fibre	Poly (vinyl chloride)	(El-Shekeil, Sapuan, Jawaid, & Al-Shuja'a, 2014)
Kenaf fibre	Polypropylene (PP)	(Salleh et al., 2014)

Table 2.3 Mechanical properties of kenaf fibre

Density (g/cm^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at break (%)	References
1.44	393 – 773	26.5	1.5 – 1.8	(Mazuki et al., 2011)
1.40	284 – 800	21 – 60	1.6	(Davoodi et al., 2010b)
1.19	240 – 600	14 – 38	n/a	(Summerscales, Dissanayake, Virk, & Hall, 2010)

2.6 Factors affecting mechanical properties of kenaf fibres

The major constituents of natural fibres are cellulose and lignin. The cellulose content results in the mechanical properties which rely upon various factors such as fibre length, fibre loading or volume fraction of fibres, fibre aspect ratio, fibre orientation, or inter-facial adhesion between the fibre matrix (Rassiah & Ahmad, 2013). A natural fibre composite's mechanical properties are extremely influenced by the matrix fibre adhesion property between the polymer matrix and fibres (Herrera-Franco & Valadez-González, 2004; Ochi, 2008; Sapuan, Leenie, Harimi, & Beng, 2006). In natural fibre composites, pre-treatment often results in superior mechanical and tensile properties because of the enhanced interfacial linkage or fibre-matrix adhesion.

The impact of fibre loading on tensile and compression properties (mechanical properties) are strongly reliant upon the kenaf fibre loading (Kwon et al., 2014). Furthermore, the effect of fibre size, fibre loading and fibre/matrix adhesion on the strength, toughness and stiffness of a variety of particulate composite having both nano and micro-fillers with small aspect ratios are reasonably significant. The resulting composite durability and strength are strongly determined by all three variables, predominantly by particle/matrix adhesion (Fu, Feng, Lauke, & Mai, 2008). It is because mechanical strength rests on the effective stress transfer between the filler and the matrix, and brittleness/toughness is governed by adhesion (Fu et al., 2008). Moreover, aspect ratio significantly affects the mechanical properties of a hybrid composite, because a high aspect ratio effectively transfers stress to the matrix (Ding, Jiang, Sun, Lian, & Xiao, 2002). Researchers also found that processing conditions/techniques have a remarkable consequence on the mechanical properties of fibre-reinforced composites (George, Sreekala, & Thomas, 2001).

Chemical or pre-treatment of the fibre chemically modifies the surface, cleans the fibre surface, reduces moisture absorption and upsurges the surface unevenness (Edeerozey, Akil, Azhar, & Ariffin, 2007). Some of the important industrial methods that are currently conducted include mercerization, acetylation, etherification, peroxide treatment, benzoylation, graph copolymerization, acrylation, maleic anhydride, titanate treatment, permanganate treatment, sodium chloride treatment, plasma, isocyanate treatment and a coupling agent such as silane treatment, are used on natural fibres to improve the fibre/matrix (Kalia, Kaith, & Kaur, 2009) interfacial bonding in a composite.

The effectiveness of a composite reinforced using natural fibres relies on the fibre-polymer matrix interface and its tendency of transferable stress to the fibre from the matrix. The foremost hindrance is the deficiency of a perfect interfacial adhesion, inherently high moisture absorption or poor resistance to moisture absorption and low melting point leading to micro cracking of the composite. Thus, this leads to the deprivation of mechanical properties, thereby making the use of natural fibre-reinforced composite less attractive (Edeerozey et al., 2007).

2.7 Effect of chemical treatment on mechanical properties of kenaf

A few research works have been conducted and shown that chemical treatment on the kenaf fibre has significantly improved its mechanical properties as compared to untreated kenaf fibre. Researchers also found an improvement in tensile, flexural, impact strength and also the stiffness of kenaf fibre using several categories of polymers (Anuar & Zuraida, 2011). Other researchers also suggested that by using 1,6-diisocyanato-hexane (DIH) and 2-hydroxylethyl acrylate (HEA), the interfacial adhesion between kenaf-UPE could be increased (Ren, Qiu, Fifield, Simmons, & Li, 2012). Hence, surface treatment of kenaf fibre considerably enhances the tensile strength and the modulus of elasticity of kenaf-UPE composites (Ren et al., 2012). The articulate impact of alkali treatment of the fibre on the composite properties are investigated by the hand lay-up technique. The most astounding impact strength was shown in a 40% kenaf fibre-reinforced composite which was expanded by 14.3% after alkali treatment (Fiore et al., 2015).

Another research discussed the interfacial adhesion between the fibres and matrix which directly influences the tensile properties of a kenaf fibre-reinforced composite (Ku, Wang, Pattarachaiyakoop, & Trada, 2011). Increasing the fibre content also prompts an increment in tensile properties and Young's modulus up to a certain value of the natural fibre composite. Treatment of kenaf fibre with 6% of NaOH (also known as the alkalisation process), Sodium Laulryl Sulphate (SLS) treatment and a randomly mixed composite enhanced the mechanical properties due to the porousness of the treated kenaf fibre/epoxy composite (Alavudeen, Rajini, Karthikeyan, Thiruchitrambalam, & Venkateshwaren, 2015). Researchers found that the alkalisation with NaOH enhanced the mechanical properties of kenaf fibre in contrast with untreated kenaf fibre with a concentration value of only 6% chemical treatment (Edeerozey et al., 2007). Therefore, this experiment was using a 5% chemical treatment and then the results was compared with 6% chemical treatment studies. In addition, the tensile strength of kenaf fibre increased with a decrease in the concentration rate and alkali solution immersion time (Mahjoub et al., 2014). Treatment of kenaf fibre with 6% NaOH split the kenaf fibre bundles into finer fibres which allowed more epoxy resin between the fibres thus leading to greater interfacial adhesion (Yousif et al., 2012).

In summary, a relevant review of previous studies on the corrugated core sandwich structure and natural fibres has been presented. Then, the mechanical properties of kenaf fibre as well as the factors that affect its properties were reviewed. The effect of chemical treatment that could lead to an improvement in kenaf property was also discussed. Therefore, this experimental study will be focused on the manufacture and evaluation of the mechanical properties of a corrugated core sandwich structure using kenaf fibre, with a 5% chemical treatment as guided by previous studies. In addition, previous references will be used in order to facilitate this study.

CHAPTER 3

MATERIALS AND METHOD

3.1 Introduction

This chapter explains the detailed flow in completing the study. The methodology followed in this study is sample fabrication, data collection, and three sets of testing to characterise the natural fibre-based kenaf/epoxy composite.

3.2 Research Methodology

A few steps needed to be followed in order to complete this study and achieve the objectives. The methodology consists of three phases which are stated as below:

A. Pre-experiment

B. Experiment

C. Post-experiment

In the pre-experiment stage, this study started with a literature review which helps in many ways to increase knowledge of fibre composites and recent studies in regard to natural fibre. From the review process, the material selection was made. After choosing the material, the experimental procedures were designed to make sure it ran smoothly. The preparation of composite materials was the last step in the pre-experiment stage.

The second phase introduced the experiment's execution process. This stage started with material testing which included tensile and flexural tests. Then, a set of corrugated core sandwich structures using natural fibre were fabricated using a steel mould according to specific parameters.

The final phase in completing this study is the post-experiment stage. This stage started with testing all the corrugated core sandwich structure sets with tensile and compression tests. In this stage, all observation and data collection were presented and analysed thoroughly.

3.3 Experimental design of corrugated core sandwich structure

The corrugated core was prepared using kenaf natural fibre sourced from Rompin, Pahang (Malaysia) and liquid epoxy resin, DOW 331 as its matrix material and Jointmine 905-3s (Supplier: Salju Bistari Sdn. Bhd., Malaysia) as the hardener (2 epoxy:1 hardener by weight %). The fibre was moulded using 4 mm, 6 mm and 12 mm thick spacers with 5%, 10% and 15% fibre weight percentage, respectively. For the 12 mm sample, an additional mercerisation process was done. All the experimental designs are simplified in Table 3.1. Once the samples were produced, they were then labelled as in Figure 3.1.

Table 3.1 Design of experiment of Kenaf/epoxy composite

Fibre type	Matrix material	Material thickness	Fibre %	Mercerisation
Kenaf natural fibre	Epoxy and Hardener	Thin (4 mm), Medium (6 mm) and Thick (12 mm)	5%, 10% and 15%	5% NaOH for 12 mm sample

Figure 3.1 Sample labelling example for kenaf and epoxy, untreated sample.

3.3.1 Corrugated core steel mould preparation

The process of manufacturing a corrugated composite material starts with the mould preparation. The mould used for the corrugated composite material was fabricated from a steel block of 290 mm in length, 210 mm in width and 24 mm in thickness for both male and female moulds as in Figure 3.3 using a Computer Numerical Control (CNC) machine. The mould was intentionally prepared to have a corrugated slope with a 45° angle to produce corrugated-end products.

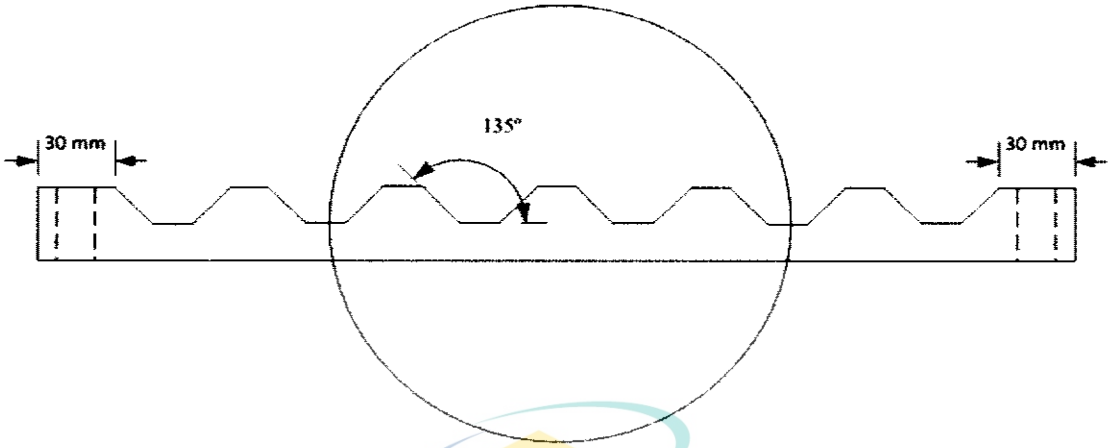

Figure 3.2 Trapezoid corrugated-core mould with 45° angle

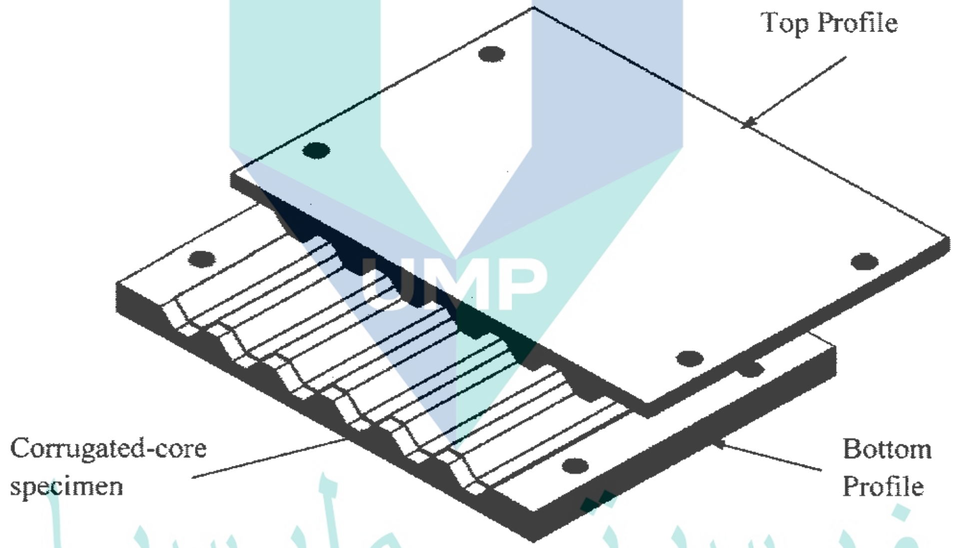

Figure 3.3 Assembly drawing of corrugated mould.

Before using the mould, it was necessary to remove all wax, debris and rust from the mould's surface. By using soda bicarbonate as a cleaning agent, the mould was soaked overnight. Then, the mould was cleaned with a brush in order to remove stain and rust. After the mould was dried at room temperature (T_{Room} = 28°C), it was then coated with a thin layer of Partall® Hi-temp Mould release wax (release agent from Rexco, USA) to avoid corrosion and to ease the de-moulding process.

3.3.2 Composite sample preparation

In this experiment, two types of short kenaf fibres with 40-80 mesh (170 – 400 micron) were used; untreated and treated kenaf fibres. The untreated fibres were obtained from Ladang Tebu Hitam, Rompin, Malaysia (40 – 80 mesh size) and prepared as the sample. Meanwhile, for treated kenaf, a 5% Sodium Hydroxide (NaOH) solution was prepared using NaOH in pellet form and then diluted with deionized (DI) water (in a weight ratio of 1 fibre:20 NaOH) (Zhang, Wang, & Keer, 2015) as in

Figure 3.5. Then, the kenaf short fibre was soaked with the NaOH solution for 1 hour (Figure 3.6).

