Hybrid Composite Material of Bombyx Silk Fiber for Ankle Foot Orthoses in Stroke Patient

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บทคัดย่อ

วัสดุผสมเป็นวัสดุ ที่นิยมใช้ในด้านกายอุปกรณ์เสริมระดับข้อเท้า ในปัจจุบัน ได้มีการนำเส้นใยหลายชนิดเพื่อมาเสริมความแข็งแรงแก่ เรซินอะคริลิก แต่ยังไม่เคยมีผู้ศึกษาถึงความเป็นไปได้ในการนำเส้นใยไหมมาใช้ การศึกษานี้จึงมีวัตถุประสงค์เพื่อศึกษา ความหนา, น้ำหนัก, ความแข็งแรง, ความแข็งแรงของแรงดึง, แรงงอ, ความความล้า, การยึดติดกันระหว่างเส้นใยและเรซินอะคริลิก, แรงกดทั้งในแนวตรง และแนวด้านข้างของกายอุปกรณ์ และความล้าของกายอุปกรณ์เสริม โดยใช้การขึ้นรูปด้วยเทคนิค การขึ้นรูปเป็นชั้นๆ(Lamination)

ผลจากการศึกษาแสดงให้เห็นว่ากายอุปกรณ์เสริมระดับข้อเท้า ด้านการทดสอบความแข็งแรงจากการดึง วัสดุผสมที่มีการเสริมความแข็งแรงด้วยเส้นใยไหม จะมีค่าความแข็งแรงเมื่อเทียบระหว่างแรงต่อน้ำหนัก ซึ่งมีค่าที่มากกว่าการเสริมความแข็งแรงด้วย คาร์บอนไฟเบอร์ และกราสไฟเบอร์ ภาพจากกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราดแสดงถึงเรื่องการยึดติดระหว่างวัสดุผสมที่มีการเสริมความแข็งแรงด้วยผ้าไหม แสดงให้เห็นถึงการยึดติดระหว่างเส้นใยไหมและเรซิ่น มากกว่าการยึดติดของวัสดุผสมที่มีการเสริมความแข็งแรงด้ายคาร์บอนไฟเบอร์ และกราสไฟเบอร์ ผลการทดลองยังชี้ให้เห็นถึง ผลความแตกต่างอย่างมีนัยสำคัญทางสถิติ ด้านคุณสมบัติทางกายภาพและคุณสมบัติทางกล ของการนำเส้นใยไหมมาเสริมความแข็งแรง ในกายอุปกรณ์ระดับข้อเท้า ผลการประเมินความพึงพอใจของการใช้อุปกรณ์ กายอุปกรณ์ที่มีการเสริมความแข็งแรงด้วยเส้นใยไหมได้รับความพึงพอใจมากกว่า จะโดดเด่นในเรื่องของราคาของเส้นใยที่ใช้เสริมความแข็งแรง ที่มีราคาถูกกว่า 10 เท่า

คำสำคัญ: วัสดุผสม, การขึ้นรูปเป็นชั้นๆ, กายอุปกรณ์เสริมระดับข้อเท้า

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ABSTRACT

Polymer composite material is a choice for the ankle foot orthoses(AFOs). Various types of fiber have been used to reinforce ankle foot orthoses. However, the possibility of using silk fiber has never been investigated. The objectives of this study were to evaluate the morphology and mechanical properties; weight, thickness, tensile strength, flexural strength, fatigues, hardness, compression testing on ankle foot orthoses and fatigues of orthoses. Such properties of the ankle foot orthoses materials were used as a guideline for othoses fabrication. Ankle foot orthoses were produced into fiber polymer composite by lamination technique. And evaluation complacency questionnaires.

This study demonstrated that definitive laminated composite matrial silk fiber with resin had a higher strength/weight h than carbon and glass fiber polymer composite. Hardness and elongation at break is comparable to carbon and glass fiber polymer composite. Furthermore, the morphology of silk fiber composite showed that silk fibers adhere with resin better than carbon fibers and glass fibers. Significantly, as physical and mechanical properties and morphology, silk fiber composite promises to be an alternative material for ankle foot orthoses. And all question score of silk fiber reinforcement are higher than carbon fiber reinforcement. The price of spiral ankle foot orthoses comparison silk fiber reinforcement cheaper than carbon fiber reinforcement 10 times.

Keyword: Composite material, Lamination, Ankle foot orthoses

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Tuanjit Na Rungsri

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CHAPTER 1

INTRODUCTION

1.1 Background and Rationale

Ankle-foot orthoses (AFOs) are used by individuals with neuromuskuloskeletal disorder to maintain proper foot drop and assist in normal gait achievement. Neuromuskuloskeletal disorder is a leading cause of disability which results from the impairment of the nervous system (Fernie G., 1990). Neurological disorders in common with stroke are motor muscle weakness, loss of balance, spasticity and mobility impairment (Joan Leung et al, 2003). The results for a stroke patient are impaired balance and decreased walking velocity (Schroeder HP, 1995). The main problem is muscle weakness, and muscle functions can be restored with the use orthoses. Gait rehabilitation takes more than six months. The orthoses are designed for mobility and improvement of the quality of life. There are two important success determinants in correcting some problems relating to loss of function so that the patient can be comfortable during walking and standing (Lusardi MM et al, 2000). AFOs are often prescribed for stroke patients. The ankle foot orthoses are designed to provide mediolateral ankle stability during stance, adequate toe clearance swing and to promote heel strike.

Lower extremities are managed by orthotics in the patients after a stroke. A spiral ankle foot orthoses (AFO) is used for stroke patients **(Figure1.1)** (Alon G et al, 2007). The ankle foot orthoses are designed to provide mediolateral ankle stability during the stance phase, prevent toe clearance during the swing phase and to promote heel strike for increasing some options for some daily activities (Teasell R et al, 2005).

Ankle foot orthoses are manufactured using a lamination technique with matrix and reinforcement. These are composite materials of resins with carbon fiber or glass fiber reinforcement. Carbon fiber and glass fiber are popular: they are fabricated by lamination technique (F.P. Gerstle et al, 2012). Composite materials are a family of high performance materials consisting of a matrix and fiber reinforced. The matrixes are thermosetting resin such as an epoxy, polyester and acrylic resin. The fiber reinforcements are aramid fiber, glass fiber and carbon fiber. The combination of a resin and a fiber results in properties of a quite different character than either constituent. These unusual properties are a result of the fiber being characterized by single crystal properties. However, carbon fiber and fiber glass are very harmful materials; causing some problems such as irritation of the skin, eyes and respiratory tract, and they are expensive materials (Beffort O., 2000).

For this present study, silk fiber was selected because of its mechanical properties, and because of its low cost and easily implemented technique. The advantages of silk fiber consist of high strength, non-irritation of the skin, and non-irritation of the eyes and respiratory tract. The Bombyx mori woven natural silk (WNS) is used as a reinforcement, considering its environmental and mechanical properties. It is among the strongest fibers produced in nature, with high specific-strength and high specific-stiffness; and is extremely elastic and resilient. Previous studies have shown that Bombyx mori silk composites material is better than Kevlar or steel in terms of elongation at failure (Craven et al. 2000). It has a good capacity to absorb energy and to dissipate this energy in the silk deforms (Perez-Rigueriro *et al.*, 2000).

In this study, we investigated the literature review; the use of natural fiber in composites is nothing new to humans. Evidence of natural fiber reinforced composites material could be found in pottery containing hemp fiber which dated back to as early as 10,000BC. (Mussig, 2010). Kelvin Loh and Willy Tan evaluated the feasibility of its mechanical properties to fabricate a natural silkworm silk-epoxy composite and explore the use of a low cost method to enhance the mechanical properties of silk fiber (Kelvin Loh and Willy Tan 2011). In this thesis, the focus is on the comparison composite material properties of carbon fiber and glass fiber with Bombyx silk fiber on resin lamination. This natural fiber reinforcement is suitable for making effective orthoses for stroke patients, at a lower cost.

Figure 1.1 Ankle foot orthoses (AFOs); (a) Orthoses (b) Orthoses on a patient

1.2 Objective

1.2.1 To fabricate silk composite for ankle foot orthoses.

1.2.2 To study the morphological, physical and mechanical properties of silk composite.

1.2.3 To fabricate ankle foot orthoses based on silk composite.

1.2.4 To study the mechanical properties of ankle foot orthoses reinforcement based on silk composite.

1.2.5 To test the complacency of a spiral ankle foot orthoses using questionnaires.

1.3 Conceptual Framework

Orthoses material for rehabilitation is a design which comes up with various properties. In this present material there are problems such as irritation of the skin, eyes and respiratory tract, and the high price of reinforcement materials. Researchers were led to explore the development of material quality and analyze the natural fibers which can be used as a replacement for synthetic fiber materials and used to produce ankle foot orthoses. Effective orthoses can be made at a lower cost and with high performance from the material for the orthoses for stroke patients.