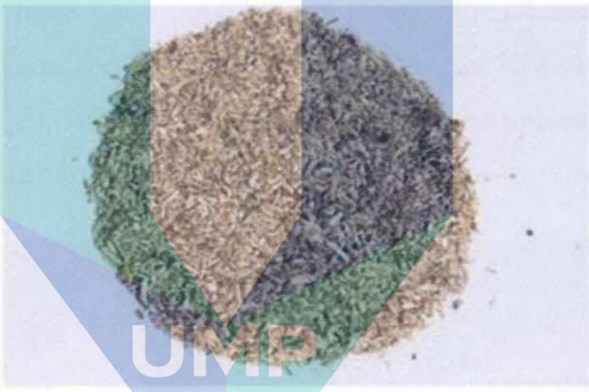

Figure 3.4 Composition of 40 – 80 mesh kenaf fibre

Figure 3.5 5% NaOH solution

Figure 3.6 Kenaf short fibre soaked with 5% NaOH solution

After 1 hour, the fibre was rinsed several times with DI water to remove any excess alkaline solution. Then, the fibre was dried in an oven at 80°C for another 24 hours (Zhang, Wang, et al., 2015). After the drying process was completed (Figure 3.7), the fibre was sealed in a plastic container in order to prevent moisture absorption.

Figure 3.7 Dried kenaf short fibre

In this research, the composite material consists of kenaf fibre and epoxy matrix. By referring to the Rule of Mixture (ROM) theory, the weight of the composite material is equal to the sum of the weight of the fibres and the weight of the matrix. Therefore:

$$w_c = w_f + w_m \quad 3.1$$

Whereby w_c denotes the weight of the composite, w_f is the weight of the fibre and w_m is the weight of the matrix. The weight fraction (mass fraction) of the kenaf fibre and the matrix are defined as:

$$W_f = \frac{w_f}{w_c} \quad 3.2$$

$$W_m = \frac{w_m}{w_c} \quad 3.3$$

As such, the sum of the weight fraction of the kenaf composite is expressed by:

$$W_f + W_m = 1 \quad 3.4$$

A summary of the Rule of Mixture based on the weight fraction (gram) used in this research is tabulated in Table 3.2 as referred to previous experiment (Bakhori et al., 2015). The same weight fraction was used for both untreated and treated samples.

Table 3.2 Composite mixture based on weight fraction

Thickness, mm	Fibre percentage, %	Material weight, g			Total weight, g
		Kenaf	Epoxy	Hardener	
4	5	12.18	154.28	77.14	243.6
	10	24.36	146.16	73.08	243.6
	15	36.54	138.04	69.02	243.6
6	5	18.27	231.42	115.71	365.4
	10	36.54	219.24	109.62	365.4
	15	54.81	207.06	103.53	365.4
12	5	36.54	462.84	231.42	730.8
	10	73.08	438.48	219.24	730.8
	15	109.62	414.12	207.06	730.8

After the preparation of the matrix material was completed, the kenaf fibre was mixed with its matrix material (with an epoxy and hardener mixing ratio of 2:1), and gently stirred in a mixing container (Figure 3.8). Then, the mixture was lay-up into the corrugated steel mould (Figure 3.10) and left to cure at room temperature.

Figure 3.8 Mixture of fibre, epoxy dan hardener

Figure 3.9 Corrugated mould with a plasticiser to avoid leaking.

Figure 3.10 Composite material poured into the mould

After 24 hours, the fibre gluing was completely cured and transformed from liquid to solid state. Then, the mould was opened and the sample gently removed as in Figure 3.11.

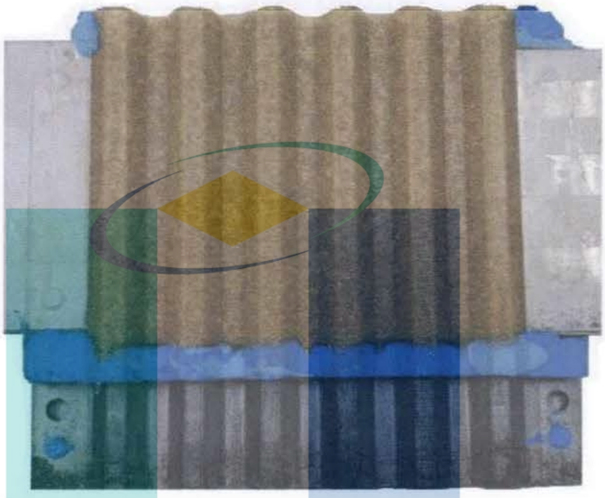

Figure 3.11 Cured corrugated core ready to de-mould

The sample was then cut into single units of 50 mm x 25 mm dimensions using a hand saw as shown in Figure 3.12. This experiment conducted the tests using single unit of the corrugated shape. Meanwhile, the top and bottom skin cover was made using hand lay-up with 3mm to 5mm thickness. The thickness of each sample was set according to the previous sub-chapter.

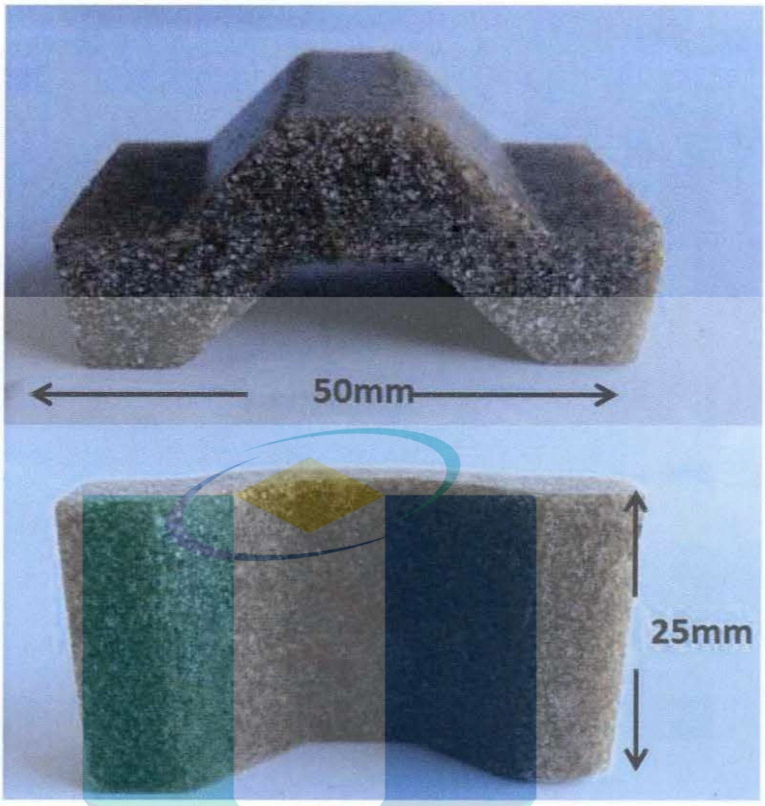

Figure 3.12 Dimensions for a single unit of 12 mm sample.

3.3.3 Tensile Test

The main reference for the tensile test followed the standard of ASTM D3039/D3039M using an Instron Universal Testing Machine with built-in Bluehill 3 software (ASTM, 2017). The Bluehilll 3 software controls the Instron testing system for the test setup and control, data collection, result generation and report preparation. The software features a graphical user interface fully implemented in Microsoft Windows. It also provides up to four real-time numerical displays (digital and/or analogue) of test data as well as graphs, results table and reports.

Bluehill 3 is the basic program for the test control. Application packages and/or optional modules can be added for specific applications as shown in Figure 3.13. Each application package contains specific test control parameters and results calculations required by the related application.

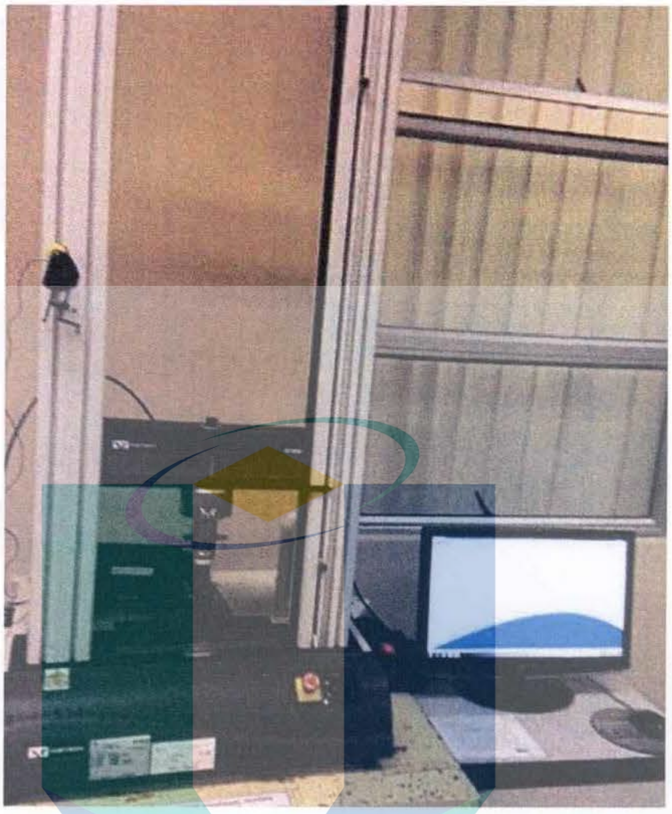

Figure 3.13 Instron Universal Testing Machine

Properties measured by this test method are the tensile strength, tensile strain, and Young's Modulus. As for the test preparation, the testing machine had both an essentially stationary head and a movable head as in Figure 3.14 and the crosshead speed of the moveable head was set to 1 mm/min.

Each head of the testing machine carried one grip for holding the test specimen so that the direction of load applied to the sample (Figure 3.14) was parallel with the longitudinal axis of the sample. The grips applied sufficient lateral pressure to prevent slippage between the grip face and the coupon.

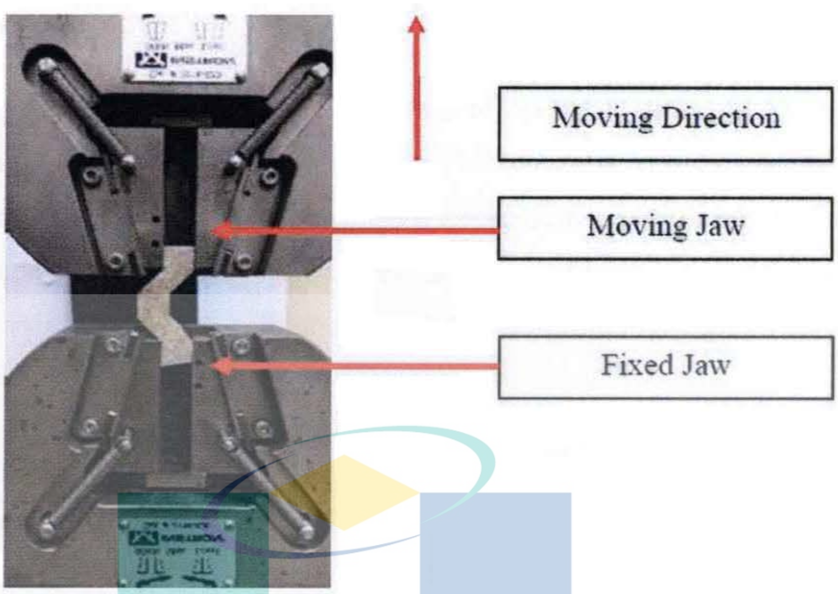

Figure 3.14 Tensile test machine setup

When loaded in tension, the Kenaf/Epoxy underwent elastic deformation phases. Initially, the specimen deformed elastically, giving a linear relationship between load and extension. These two parameters were then used to calculate the engineering stress versus engineering strain curves. Here, the engineering stress and strain were calculated using:

$$\sigma = \frac{P}{A_0} \qquad 3.1$$

$$\varepsilon = \frac{L_f - L_0}{L_0} = \frac{\Delta L}{L_0} \qquad 3.2$$

Where σ is the engineering stress, ε is the engineering strain, P is the external load, A_0 is the original cross-sectional area of the specimen. L_0 is the original length of the specimen and L_f is the final length of the specimen. The unit for stress is N/m^2 or equivalent to Megapascal (MPa). Meanwhile, for measuring strain, the unit was set in mm/mm.

3.3.4 Compression test

The compression test followed the standard of ASTM D1621-16 (ASTM, 2016). The test provides information with regards to the behaviour of cellular materials under compression loads. The test data is obtained from a complete load-deformation curve and it is possible to compute the compression stress at any load (such as compression stress at proportional-limit load or compression strength at maximum load) and to calculate the Young's Modulus.

At the time of testing, the parallelism of the compression platens is important and it is recommended that a spherical seating style compression platen be utilised along with a rigid platen. The self-aligning nature of this fixture will maximise the contact area between the platen and the specimen. Swivel seating can be placed on the platen attached to the instrument's base or load cell in the moving crosshead. To reduce possible affect from off-centre loading, it is preferred to place the swivel seat in the base as in Figure 3.15. The velocity of the moving plate was set to 1 mm/min while the specimen dimension was 50 mm x 25 mm x 32 mm as in Figure 3.16.