Conceptual Framework

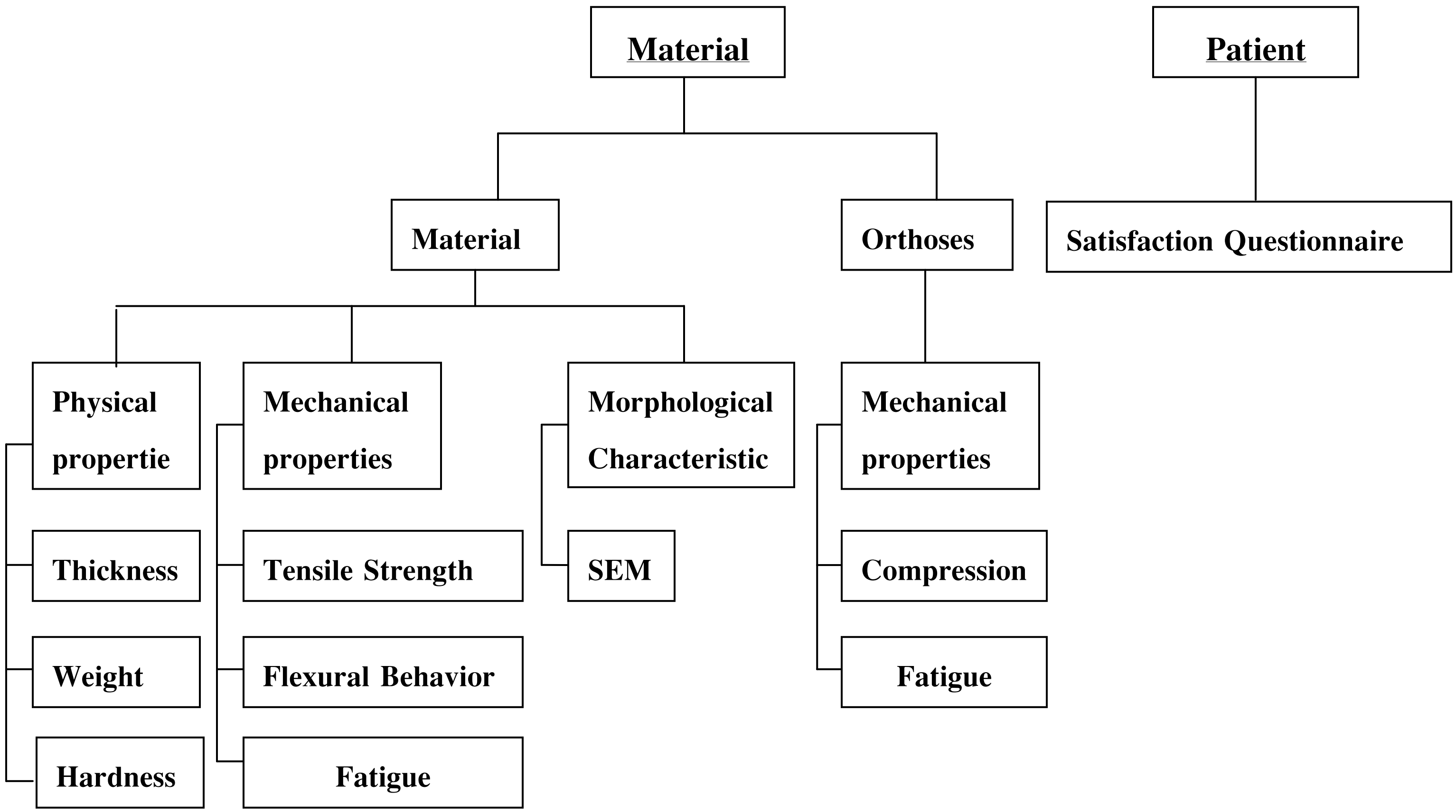


Figure 1.2 Conceptual frameworks

1.4 Review of Literature

In previous research, Grissom SP. and Blanton S. treated upper motor neuron plantarflexion contractures by using an adjustable ankle-foot orthoses study in 6 patients received ankle-foot orthoses can be reduced. Plantarflexion contractures significantly decreased (Grissom SP et al, 2001).

Hemi pareses were present ankle-control disturbances, equinovarus deformity, leading to difficulty in walking and the increase of risk from falling. Ankle-foot orthoses (AFO) are frequently prescribed to correct the ankle joint alignment and increase the walking speed and the stride length during ambulation. Wearing AFO significantly improved the stride and step length on both the unaffected and affected sides, the step width, the walking speed, the frequency of the step and functional ambulation ability (Abe H et al, 2009).

Table1.1 Previous research on prosthetic and orthotic materials has focused on laminate material.

Years	Study	Results
1992	Tensile strengths for carbon fiber with epoxy resin (Taylor DA et al, 1992)	The carbon 0/90 degree had tensile strengths 433 to 588 MPa The canbon 45 degree had tensile strengths 12.2 to 46.8 MPa
2005	Analyzed 24 combinations of prosthetic laminates and resins (8 lay-up materials and 3 types of resins) (Phillips SL et al, 2005)	The classified as low tensile strength are 18 to 24 MPa. (Perlon, nylon, cotton, nyglass, and spectralon.) The classified as middle tensile strength are 67 to 109 MPa. (Fiberglass) The classified as high of tensile strength are 236 to 249 MPa. (Carbon)

Years	Study	Results
2005	The study concluded that pure fiberglass material performed the worst in regards to flexural properties, followed by nyglass between two layers of carbon fiber (Taylor D et al, 2005)	The carbon/carbon lay-up is stronger in shear and thus bending. The fiberglass/fiberglass samples deformed extensively with the maximum gross force being 20.8 lbs Adding low angle fibers (220 and 00) of fiberglass and carbon between layers of carbon braid greatly improved bending strength.
2009	Polyethylene fiber is produced from gel-spinning process evaluated three types of materials (Shekhar B et al, 2009)	Tensile strength three materials. 1. Carbon samples to be in the range of 83-89 MPa 2. Spectra-carbon to be in the range of 27 to 36 MPa 3. Spectra-nylon to be in the range of 28 to 30 MPa.

Previous research preferred fiber layers for the bar carbon fiber. It has high physical strength properties and enormously low specific gravity. Moreover, it is very lightweight and strong.

Performance criteria for orthotic devices include sufficient strength to withstand maximum stresses resulting in a dramatic improvement for dorsiflexion, durability, minimal weight and minimal fabrication cost. Unfortunately, the design for these goals is difficult because of a lack of comprehensive data on component material properties.

A previous study is about the tensile properties of bamboo-fiber reinforced epoxy composites. The composite sample was fabricated with five different fiber lengths of bamboo fiber (2, 4, 6, 8 and 10 mm). The fabrication was made by hand lay-up techniques. Mechanical properties were determined to use tensile testing. An interaction between fiber and matrix was observed from the scanning electron microscope micrographs. The tensile strength was increased, but the elongation break was not significant (Kongkeaw P et al, 2011).

Since the advantages of natural fibers such as silk exhibit low density (density of silk is in the range of 1.32-1.40 g/cm^3 whereas density of glass fiber and aramid fiber are 2.55 and 1.44 g/cm^3, respectively (Jain N et al, 2007), with high strength, acceptable specific strength, enhanced energy recovery, recyclability and biodegradability and are non-harmful. Moreover, it showed low electrical conductivity when it was compared with metal alloy and carbon fibers. Furthermore, it was used for many purposes in this area.

1.5 Scope of the Study

In this study, we tested different composite materials that were used for the spiral ankle foot orthoses at the Rehabilitation Clinic at Songklanagarin Hospital in 2012-2013.

1.5.1 To study silk fiber composites that were developed for replacement of carbon fiber and glass fiber composites.

1.5.2 To design a spiral ankle foot orthoses that is specific to stroke patients and orthoses evaluation effectiveness by using questionnaires.

1.6 Research Hypothesis

1.6.1 Orthotic devices from using Bombyx silk material reinforcement in the ankle foot
orthoses will provide good morphological, physical and mechanical properties.

1.6.2 The new material in orthotic devices options to the new choice for medicine.

1.7 Research Outcome Benefits

1.7.1 To reduce production costs in material and have good qualifications equivalent to the ankle foot orthoses standard.

1.7.2 To reduce harmful materials that are used for the patients and the orthotists.

1.7.3 To extend the application of silk fiber in medicine.

CHAPTER 2

PRINCIPLES AND THEORIES

2.1 Bombyx mori Silk Fibers

Natural silk fibers have the potential to be used for reinforcement in composites materials. The advantages of using silk fiber biomaterials are their high strength, reduced weight, are environmentally friendly, skin-irritation free, comfortable, low cost, and are good at interfacing with resin(A.P. Irawana et al, 2011; Zulkifli R et al 2009).

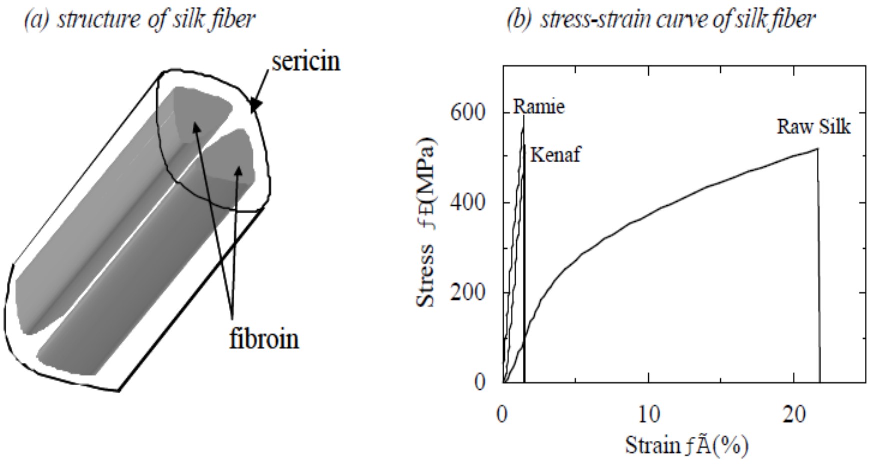
In the **table 2.1** shown : Mechanical properties of common natural (Spider Silk, Enhanced B Mori Silk, B. Mori Silk, Flax, Hemp) and Synthetic Fibers (Kevlar, carbon, E-glass, Dyneema, High Grade Steel) (Loh KMK)

Table 2.1 Mechanical properties of common natural fiber (Zulkifli R et al, 2009)

Type of Fiber	Material	Density (g/cm^3)	Tensile strength (MPa)	Young's Modulus (GPa)	Elongation at Failure (%)
Natural Fibres	Spider Silk	1.3	1300-2000	30	19-30
	Enhanced B.Mori silk	1.3-1.38	600-700	12.2	30-35
	B. Mori Silk	1.3-1.38	500	8.5-8.6	15
	Flax	1.45	500-900	50-70	1.5-4.0
	Hemp	1.48	350-800	30-60	1.6-4.0
Synthetic Fibres	Kevlar 49	1.44	3600-4100	130	2.8
	Carbon	1.4	4000	235	2
	E-glass	2.5	3100-3800	76-79	4.8
	Dyneema	0.97	2300-3500	500	2.7-4.5
	High Grade Steel	7.8	1000	200	30

Silk fiber is produced from silk worms that feed on mulberry leaves from the moment they are born until they are ready to spin their cocoons, which is about 35 days. This fiber is known as raw silk which is then spun into silk yarn and threads.

*Bombyx **mori*** (Latin for the silkworm of the mulberry tree) silk fibers are produced year round in Thailand. The insect is important being a primary producer of silk. A silkworm's preferred food is mulberry leaves, which it eats for about 35 days. The fiber it produces, known as raw silk, is then spun into silk yarn and threads. Most production is after the rice harvest in the southern and northeastern parts of the country. Silk fibers are produced by two types of silkworms; they are from the cultured Bombycidae and the wild Saturniidae. The natural silkworm silk fiber contains hydroxyl groups which are called hydrophilic (Mei-po Ho et al, 2011). The natural silk fiber has good properties; it is a very good absorbent of moisture, is lightweight, can retain heat, can be worn both in summer and in winter, has high tensile strength, and has the ability of bending and compression (Kimura T et al). The advantages of natural silk fiber over plant-based natural fibers are many include the production of the following items; bulletproof vests, and materials of medical use. Properties of Bombyx mori silk fiber include the following: continuous fiber type, high toughness, high crystallinity, and high tensile strength **Figures 2.1.** The structure of silk fiber and the tensile property together with those of cellulosic fibers. (a) The silk is formed from fibroin and sericin and two fibroin fibers are bonded by sericin. This can be seen in Fig. (b). Silk fiber is characterized as a fiber with large elongation (Seong Ok Han 2006). Therefore, Bombyx mori silk has been chosen for this research to make the people in Thailand recognize its beauty and importance and economical suitability for the country.