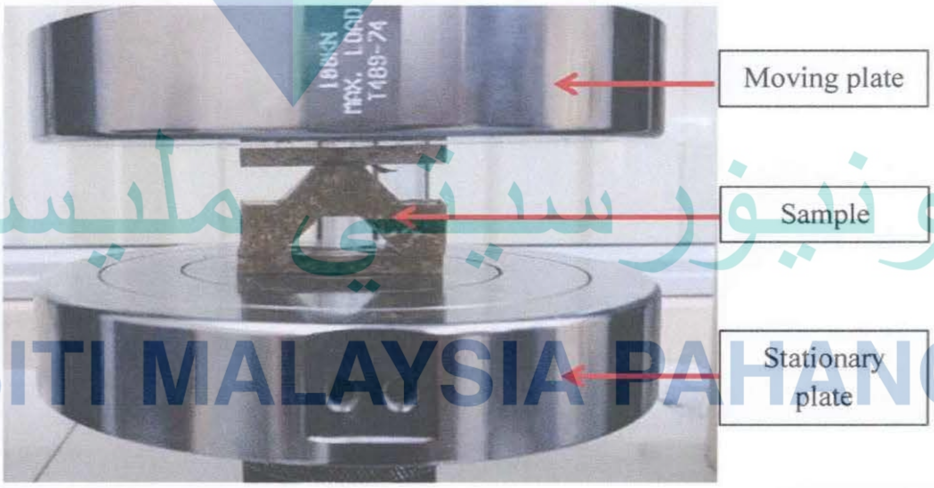

Figure 3.15 Compression test setup

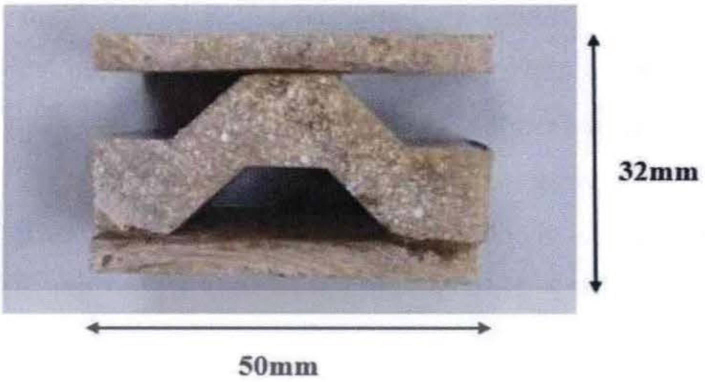

Figure 3.16 Dimensions of compression test sample

3.3.5 Physical Observation Using Microscope

Finally, a microscope study using DynoCapture 2.0 was performed to illustrate the failure mechanism during the tests. After testing, the test samples were viewed under the microscope to study the changes in failure mechanism as a function of thickness and fibre loading dynamic events.

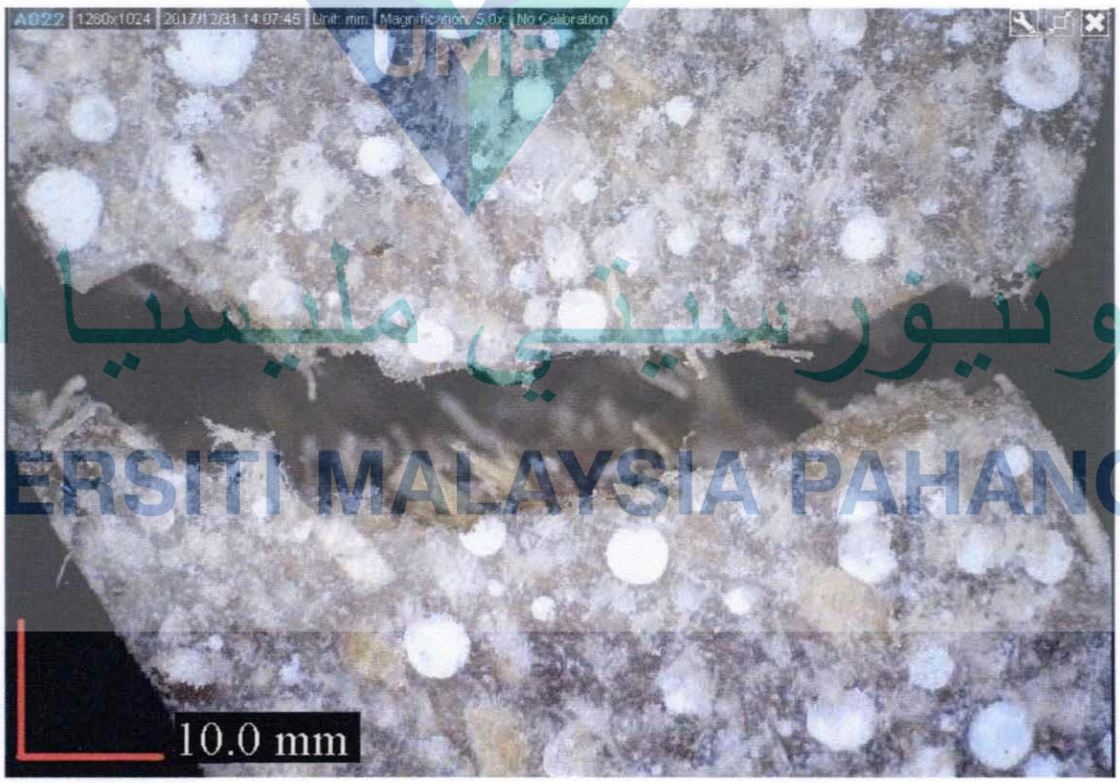

Figure 3.17 Actual image captured using DinoCapture 2.0 to view microscopic failure mechanism of test sample. The scale is 10 mm with 5.0x magnification

In this chapter, the details of the fabrication of the mould, and the corrugated core sandwich structure was presented, as well as the experimental setup and testing procedure. The corrugated core sandwich structure was fabricated using different fibre loading and thickness. The specimen geometries and fabrication were explained in detail. The basic mechanical properties of materials were examined via tensile and compression tests. This experimental setup can also be found in other studies (M. R. M. Rejab, 2013) that relates with the mechanical properties of kenaf and other natural fibre experimental procedures.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter explains the mechanical properties of the composite for both tensile and compression tests (untreated and treated samples).

4.2 Tensile properties for untreated kenaf/epoxy composite

The stress-strain curves for untreated fibre with 4 mm thickness are given in Figure 4.1. Here, the maximum tensile stress was recorded at 3.54 MPa (KEU.4.10 sample no. 2) and the maximum strain value was 0.022 (KEU.4.5 sample no 1) as tabulated in Table 4.1 and shown in Figure 4.1. The composite exhibited a roughly linear response up to the maximum stress value for all thicknesses and supported by previous research (Bakhori et al., 2015).

Table 4.1 Tensile test results for 4 mm untreated kenaf fibre

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KEU.4.5	1	2.07664	0.02252	106.36
	2	2.34586	0.02204	133.55
	3	2.82574	0.01902	124.21
	Average:	2.41068	0.02119	121.37
KEU.4.10	1	3.26875	0.02028	145.69
	2	3.54977	0.01833	165.81
	3	2.34144	0.02235	130.46
	Average:	3.05322	0.02032	147.32
KEU.4.15	1	2.64772	0.01169	217.48
	2	3.23747	0.01895	171.64
	3	3.09950	0.01839	150.80
	Average:	2.99490	0.01634	179.97

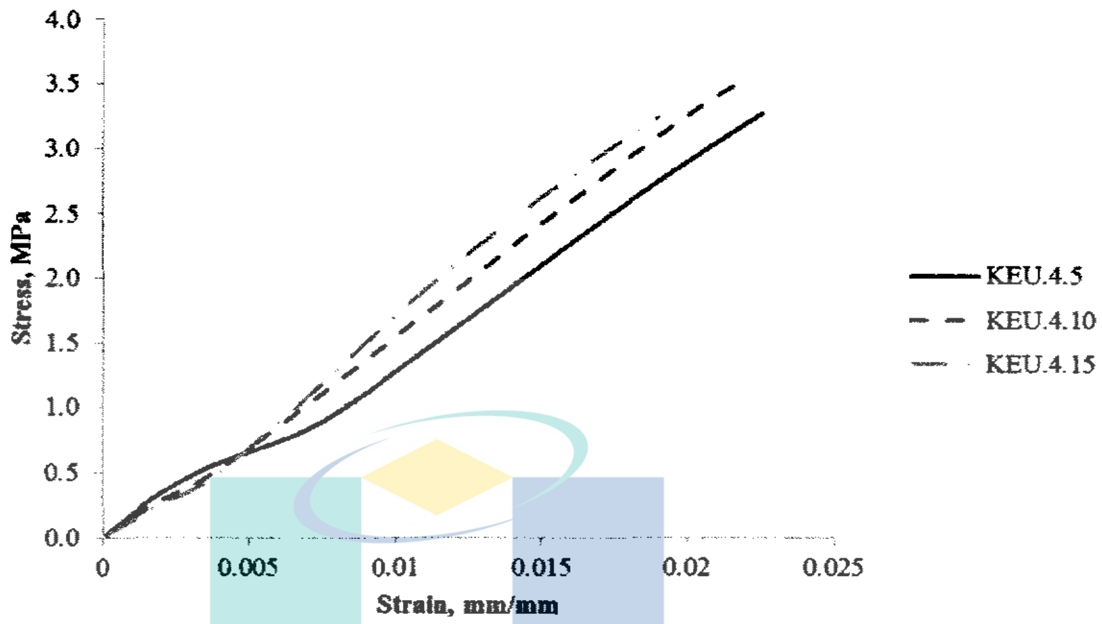

Figure 4.1 Stress-strain curves for 4 mm untreated kenaf fibre from the maximum stress value KEU.4.5 (sample 3), KEU.4.10 (sample 2) and KEU.4.15 (sample 2).

Meanwhile, for the 6 mm untreated kenaf fibre, the tensile average stress value test results was a bit lower compared to the 4 mm kenaf fibre. Here, the maximum stress was recorded in sample KEU.6.15 (3.49 MPa) and the maximum strain to failure at 0.044 which was also from the same thickness; as tabulated in Table 4.2. Also, in Figure 4.2, the composite shows a linear response to the maximum stress value.

Table 4.2 Tensile test results for 6mm untreated kenaf fibre.

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KEU.6.5	1	2.53636	0.01864	145.23
	2	2.24539	0.01198	130.95
	3	2.44525	0.01885	141.76
	Average:	2.40900	0.01649	139.31
KEU.6.10	1	2.78390	0.01770	74.79
	2	2.74430	0.01691	72.69
	3	2.08370	0.01740	42.44
	Average:	2.53730	0.01734	63.31
KEU.6.15	1	3.01355	0.04497	156.66
	2	2.70135	0.03778	228.78
	3	3.49741	0.04181	195.06
	Average:	3.07077	0.04152	193.50

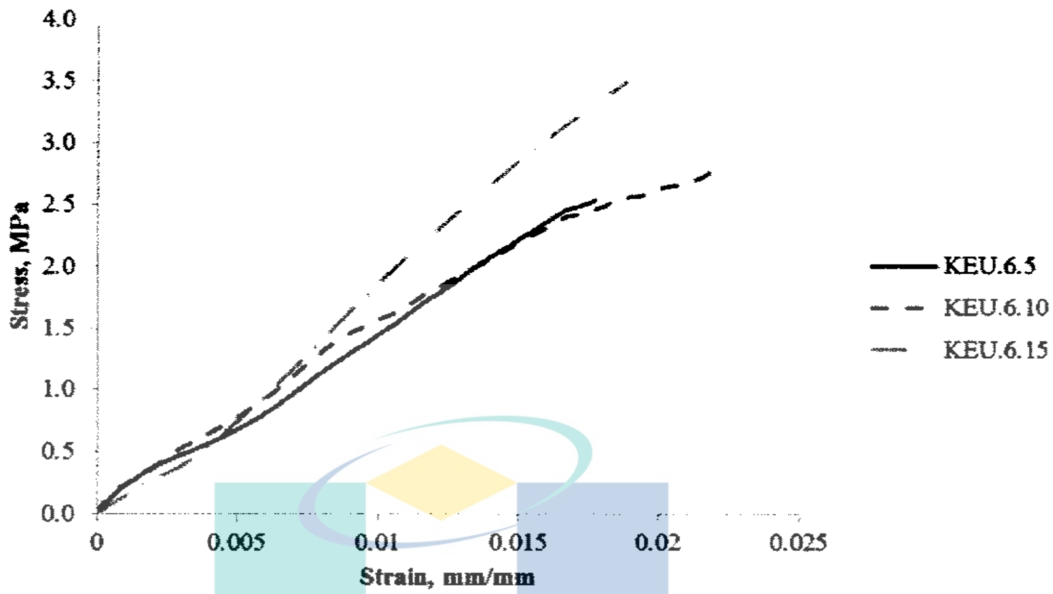

Figure 4.2 Stress-strain curves for 6 mm untreated kenaf fibre from the maximum stress value for KEU.6.5 (sample 1), KEU.6.10 (sample 1) and KEU.6.15 (sample 3).

Meanwhile, for untreated fibre with 12 mm thickness, the maximum tensile stress was recorded at 4.80 MPa (KEU.12.15 sample no. 2) and found to be the highest among all thicknesses tested as in Figure 4.3. At this point, the composite failed across the width of the sample, as shown in Figure 4.4, and provoking a rapid drop in the stress-strain curve.

Table 4.3 Tensile test results for 12 mm untreated kenaf fibre

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KEU.12.5	1	2.93372	0.01596	199.45
	2	3.65145	0.01476	225.48
	3	3.50966	0.01647	238.95
	Average:	3.36494	0.01573	221.29
KEU.12.10	1	2.22141	0.00613	349.42
	2	4.08431	0.01811	235.79
	3	3.80582	0.01409	275.87
	Average:	3.37051	0.01278	287.03
KEU.12.15	1	4.27533	0.01522	278.73
	2	4.80602	0.01691	330.65
	3	4.24074	0.01531	260.91
	Average:	4.44070	0.01581	290.10

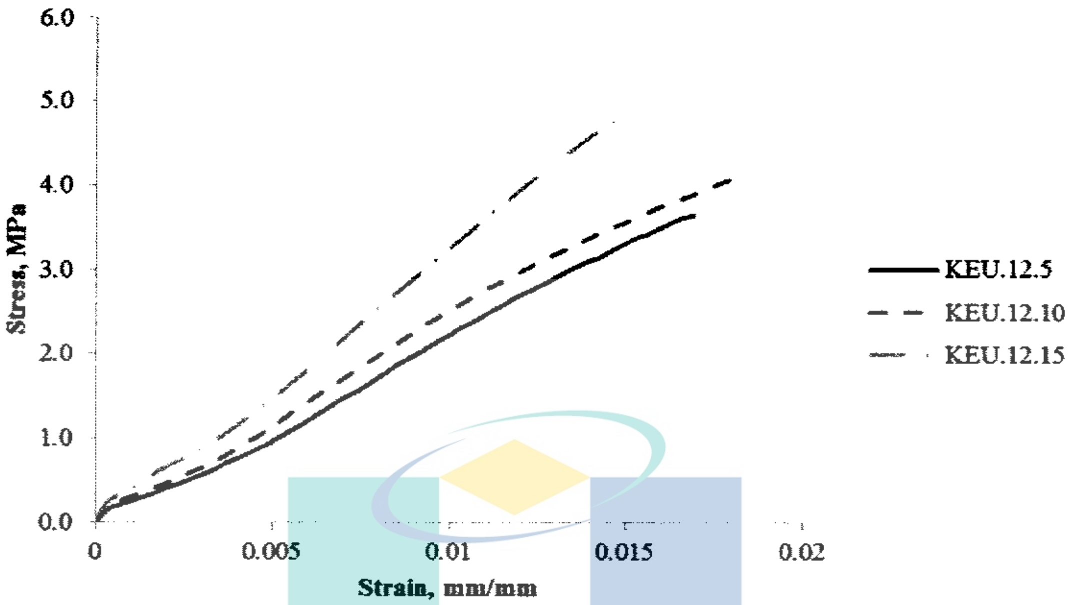

Figure 4.3 Stress-strain curves for 12 mm untreated kenaf fibre from the maximum stress value for KEU.12.5 (sample 2), KEU.12.10 (sample 2) and KEU.12.15 (sample 2).

From the tensile testing, all specimens show a high degree of brittleness. The fracture characteristic in this experiment is shown in Figure 4.4.

Figure 4.4 Shear failure near bottom of sample (KEU.12.15)

When load was applied, the sample (KEU.12.15) tended to break at the bottom neck (45° position). At this point, the composite failed over the width of the sample, and reached its maximum point in the stress-strain curve (as shown in Figure 4.4) and broke with shear stress failure mode. However, when compared to the KEU.12.10 sample, the composite failed at the centre of the sample (Figure 4.5). Moreover, the failure for the KEU.12.5 sample was found at both the neck and centre of the composite as in Figure 4.6.

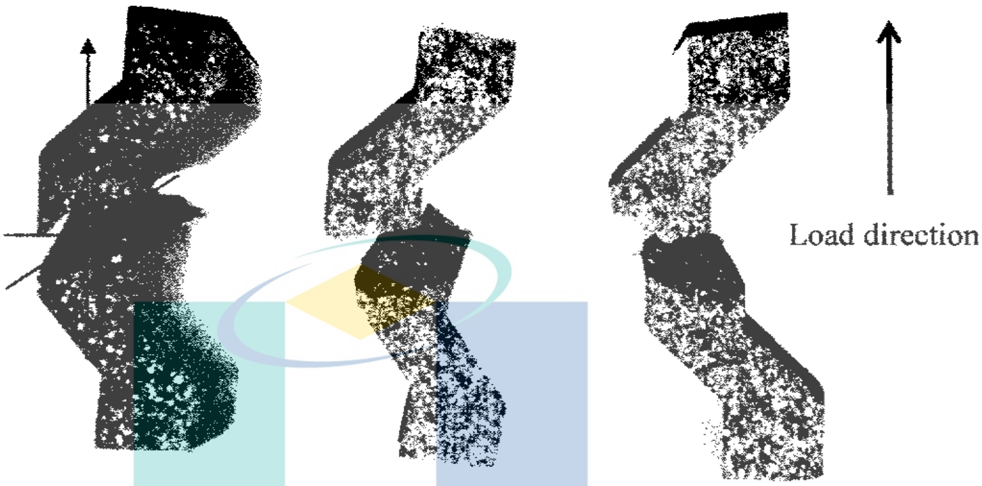

Figure 4.5 Shear failure at centre of sample (KEU.12.10)

Figure 4.6 Shear failure at centre of sample (KEU.12.5)

The positions where the samples broke/failed were different probably because of uneven length and width, fibre loading and gripping strength. As the samples were cut-to-size manually, there were some differences in terms of the length and width, but still in the appropriate tolerance (± 3mm). This also happened where the same failure was found at different positions for the 4 mm and 6 mm samples (Figure 4.7) during the tensile test due to their different thicknesses and fibre loadings.

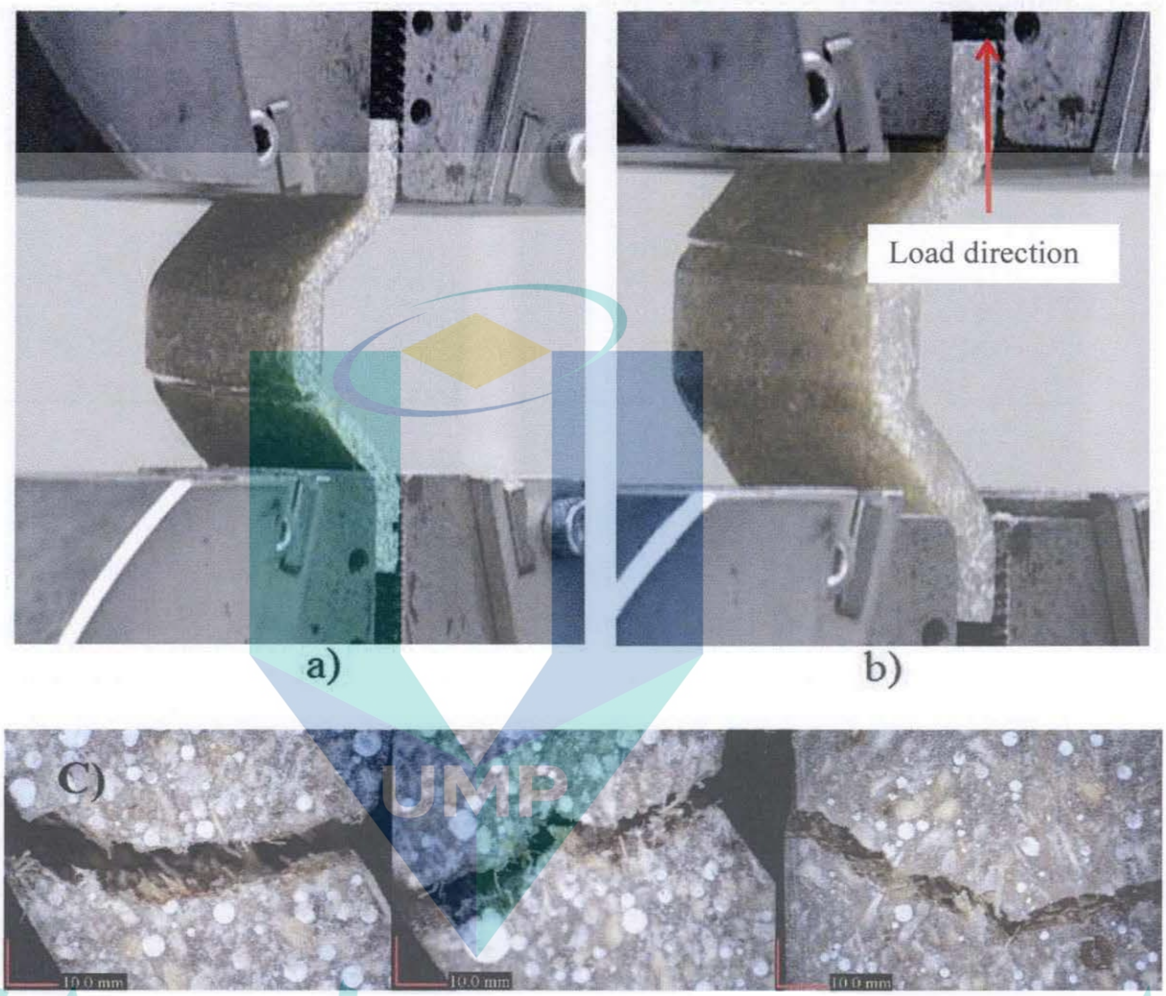

Figure 4.7 Example of sample break during tensile test: a) KEU.4.5, b) KEU.6.15 while c) is the microscopic view of samples.

4.3 Tensile properties for treated kenaf/epoxy composite

After the chemical treatment was done for the 12 mm samples, they were then taken to undergo the tensile test as well. For treated fibre with 12 mm thickness, the maximum tensile stress results was recorded at 5.87 MPa (KEU.12.15 sample no. 2) while its maximum strain value was 0.026 as in Table 4.4.

Table 4.4 Tensile test results for KET.12.5

Sample Name	Sample no.	Max Stress, MPa	Max Strain, mm	Young's Modulus, MPa
KET.12.5	1	5.45030	0.01165	469.72
	2	3.55960	0.01636	197.05
	3	4.74697	0.00900	521.09
	Average:	4.61720	0.01234	395.95
KET.12.10	1	5.36070	0.01066	495.84
	2	5.54503	0.01165	469.72
	3	3.67422	0.02666	106.87
	Average:	4.85998	0.01632	357.48
KET.12.15	1	4.18631	0.00832	415.29
	2	5.87952	0.01633	296.37
	3	5.78861	0.01567	336.56
	Average:	5.28481	0.01344	349.41

The treated kenaf fibre had a similar failure to untreated kenaf fibre. For example, for samples KET.12.15, all samples failed at the bottom (Figure 4.8). However, untreated fibre samples were completely broken from their original states compared to treated fibre. The maximum stresses for both treated (KET.12.15: 5.88 MPa) and untreated fibre (KEU.12.15: 4.80 MPa) were also different by at least an 18% increment from untreated to treated composite.

Figure 4.8 Tensile failure at bottom of sample (KET.12.15)

As compared in microscopic surface view to untreated sample, the surface of treated samples seems to be finer than untreated samples as in Figure 4.9. Single fibre pulled out and breaking can be viewed on the surface of untreated fibre and that resulted lower strength as compared to treated fibre.