Figures 2.1 The structure of silk fiber and stress-strain curve of silk fiber

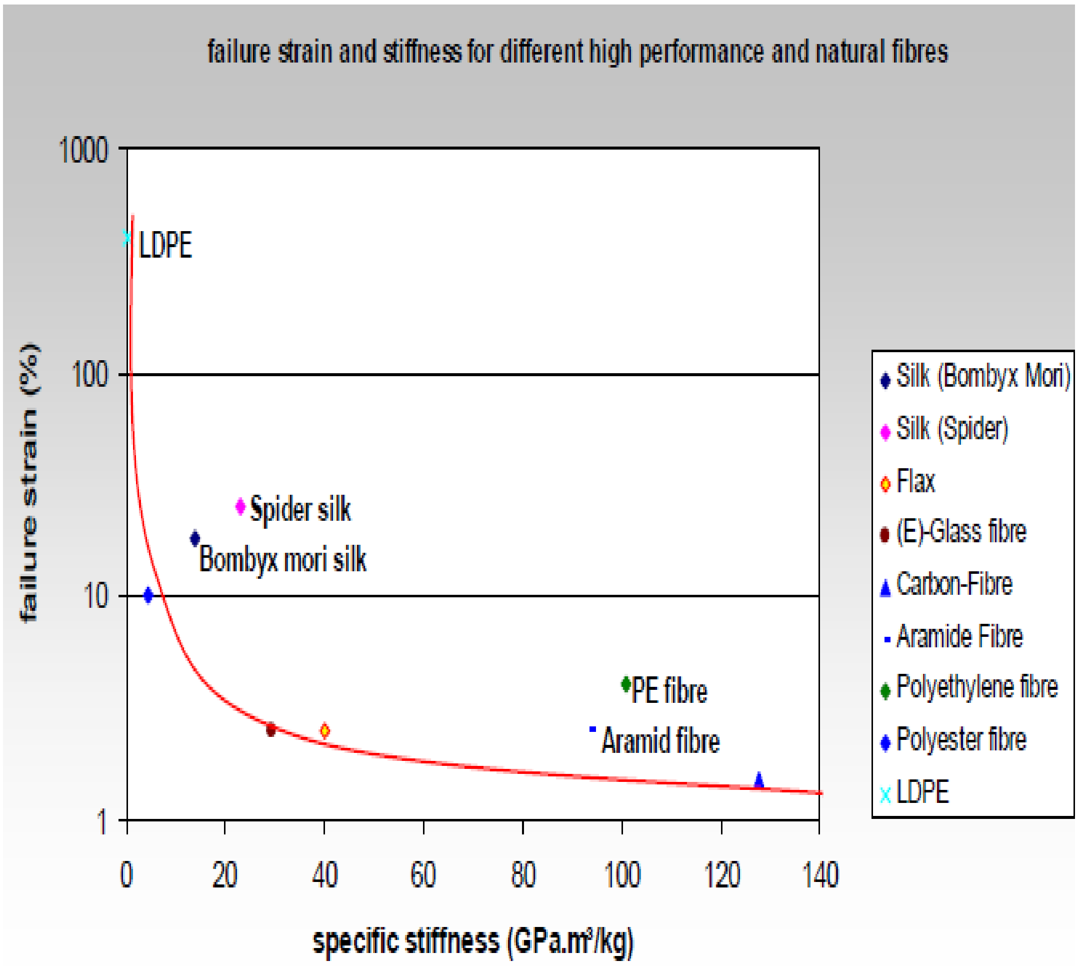
(Seong Ok Han, 2006)

Bombyx silk structure is composed of two main chains of fibroin protein made up of parallel bundles of nano-fibrils. Fibroin is coated with gummy sericin protein. The chemical composition of fibroin consists of amino acids glycine. Alanine and serine are present in the form of beta sheets and high tensile strength of silkworm.

Table 2.2 Properties of Bombyx mori silk natural fiber composites (Ude et al, 2010)

Properties of Bombyx mori plain woven natural fibric	
Elongation	9%
Modulus of elasticity	22 GNm
Thickness	0.42 mm
Ultimate strength	11 GNm

Table 2.3 Failure strain and stiffness for differencing high performance and natural fiber (Ude et al, 2010)



The polymer matrix could be applied for its structural usage in the fabrication of lightweight bodies and other composite structures where energy absorption is a key design factor.

Table 2.4 Ratio of absorbed energy of fiber (i-SUP 2008 Natural fiber composites)