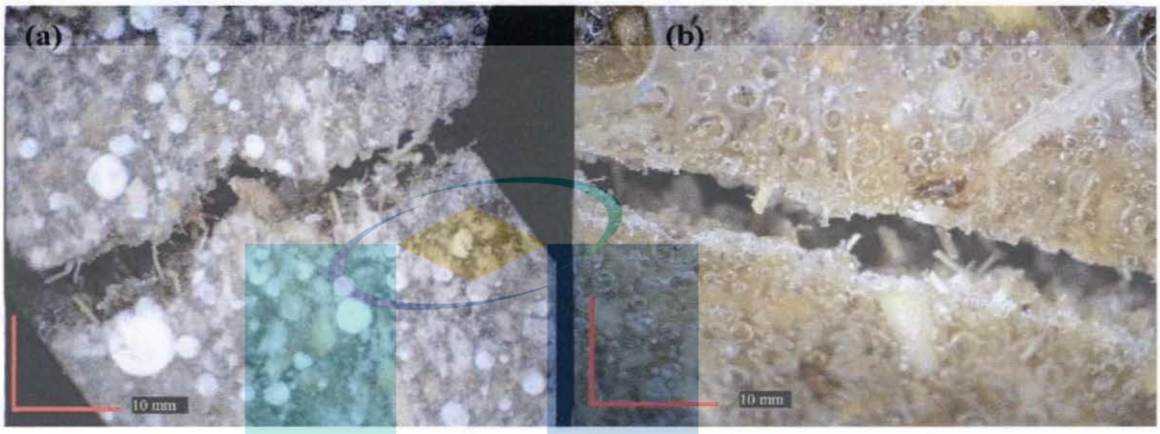

Figure 4.9 Microscopic view for (a) untreated sample KEU.4.5 and (b) treated samples KET.12.5

4.4 Effects of varying thickness, fibre loading and treatment on kenaf/epoxy composite using tensile test

The effects of varying the thickness and fibre loading on kenaf/epoxy trapezoidal corrugated cores were studied using the tensile test. The average value of the maximum stress for all samples in each thickness and fibre loading is shown in Figure 4.10. Starting from the 4 mm samples, the stress values seems to have an increasing trend. It clearly shows that at higher composite thickness and fibre loading, the composite strength will increase. The KEU.12.15 samples exhibited a higher tensile strength (stress: 5.28 MPa) and more brittle response (strain: 0.013) than the KEU.4.5 samples (stress: 2.42 MPa, strain: 0.02). In addition, the usage of 15% fibre loading in this experiment had a positive impact in terms of tensile strength results. In contrast, some researchers recommend using 20% of kenaf fibre loading to gain improvement in the mechanical properties of kenaf fibre (Deka et al., 2013). The Young's Modules value was also found to be proportionally increased as the thickness and fibre loading is increased as mention in previous experiment (Bakhori et al., 2015)

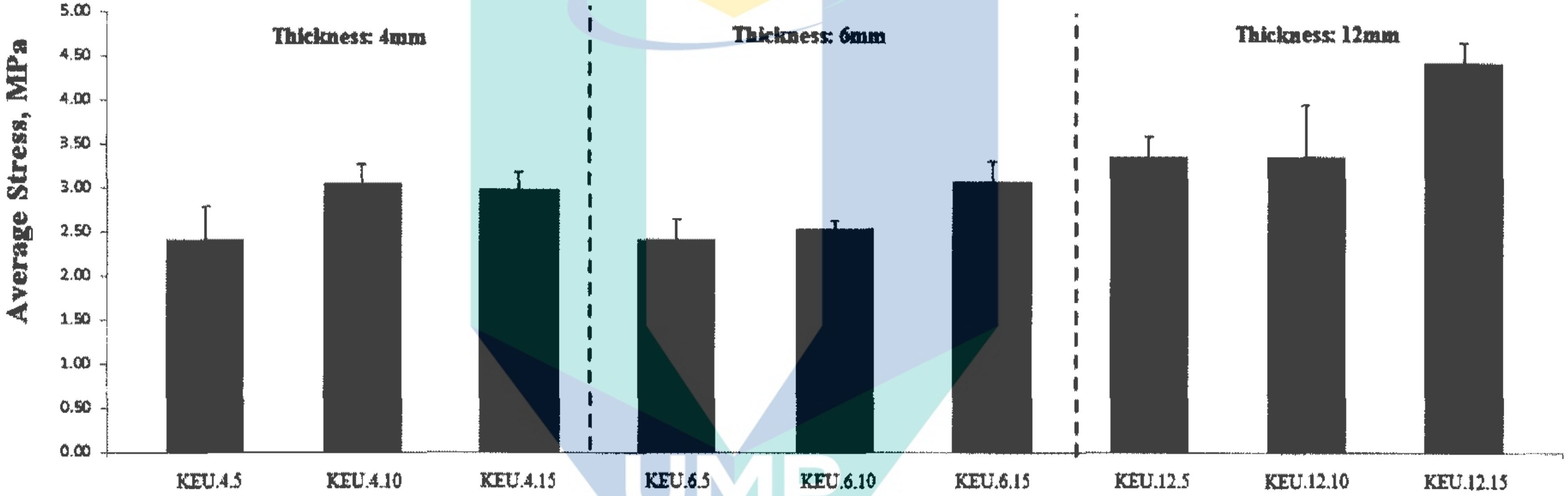

Figure 4.10 Average maximum tensile stress for all kenaf/epoxy composite specimens.

By comparing both 12 mm samples of treated and untreated fibre, Figure 4.11 clearly shows an increment in terms of the tensile strength of the kenaf/epoxy composite. The highest stress value recorded for treated 12 mm samples was 5.88 MPa (KET.12.15, sample no. 2) which is on average 18% better than untreated kenaf fibre (KEU.12.15, sample no. 2). The results obtained from this experiment support previous research (Anuar & Zuraida, 2011; Ren et al., 2012) that treated fibre has a stronger adhesion bonding than untreated fibre, thus giving better results in tensile strength. Also, other researchers (Alves Fidelis, Pereira, Gomes, de Andrade Silva, & Toledo Filho, 2013) have stated that chemical treatment on fibre gives an increase in the tensile module of at least 11% relative to that of the composite with untreated fibre.

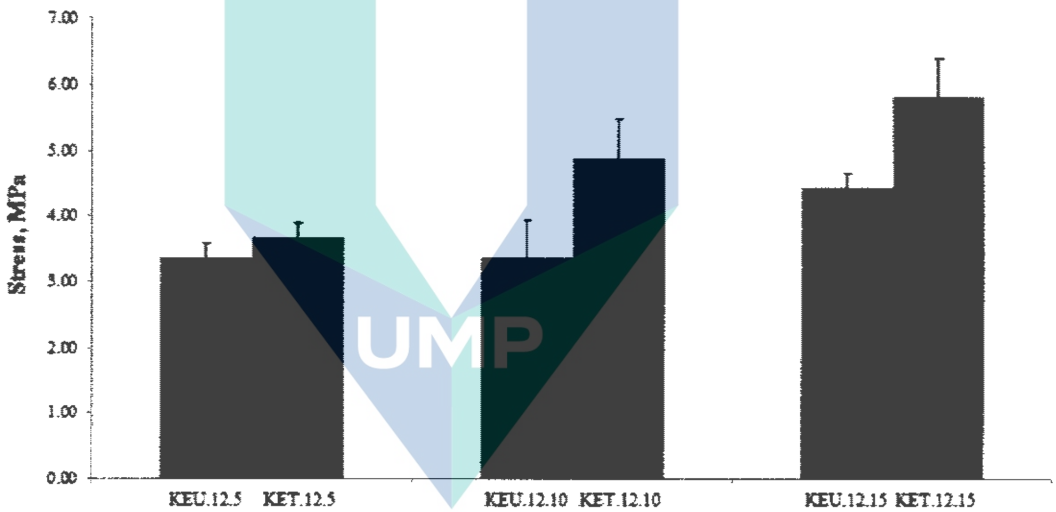

Figure 4.11 Untreated and treated kenaf fibre tensile stress for 12 mm samples after tensile test.

4.5 Compression properties for untreated kenaf/epoxy composite

The compression test was carried out to determine the compression strength of the samples under compression loading. In addition, the failure behaviour in the kenaf fibre composite is shown in this sub-chapter. For untreated fibre with 4 mm thickness, the maximum compression stress result was recorded at 2.61 MPa while the maximum strain value was 0.024 as in Figure 4.12. Here, samples KEU.4.5 and KEU.4.10 showed a linear response towards maximum stress values before they broke and dropped. Unlike sample KEU.4.15, the composite tended to displace more at the start of test but still broke at nearly 2.54 MPa (Figure 4.12). This may be due to effects associated with the machine compliance and perhaps, due to the fact that the skin may not have been parallel to its core.

Table 4.5 Compression test results for 4 mm untreated kenaf fibre

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KEU.4.5	1	1.93262	0.01859	106.36
	2	2.19150	0.01667	133.55
	3	2.11021	0.01729	130.46
	Average:	2.07811	0.01752	123.45
KEU.4.10	1	2.50511	0.01737	145.23
	2	2.20695	0.01656	130.95
	3	2.76130	0.02183	74.79
	Average:	2.49112	0.01858	116.99
KEU.4.15	1	2.61845	0.02480	95.126
	2	2.49680	0.01000	217.5
	3	2.51538	0.02000	117.29
	Average:	2.54354	0.01826	143.31

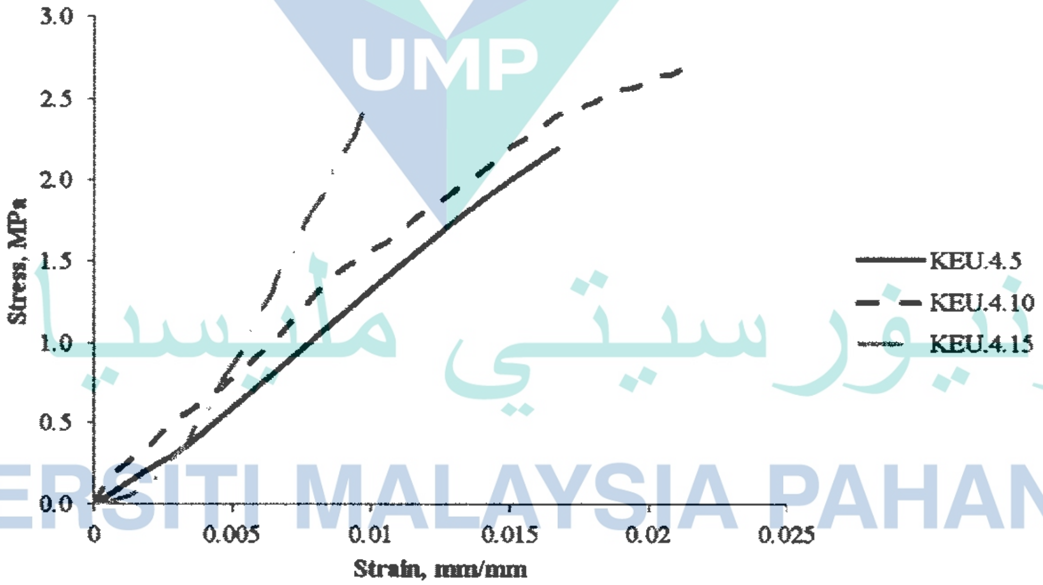

Figure 4.12 Stress-strain curves for 4 mm untreated kenaf fibre

Meanwhile, for untreated fibre with 6 mm thickness, the maximum compression stress result was recorded at 3.72 MPa while the maximum strain value was 0.026 as in Figure 4.13. The average compression strength for all samples was found to be 2.08 MPa as in Table 4.6.

Table 4.6 Compression test results for 6mm untreated kenaf fibre

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KEU.6.5	1	2.12471	0.00579	349.42
	2	2.72457	0.02082	72.69
	3	2.08329	0.01470	42.44
	Average:	2.31086	0.01377	154.85
KEU.6.10	1	2.90048	0.014090	199.45
	2	3.55052	0.016005	197.05
	3	3.68739	0.026356	106.87
	Average:	3.37946	0.019089	167.79
KEU.6.15	1	3.61384	0.01655	225.48
	2	3.48010	0.01497	238.95
	3	3.72064	0.01374	275.87
	Average:	3.60486	0.01509	246.77

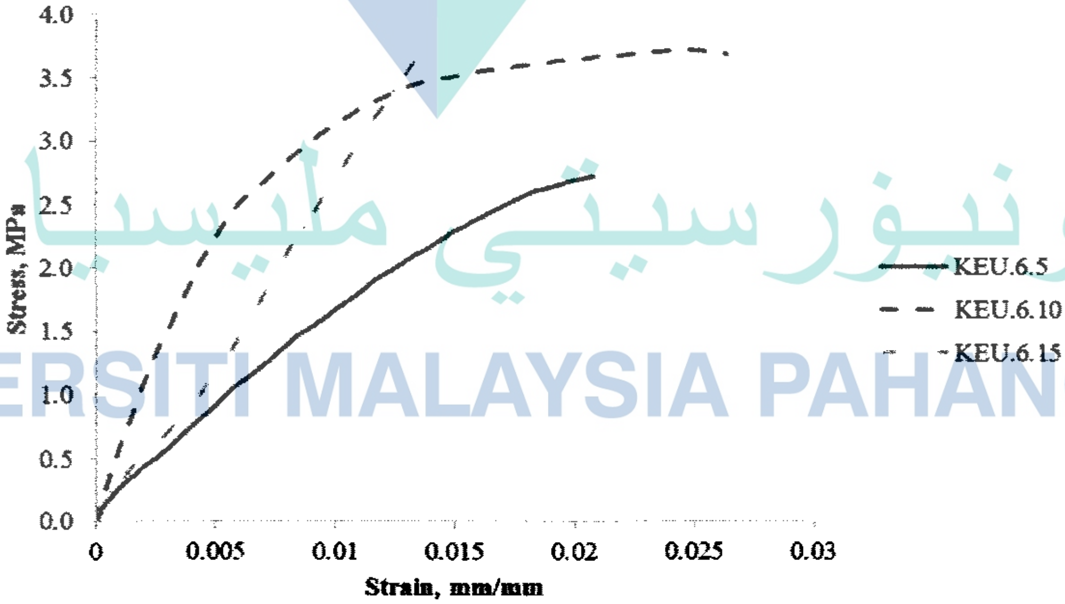

Figure 4.13 Stress-strain curves for 6mm untreated kenaf fibre

For untreated fibre with 12mm thickness, the maximum compression stress result was recorded at 4.72 MPa (KEU.12.5) as tabulated in Table 4.7 while the maximum strain value was 0.06.

Table 4.7 Compression test results for 12mm untreated fibre

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KEU.12.5	1	4.20730	0.01562	278.73
	2	4.72028	0.01442	330.65
	3	4.15784	0.01611	260.91
	Average:	4.36181	0.01538	290.09
KEU.12.10	1	3.68739	0.02635	106.87
	2	4.65947	0.00867	521.09
	3	4.35889	0.06680	197.05
	Average:	4.23525	0.03394	275.00
KEU.12.15	1	4.55580	0.0534	105.09
	2	4.25708	0.0282	146.95
	3	5.30487	0.0400	140.23
	Average:	4.70581	0.0405	130.76

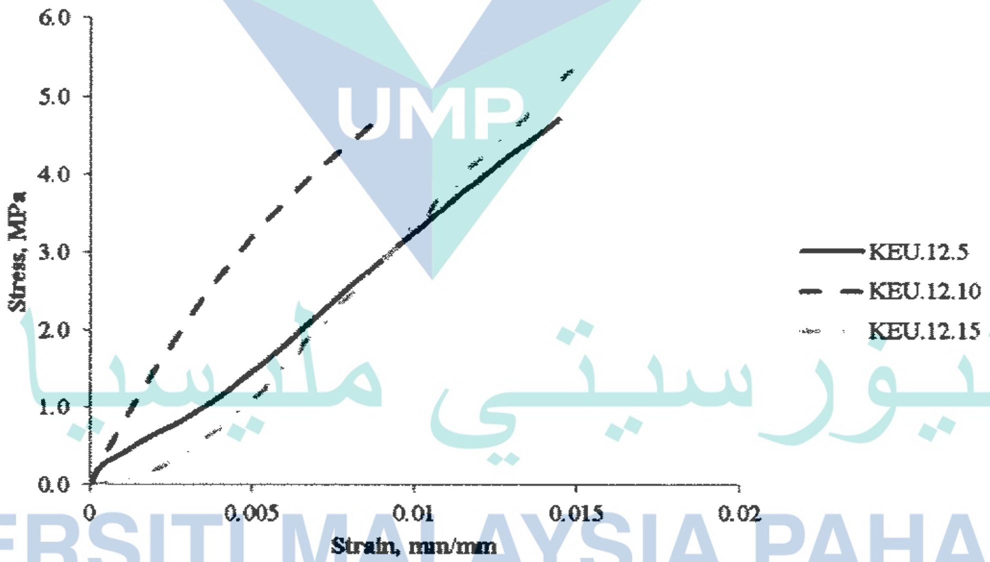

Figure 4.14 Stress-strain curve for 12mm untreated kenaf fibre

Figure 4.15 shows the mechanical response after the compression test for KEU.12.5, KEU.12.10 and KEU.12.15 samples. Disfigurement during this test was small and consistently dispersed throughout the samples. The samples failed via a rupture or deformation of the wall and buckling. The failure of the corrugated core sandwich structure after undergoing the compression test can be seen at three different positions starting with de-bonding at the top, and at both edges of the samples. The failure of samples was then followed by fibre breaking at the corrugated core. All samples from 4 mm thickness to 12 mm thickness of either untreated or treated fibre were found to have failed at almost the same position.

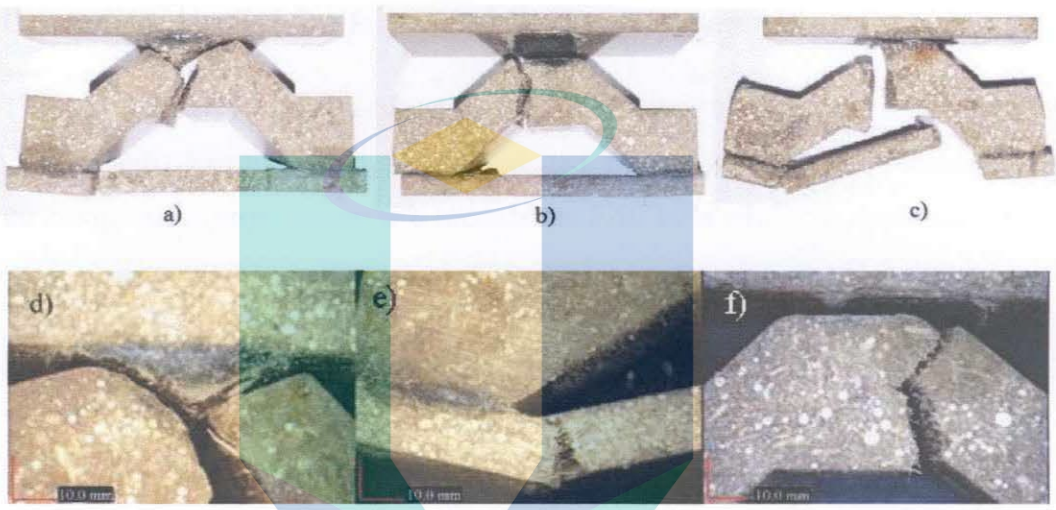

Figure 4.15 Fracture/fibre breaking and debonding after compression test for KEU.12.15 (a), KEU12.10 (b), and KEU.12.5 (De-bonding) (c) samples (Sample fails at both edges), microscopic view at broken sample (d) KEU 12.15, (e) KEU 12.10 and (f) KEU 12.5

For KEU.12.5, the bottom skin was completely broken as compared to KEU.12.15; hence the maximum compression strength was found to be 4.72 MPa which is 10% less than KEU.12.15 (5.30 MPa). Meanwhile, for the 6 mm and 4 mm thicknesses, the corrugated structures were found to have minor fracture/fibre braking compared to the 12 mm samples as shown in Figure 4.16.

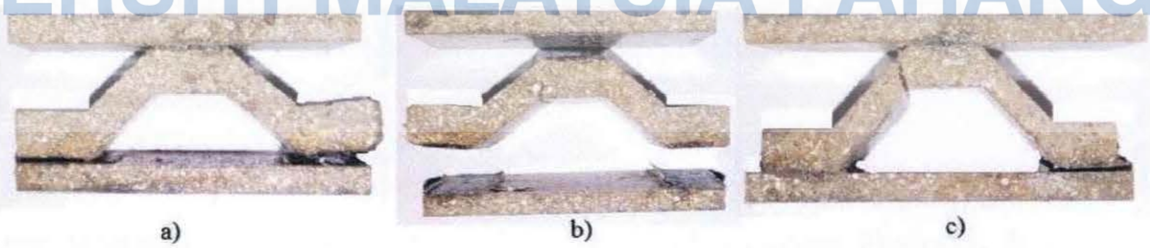

Figure 4.16 Fracture/fibre breaking and debonding after compression test for KEU.6.15 (a), KEU.6.10 (b) and KEU.6.15 (c) samples.

This shows that even though the 6 mm thick sample recorded a lower strength (for example KEU.6.15 with maximum compression stress of 3.72 MPa), the failure was not equally linear with the increment in fibre loading and sample thickness (for example KEU.12.15 with maximum compression stress at 5.30 MPa).

4.6 Compression properties for treated kenaf/epoxy composite

Treated samples also underwent compression tests to study the behaviour of composite strength. Example, for the 5% treated fibre with 12 mm thickness, the maximum compression stress result was recorded at 5.50 MPa while the maximum strain value was 0.04. The average compression strength for all samples was found to be 5.39 MPa as in Table 4.8.

Table 4.8 Compression test results for 12 mm treated kenaf fibre

Sample Name	Sample no.	Max Stress, MPa	Max Strain	Young's Modulus, MPa
KET.12.5	1	5.30458	0.040	140.23
	2	5.50068	0.030	134.37
	3	5.37152	0.035	166.38
	Average:	5.39226	0.035	146.99
KET.12.10	1	5.19998	0.01660	284.52
	2	6.28796	0.01900	318.96
	3	5.15836	0.03500	109.33
	Average:	5.54877	0.02353	237.60
KET.12.15	1	6.96474	0.02420	228.95
	2	6.51014	0.02500	234.10
	3	6.38510	0.01800	343.76
	Average:	6.61999	0.02240	268.94

For the 10% treated fibre with 12 mm thickness, the maximum compression stress result was recorded at 6.28 MPa while the maximum strain value was 0.035 as in Table 4.8. The average compression strength for all samples was found to be 5.54 MPa.

As expected, the failure for the 12 mm treated fibre was found to be the same as the 12 mm untreated fibre. There are two brittle types of behaviour observed; fibre braking and de-bonding. The sample failed at the top of the corrugated core, at both right and left edges, and/or its skin as shown in Figure 4.17.

a) b) c)

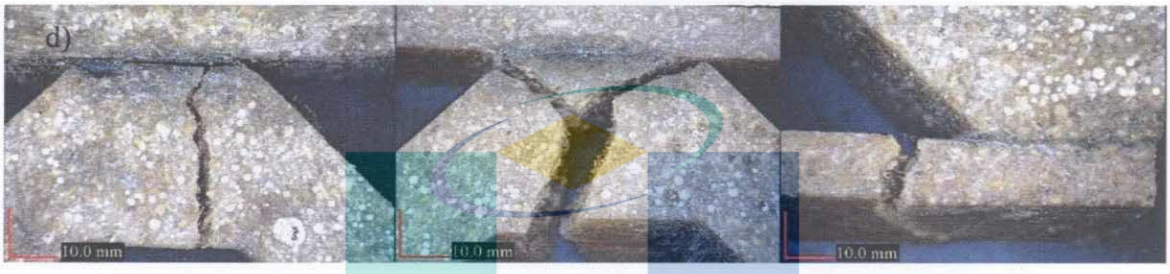

Figure 4.17 Fracture/fibre braking and debonding after compression test for KET.12.15 (a), KET.12.10 (b) and KET.12.5 (c) samples while (d) microscopic view of the broken samples.

4.7 Effects of varying thickness, fibre loading and treatment on kenaf/epoxy composite using compression test

The effects of varying the thickness and fibre loading on the kenaf/epoxy trapezoidal corrugated core was studied using the compression test. The average value of maximum stress for all samples in each thickness and fibre loading is shown in Figure 4.18. Starting from the 4 mm samples, the trend of stress value seems to be obviously increasing. It clearly shows that at higher composite thickness and fibre loading, the composite strength will increase. The KEU.12.15 samples exhibited a higher tensile strength (stress: 4.70 MPa) and more brittle response (strain rate: 0.04) than the KEU.4.5 samples (stress: 2.07 MPa, strain rate: 0.017). In addition, the usage of 15% fibre loading in this experiment had an impact in terms of the tensile strength results.

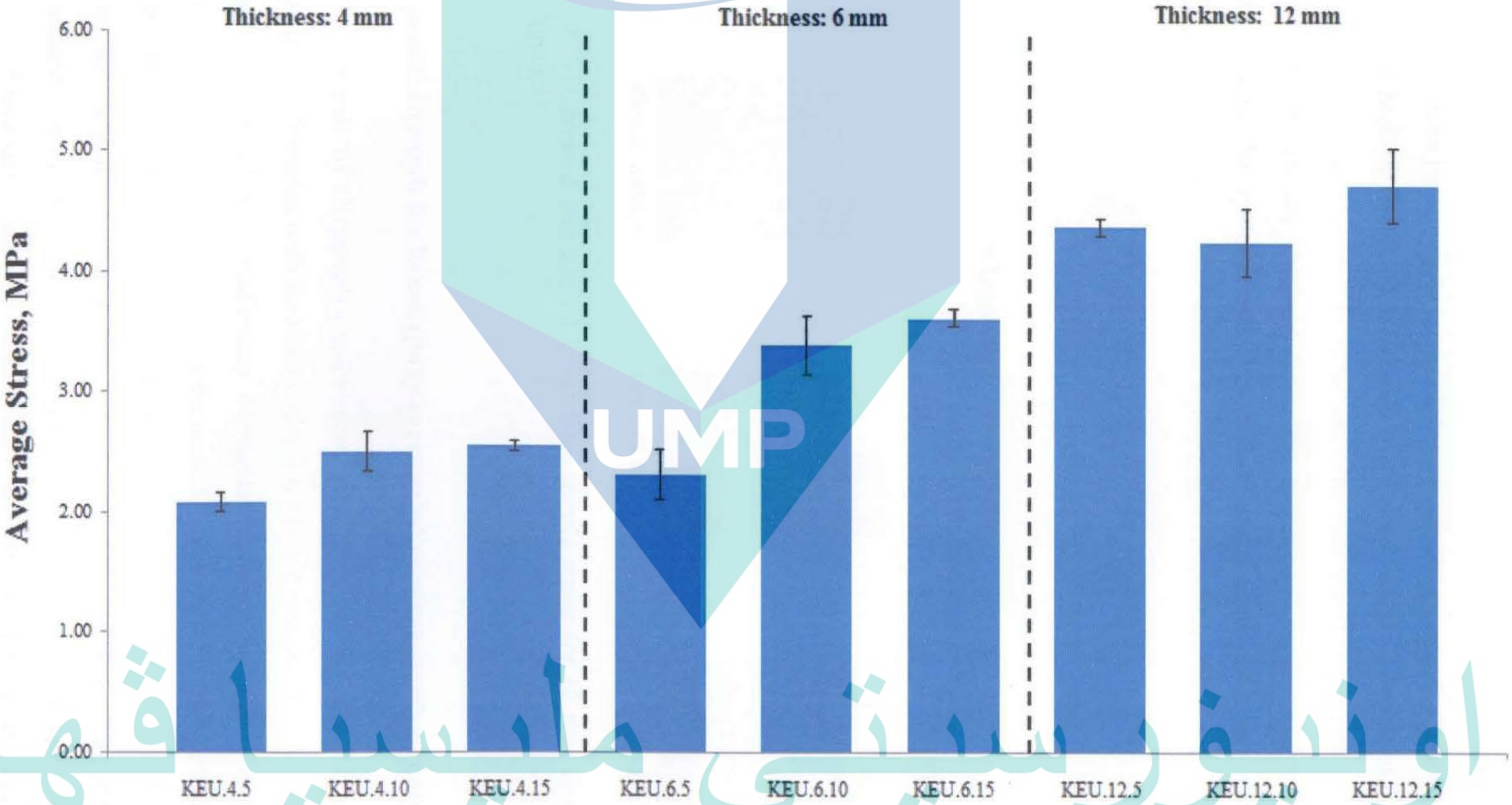

Figure 4.18 Average stress for all kenaf/epoxy composite samples after compression test.