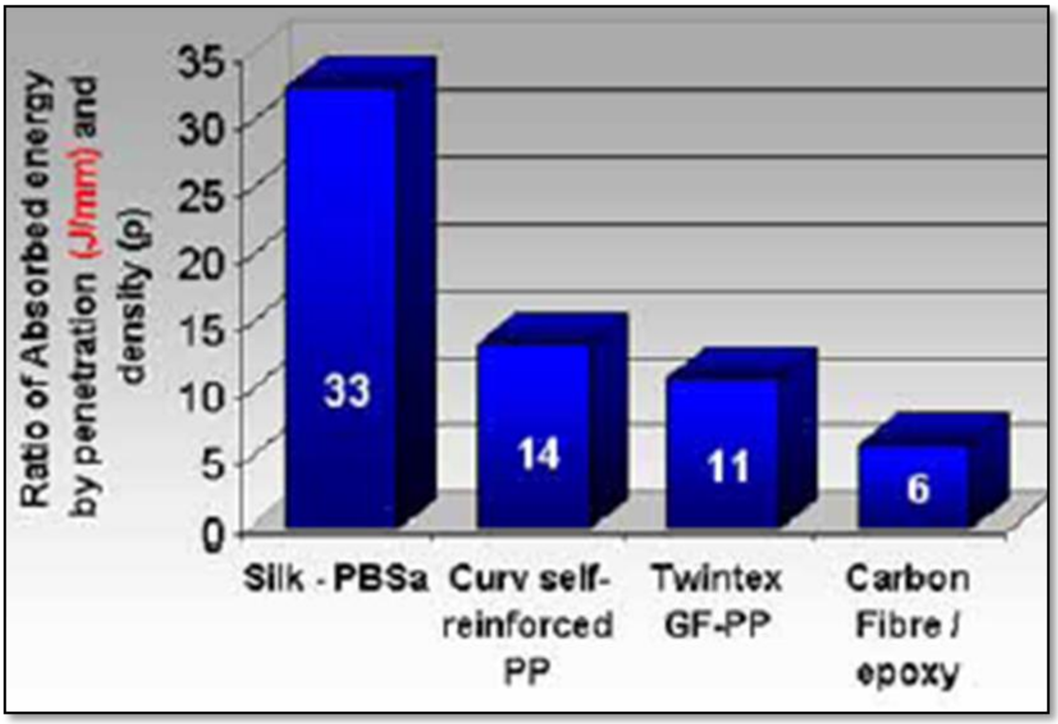
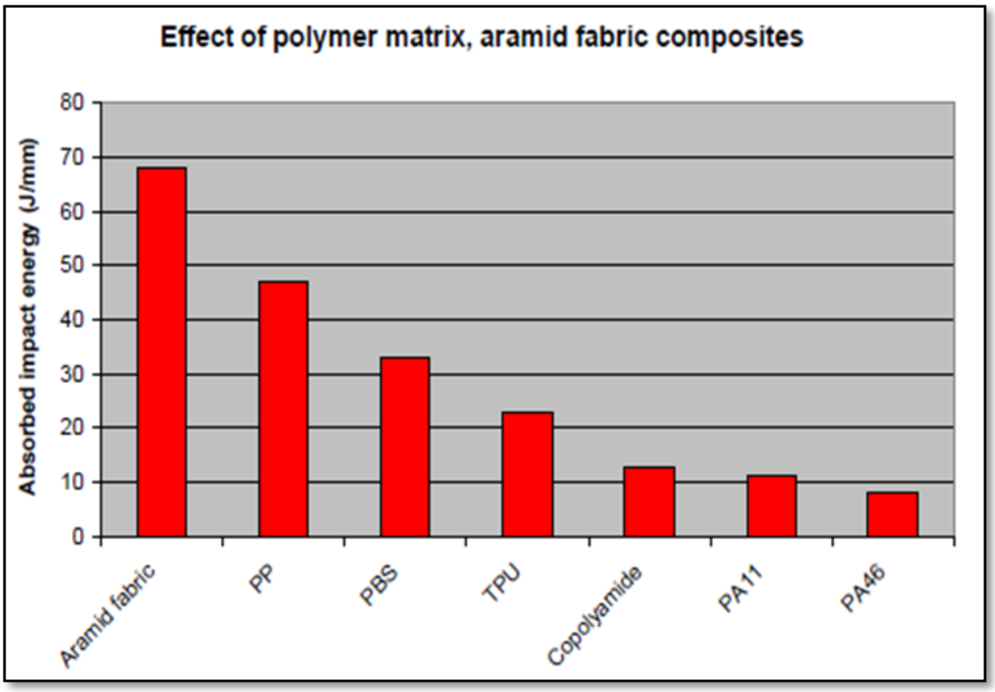


Table 2.5 Effect of polymer matrix on absorbed impact energy (i-SUP 2008 Natural fiber composites)



The cocoon is spun and before the worm hatches through the silk into a moth, the cocoon is soaked in hot water then unraveled, producing filaments that can be up to a mile long in size. The raw silk is then processed to remove the sericin the natural "gum" that protects the fibers and causes them to stick to each other as the cocoon was spun. Silk is a protein fiber, similar to wool or to human hair.

Weight of silk fabric with in 4 categories

1. Light weights are weight per unit area less than 91grams per square meter.
2. Medium weights are weight per unit area from 91 grams per square meter to 121 grams per square meter.
3. Heavy weights are weight per unit area from 121 grams per square meter to 160 grams per square meter.
4. Extra heavy weights are weight per unit area more than 160 grams per square meter.

2.2 Material Choices in Orthotic Design

The ankle foot orthotics of this type are contoured to the entire foot and used to reduce abnormal motion or abnormal position of the ankle-foot. There are used to control abnormal motion or position of the lower limb. The orthotist will take a medical evaluation, biomechanical examination, ranges of motion, and muscle activity for choosing the types of materials; plastic, elastic, metal, and composite materials.

Ankle foot orthotic materials

- **Thermoplastics**

These are materials that soften when heated and harden when cooled. There are several groups of plastics used in the orthotic industry, and they are sold in different strengths, thicknesses and colors.
Polypropylene; A plastic material of low specific gravity and high stiffness. This combination of light weight and high strength makes it ideal for manufacturing rigid foot orthotics although any notch or groove on the finished shell can create a stress point that may eventually crack.

- **Thermosetting**

Composite carbon fibers; combining resin, hardener with carbon fibers creating a rigid sheet material. Carbon fiber and fiber glass are good for thin and functional orthotics. It is strong in a load-bearing direction, but it is weak in directions where there is little load-bearing.

- **Metal**

Metal orthoses is usually a double upright, metal device, with a leather covered band at the calf. The ankle joints may be adjustable to control ankle motion or assist with toe pickup. The joints attach to a metal stirrup that is fastened directly to the shoe, but may be attached to a metal footplate that slides into a shoe. A metal AFO is often used where swelling of the leg and foot is presented or there is a risk of sores on the foot.

2.3 Composite Material

Presently, composite materials, especially fiber-reinforced ones, exhibit their roles in many applications such as the body part of vehicles, and electronic devices. They have strong but light weight properties. (Sapuan S.M et al 2006) Two materials that are popular for fabricating composite materials are fiber glass and carbon fiber. In polyester fiber, however, the fiber glass has a low rating in hardness, cannot resist scratches, has a low shear force, and is degradable in nature and it is a very harmful material. Problems include the irritation of the skin, eyes and respiratory tract. Aramid fiber has compressive strength, tensile strength and poor character in compression. In addition, the price is also very high. Besides, technology is developing environmentally friendly materials, natural fibers that degrade naturally, are not harmful, cost little, and are made from local materials

Composite materials are two or more chemically distinct materials which have been improved in some properties over the individual materials when combined. Composites could be natural or synthetic and ideal for structural applications when strength-to-weight and stiffness-to-weight ratios are required (Carlton Fillauer, 1934). The material positive properties include strength, corrosion resistance, stiffness, being lightweight, having a long fatigue life, temperature-dependent behavior, thermal conductivity, acoustical insulation and thermal insulation.

Composite materials are a group of high performance materials consisting of a matrix reinforced with fiber. The matrix can be thermosetted by epoxy resin, polyester or acrylic resin. Carbon and fiberglass can be reinforcement materials. The composite materials are a combination of a resin and a reinforced fiber, resulting in different properties. The strength of the composites is limited by the properties of the fiber. The fiber reinforcement are many propertied depending on the length of reinforced fiber and the strength of bonding between fiber reinforcement and matrix.

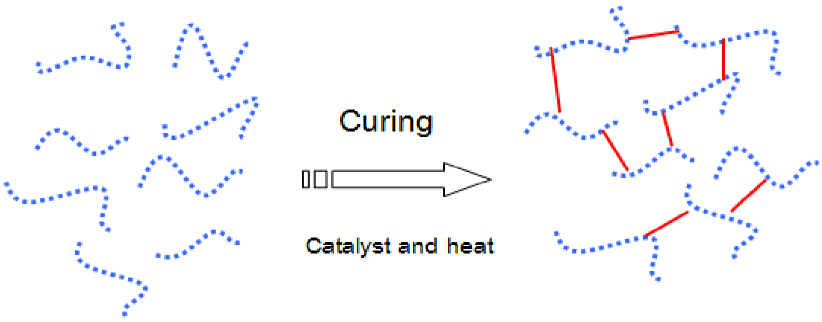
2.3.1 Polymer Matrixes

The matrix is the monolithic material into which the reinforcement is embedded, and is completely continuous. There is a path through the matrix to any point in the material, unlike two materials sandwiched together. In structural applications, the matrix is usually lightweight within high-strength structural composite material walls. The matrixe functions are maintaining the shape of the composite structure, and the alignment of the reinforcement, protecting the reinforcement, distributing load application and preventing the fiber from environmental damage.

Two matrixes are thermosetting polymer and thermoplastic polymer for fiber-reinforced bonding between fiber and matrix.

2.3.1.1 Thermosetting polymer

Thermoset is a material that cures or hardens into a given shape, generally through the application of heat. Curing is an irreversible chemical reaction in which permanent connections are made between the material's molecular chains. These cross-links give the cured polymer a three-dimensional structure as well as a higher degree of rigidity than it possessed prior to curing. Before curing properties, it includes low viscosity, being excellent to flow for impregnation (A). After curing properties (B), it includes rigidity, high strength, solvent resistance, good oxidative stability and good thermal stability **(Figure 2.2)**



(A) (B)

Figure 2.2 Structure of thermosetting polymers

(A) Before curing (B) After Curing

Acrylic Resin

Acrylic resins are a group of thermosetting plastic substances derived from acrylic acid, methacrylic acid or other related compounds. Formulae of Acrylic resin are a general term for any one of the plastics (resin) generated through chemical reaction by applying polymerization initiator and heat to a monomer. The chemical name for the resin produced from the methyl ethacrylate monomer (MMA) is polymethyl methacrylate (PMMA). MMA is a transparent and colorless fluid substance (Peter A et al, 2008). One of the main characteristic features of PMMA is its high transparency **(Figure 2.3)**. With its high weather resistance, it has been known to last over 30 years. It does not easily turn yellow or crumble when it is exposed to sunlight.

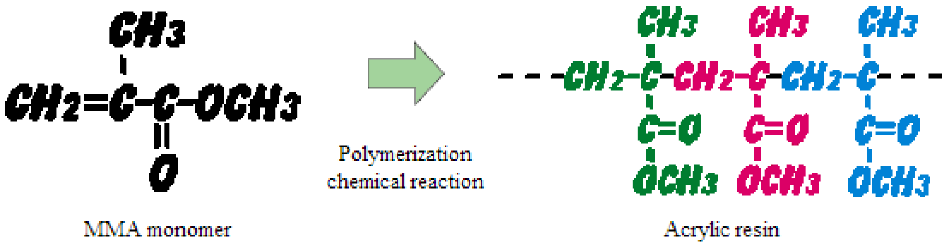


Figure2.3 Formulae of Acrylic resin
(Peter A et al, 2008)

The advantages of acrylic resins are better stain protection (washability), water resistance, good adhesion, good blocking ('strap down'), resistance to cracking and resistance to alkali cleaners.