In a comparison of both the 12 mm samples of treated and untreated fibre, Figure 4.19 clearly shows an increment in terms of the compression strength of the kenaf /epoxy composite. The highest stress value recorded for treated 12 mm samples was 6.96 MPa (KET.12.15, sample no. 1) which is 24% better than untreated kenaf fibre (KEU.12.15, sample no. 3). The results obtained from this experiment support previous research (Anuar & Zuraida, 2011; Ren et al., 2012) that treated fibre has a stronger adhesion bonding than untreated fibre, thus giving better results in compression strength.

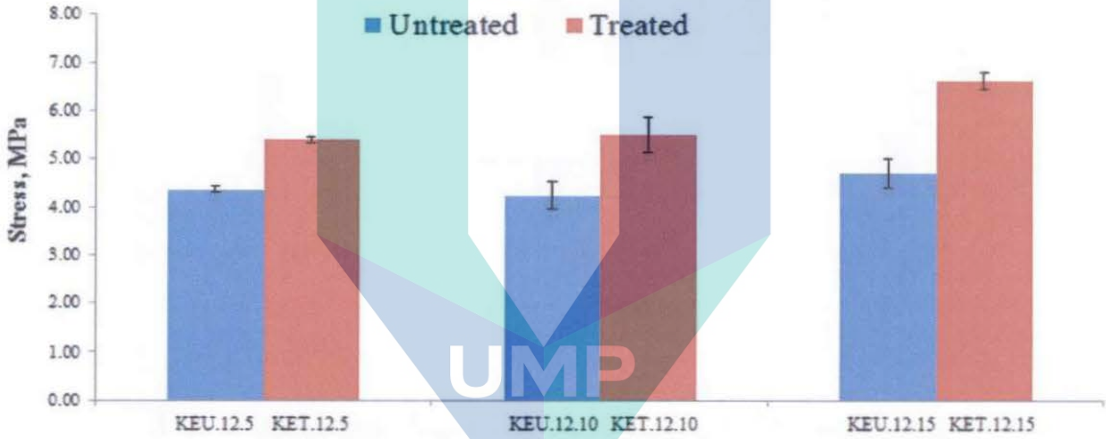

Figure 4.19 Untreated and treated kenaf fibre tensile stress for 12 mm samples after compression test.

4.8 Specific strength for kenaf/epoxy corrugated core sandwich structure

The weights of all samples were recorded before undergoing the tensile and compressive tests. Samples with skin and without skin were weighed in order to calculate the specific strength of the kenaf/epoxy corrugated core sandwich structure. Specific strength is the strength-to-weight ratio of the material. The specific strength of a material is given by the tensile or yield strength divided by the density of the material with the units Pa.m^3/kg. A material with a high specific strength has a low weight with the aforementioned benefits, but also has a high strength. To calculate the specific strength, it was assumed that the volume for each sample was based on the multiplication of its length, width and height. For density, a standard equation was used as below:

$$\rho = \frac{m}{V} \tag{4.1}$$

where ρ (density) is defined as mass (m) per unit volume (V) and the strength of each sample (in Pascal unit) is divided with the sample density to get final results as in Table 4.9.

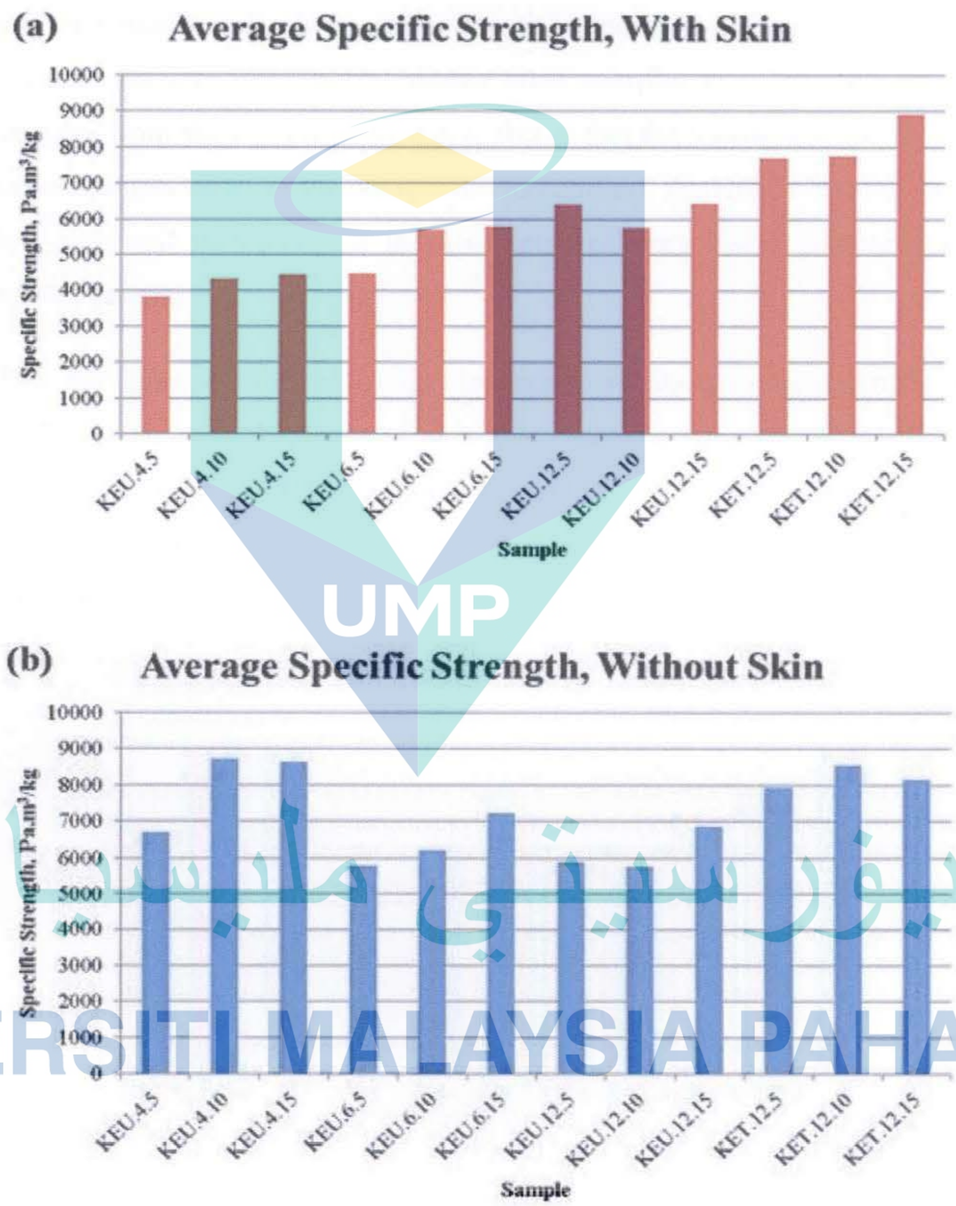

Figure 4.20 Average Specific Strength for all samples, (a) with skin and, (b) without skin.

Based on Figure 4.20, most of the samples' specific strength increased proportionally with the sample thickness. However, for samples without skin, there were several unexpected spike-ups especially for KEU.4.10 and KEU.4.15 samples. The highest recorded specific strength in this experiment was 11291.12 Pa.m^3/kg from KEU.4.10 (sample no 2) itself while the lowest strength was 3694.93 Pa.m^3/kg from KEU.12.10 (sample no 1). The range between both values is 7596.18 Pa.m^3/kg. One of the reasons for the sudden spike in specific strength is due to high tensile test results for KEU.4.10 sample no. 2 (3.54977 MPa) among other samples with the same thickness including samples from the compression test. It shows that the tensile test had an impact on the specific strength value of the composite. In addition, the tensile test samples did not have any skin and therefore, the mass of samples were lower compared to the compression test samples.

Unlike the sample with skin, the increment of its specific strength looks significantly increased over thickness. The highest specific strength recorded was in sample no 1 from KET.12.15 (9463.10 Pa.m^3/kg) and the lowest was sample no 1 from KEU.4.5 (3524.45 Pa.m^3/kg). The range between both highest and lowest values is 5938.64 Pa.m^3/kg.

Table 4.9 Summary of Specific Strength for kenaf/epoxy composite

Sample name	No.	Stress, MPa Without skin	Stress, MPa With Skin	Volume, mm^3 Without skin	Volume, mm^3 With Skin	Mass, g Without skin	Mass, g With skin	Density, kg/m^3 Without skin	Density, kg/m^3 With skin	Specific strength, $Pa.m^3/kg$ Without skin	Specific strength, $Pa.m^3/kg$ With skin
KEU.4.5	1	2.07	1.93	14187	24187	5.32	13.26	375.17	548.34	5535.11	3524.45
	2	2.34	2.19	14762	24762	5.56	13.11	376.77	529.80	6226.09	4136.45
	3	2.82	2.11	15512	25512	5.24	14.07	338.37	551.87	8350.98	3823.71
Average		2.41	2.07	14820	24820	5.37	13.48	363.44	543.34	6704.06	3828.21
KEU.4.10	1	3.26	2.50	15050	25050	5.62	14.90	373.80	594.98	8744.47	4210.36
	2	3.54	2.20	17100	27100	5.37	14.12	314.38	521.24	11291.12	4234.00
	3	2.34	2.76	15200	25200	5.80	15.25	381.61	605.32	6135.65	4561.70
Average		3.05	2.49	15783	25783	5.60	14.76	356.60	573.85	8723.75	4335.36
KEU.4.15	1	2.64	2.61	1525	25125	5.26	14.40	348.11	573.50	7605.79	4565.66
	2	3.23	2.49	16925	26900	5.36	14.21	317.16	528.53	10207.56	4723.96
	3	3.09	2.51	15262	25137	5.84	15.65	382.71	622.63	8098.69	4039.91
Average		2.99	2.54	15570	25720	5.49	14.75	349.33	574.89	8637.34	4443.18
KEU.6.5	1	2.53	2.12	18600	28600	7.74	14.25	416.58	498.28	6088.44	4264.03
	2	2.24	2.72	18900	28900	7.80	15.55	413.01	538.20	5436.57	5062.30
	3	2.44	2.08	18062	28062	7.49	14.22	415.21	506.94	5889.13	4109.48
Average		2.40	2.31	18520	28520	7.68	14.67	414.93	514.48	5804.71	4478.60
KEU.6.10	1	2.78	2.90	19000	29000	8.04	15.23	423.17	525.24	6578.62	5522.18
	2	2.74	3.55	19612	29612	7.57	18.32	386.08	618.77	7108.01	5737.97
	3	2.08	3.68	18500	28500	7.78	17.99	420.96	631.32	4949.78	5840.70
Average		2.53	3.37	19037	29037	7.80	17.18	410.07	591.78	6212.14	5700.28
KEU.6.15	1	3.01	3.61	20625	30625	8.99	18.85	436.07	615.51	6910.65	5871.22
	2	2.70	3.48	20275	30275	8.74	19.18	431.46	633.66	6260.91	5491.99
	3	3.49	3.72	21237	31237	8.72	19.36	410.86	619.80	8512.25	6002.87
Average		3.07	3.60	20712	30712	8.82	19.13	426.13	622.99	7227.94	5788.69

Table 4.9 Summary of Specific Strength for kenaf/epoxy composite (continued)

Sample name	No.	Stress, MPa Without skin	Stress, MPa With Skin	Volume, mm^3 Without skin	Volume, mm^3 With Skin	Mass, g Without skin	Mass, g With skin	Density, kg/m^3 Without skin	Density, kg/m^3 With skin	Specific strength, $Pa.m^3/kg$ Without skin	Specific strength, $Pa.m^3/kg$ With skin
KEU.12.5	1	2.93	4.20	25537	35537	14.12	25.73	553.11	724.02	5303.94	5810.95
	2	3.65	4.72	25625	35625	15.48	23.42	604.33	657.66	6042.05	7177.30
	3	3.50	4.15	26912	36912	14.85	24.42	551.98	661.83	6358.20	6282.31
Average		3.36	4.36	26025	36025	14.82	24.52	569.81	681.17	5901.40	6423.52
KEU.12.10	1	2.22	3.68	25825	35825	15.52	26.88	601.20	750.49	3694.93	4913.25
	2	4.08	4.65	26025	36025	15.78	25.62	606.34	711.40	6736.00	6549.71
	3	3.80	4.35	26037	36037	14.51	26.88	557.35	746.12	6828.37	5842.07
Average		3.37	4.23	25962	35962	15.27	26.46	588.29	736.00	5753.10	5768.34
KEU.12.15	1	4.27	4.55	27825	37825	16.76	26.15	602.50	691.50	7095.88	6588.23
	2	4.80	4.25	23075	33075	16.95	26.22	734.67	792.92	6541.70	5368.80
	3	4.24	5.30	27412	37412	16.68	27.04	608.66	722.99	6967.29	7337.34
Average		4.44	4.70	26104	36104	16.80	26.47	648.61	735.81	6868.29	6431.46
KET.12.5	1	5.45	5.30	25650	35650	14.35	25.70	559.53	720.96	9740.74	7357.64
	2	3.55	5.50	25812	35812	15.62	23.94	605.45	668.54	5879.18	8227.79
	3	4.74	5.37	25187	35187	14.54	24.94	577.40	708.85	8221.15	7577.72
Average		4.61	5.39	25550	35550	14.84	24.86	580.80	699.45	7947.02	7721.05
KET.12.10	1	5.36	5.19	26475	36475	15.65	26.68	591.20	731.64	9067.44	7107.23
	2	5.54	6.16	26662	36662	15.00	25.62	562.88	698.88	9851.16	8816.39
	3	3.67	5.15	27712	37712	15.14	26.38	546.39	699.71	6724.41	7372.06
Average		4.85	5.50	26950	36950	15.26	26.23	566.82	710.08	8547.67	7765.22
KET.12.15	1	4.18	6.96	26162	36162	17.66	26.61	675.19	735.98	6200.14	9463.10
	2	5.87	6.51	25950	35950	16.59	26.15	639.54	727.46	9193.28	8949.06
	3	5.78	6.38	26637	36637	16.86	27.94	633.13	762.77	9142.84	8370.90
Average		5.28	6.61	26250	36250	17.04	26.90	649.29	742.07	8178.75	8927.69

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

In this chapter, a conclusion is provided to summarise this research. Recommendations and suggestions with regards to this research will also be included for future reference. The main point of this research work was to manufacture and to explore the mechanical properties of kenaf fibre based on a corrugated core composite. Based on the findings of this research, the following conclusions can be drawn.

5.2 Conclusions

i) Objective 1: To investigate the effect of chemical treatment on kenaf fibre to the performance of a kenaf/epoxy corrugated composite.

Tensile and compression tests were conducted to study the mechanical performance of a corrugated core kenaf fibre composite. For 12 mm samples, the kenaf fibres were treated with a 5% alkaline solution (NaOH) in a weight ratio of 1 fibre:20 NaOH. As a result, the tensile and compression stress limits significantly increased. The highest stress value for treated kenaf fibre was recorded at 5.88 MPa, which is 18% (using average values) higher than the untreated kenaf fibre. The same behavioural results were found in the compression test where the highest recorded stress value for treated kenaf fibre was 6.96 MPa, whereas the highest recorded stress for untreated kenaf fibre was only 5.30 MPa. It shows that the chemical treatment using the 5% NaOH solution affected the mechanical performance of the kenaf fibre composite in terms of stress limit value.

ii) Objective 2: To study the effect of varying the parameters and properties of a kenaf/epoxy corrugated core sandwich structure.

The kenaf fibre composite samples were intentionally fabricated with three different thicknesses. After going through tensile and compression tests, the stress value increased as the thickness increased. In the 4 mm tensile test, the lowest stress value was recorded at 2.07 MPa (from sample KEU.4.5) and the stress increased to 3.49 MPa for the 6 mm samples (KEU.6.15) as the fibre content increased from 5% to 15% by weight. Meanwhile, for the compression test, the 12 mm samples with 15% fibre had a stress value (5.30 MPa) which was higher than the 6 mm samples with the same fibre loading (3.72 MPa). It clearly shows that the increment in sample thickness and fibre loading resulted in the increment of stress values for both tensile and compression tests.

Specific strength increased proportionally with the sample thickness. However, for samples without skin, there were several unexpected spike-ups especially for KEU.4.10 and KEU.4.15 samples. The highest recorded specific strength in this experiment was 11291.12 Pa.m^3/kg from KEU.4.10 (sample no 2) itself while the lowest strength was 3694.93 Pa.m^3/kg from KEU.12.10 (sample no 1). Unlike the sample with skin, the increment of its specific strength looks significantly increased over thickness. The highest specific strength recorded was in sample no 1 from KET.12.15 (9463.10 Pa.m^3/kg) and the lowest was sample no 1 from KEU.4.5 (3524.45 Pa.m^3/kg).

5.3 Recommendations for future work

The performance of a kenaf fibre corrugated core sandwich structure has been shown in this research. Here are some recommendations for future work:

i) Further testing should be carried out to identify the mechanical performance and characteristics of kenaf fibre corrugated core sandwich structures. For example, researchers may run shear tests, bi-axial loading tests and varying the sample thickness.

ii) Instead of using kenaf fibre, it is also recommended to study the corrugated core sandwich structure using other natural fibres and matrix material. A similar method can be applied using other natural fibres such as hemp, jute, and sisal. Different methods like varying the chemical treatment composition can also be applied for future experiments.

iii) A simulation study, for example Finite Element (FE) can be carried out to compare the results from the current experiment. In this research, no Finite Element studies were conducted and therefore, this analysis can be done in the future.

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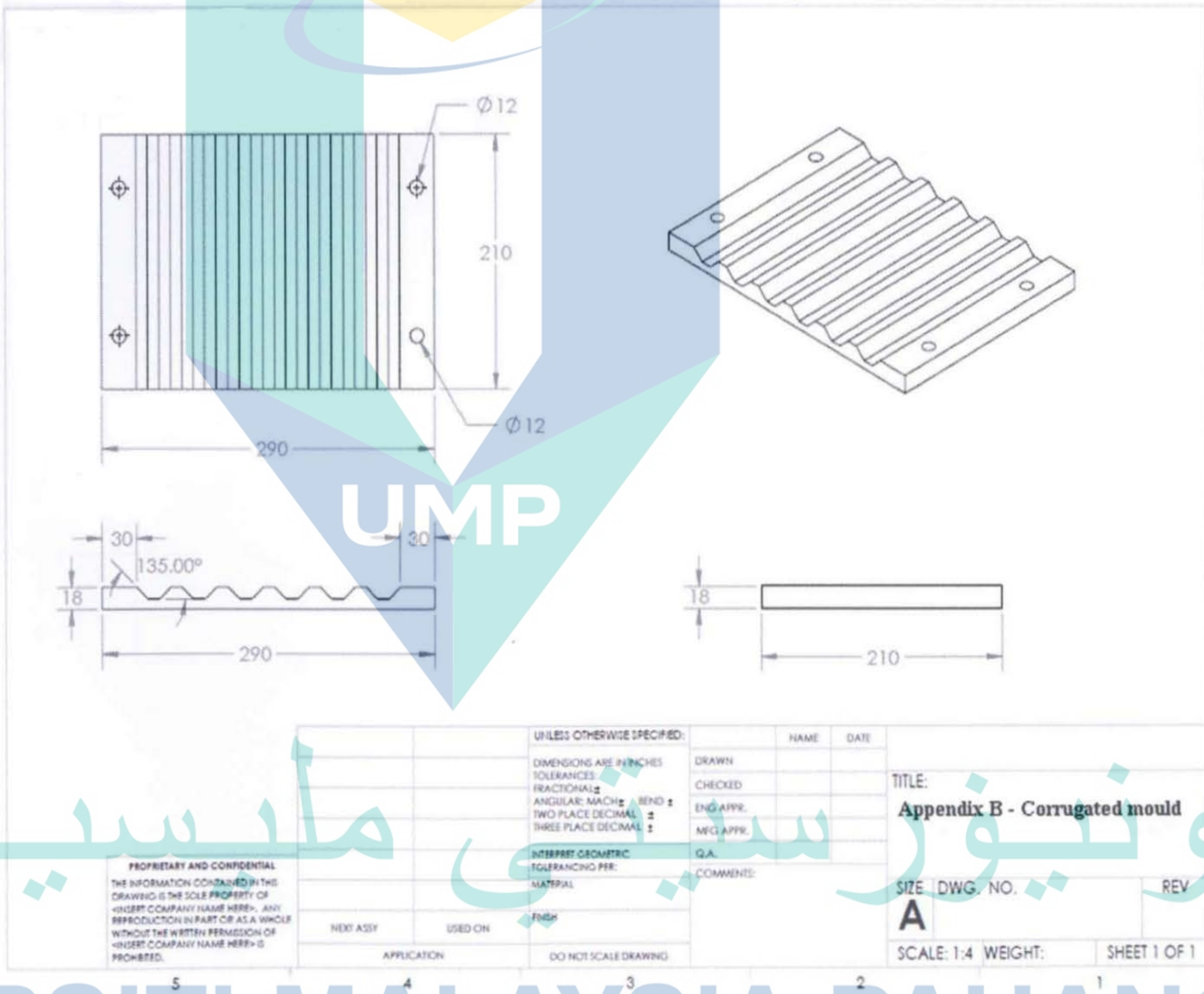
APPENDIX A

LIST OF PUBLICATION AND CONFERENCES

The 3rd International Conference on Mechanical Engineering Research (ICMER) 2015, Kuantan Pahang Malaysia, NATURAL FIBER REINFORCED COMPOSITES: A REVIEW ON POTENTIAL FOR CORRUGATED CORE OF SANDWICH STRUCTURES, A.F. Jusoh, M.R.M. Rejab, J.P Siregar, D. Bachtiar.

APPENDIX B



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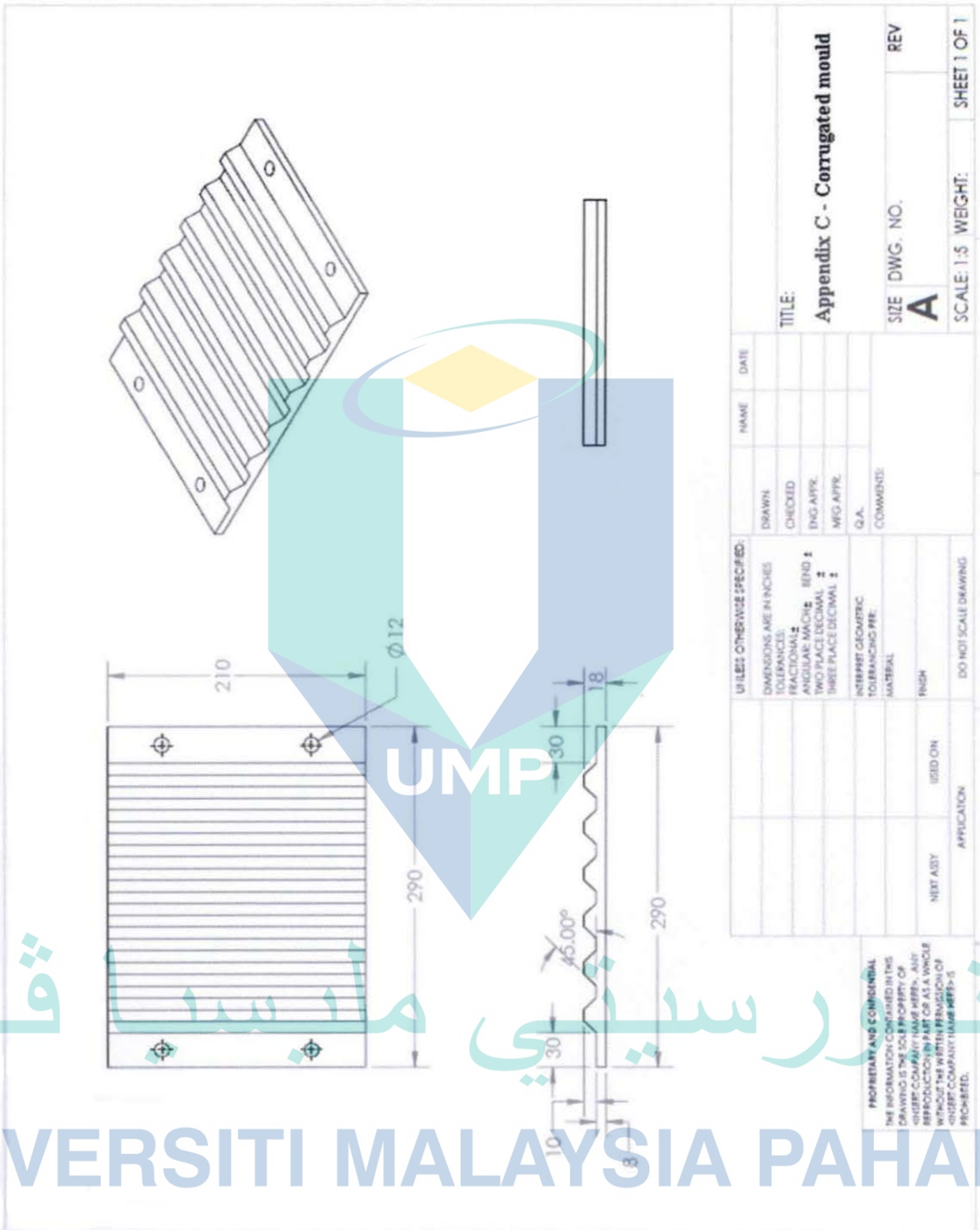
APPENDIX C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