2.3.1.2 Thermoplastic polymer

A thermoplastic material softens when the material is heated. It begins in pellet form, and then becomes softer and more fluid as heat increases. This fluidity allows it to be injected under pressure from a heated cavity into a cool mold. As it is cool, the thermoplastic will be hardened in the shape of the mold, but there is no chemical curing at work. No cross-links form (**Figure 2.4**).

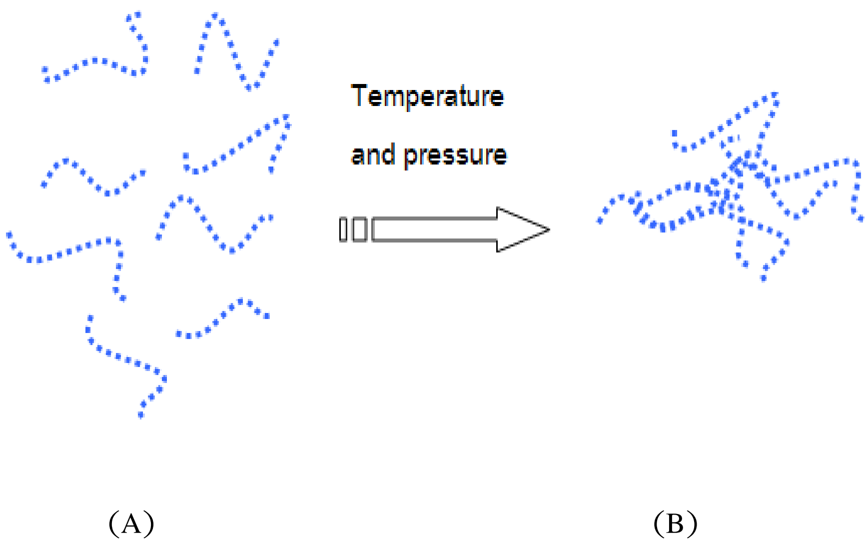


Figure 2.4 Structure of thermoplastic polymers
(A) Before Heat (B) After Heat

2.3.2 Fiber Reinforcement

The typical composite consists of a matrix holding reinforcing materials. The reinforcing material, the most important is the fibers which supply the basic strength of the composite. However, the reinforcing materials can contribute much more than the strength. They can conduct some heat or resist some chemical corrosion. They can resist or conduct electricity. They may be chosen for their stiffness (modulus of elasticity) or for many other properties (Leonard H, 1994).

Fiber reinforcements have polyester fiber and natural fiber. Natural fiber composites have potential material to be developed and are used as alternative substitute materials of conventional materials such as metals and synthetic fiber composites. Natural fibers are materials that can be recycled, have high strength, stiffness, are more environmentally friendly (Sapuan S.M. et al, 2006), potentially abundant, and less costly than synthetic fibers (Justiz-Smith N.G et al, 2008).

The purpose of reinforcement in structures is to increase the strength without greatly increasing weight. These structures are utilized to resist buckling in axial or end loading and transverse loading perpendicular to the plane of the material. **Figure2.5**

The great strength characters of fiber reinforcement are;

- Diameter is small
- Length to diameter ratio is higher
- Flexibility is higher

The advantages of fiber reinforcement are;

- High strength and stiffness
- Low weight ratio
- Material can be designed in addition to the structure
- Can manufacture structures and eliminate joints

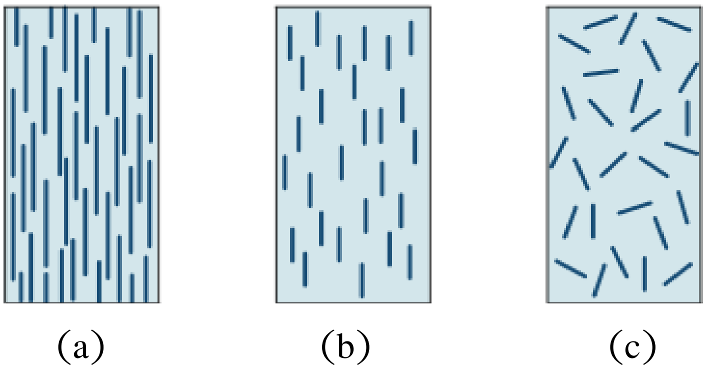


Figure 2.5 Types of fiber-reinforced composite materials; a) Continuous and aligned fiber-reinforced, b) Discontinuous and aligned fiber-reinforced, c) Discontinuous and random-oriented fiber-reinforced. (http://en.wikipedia.org/wiki/Fiber-reinforced)

2.3.2.1 Synthetic Fiber

<u>Carbon fiber</u>

Carbon fibers are commercially available with a variety of tensile modulus values ranging from 207 GPa on the low side to 1,035 GPa on the high side. In general, the carbon fibers have higher tensile, compressive strengths and higher tensile strains-to-failure than the high-modulus fibers. The advantages of carbon fibers are that they have exceptionally high tensile strength, weight ratios as well as tensile modulus, very low weight ratios, high fatigue strengths and high thermal conductivity.

- High tensile strength and pressure resistance (in laminate)
- High modulus of elasticity (Healthcare OB, 2007).

Fiber orientation is defined by angles **(Figure 2.6).** A lay-up may consist of 0^0 fiber to handle basic stresses from bending 90^0 fiber to handle perpendicular, delaminating stresses and 45^o Fiber to handle shear (Klasson BL, 1995). Designs of material angles are forced and different **(Figure 2.7).**

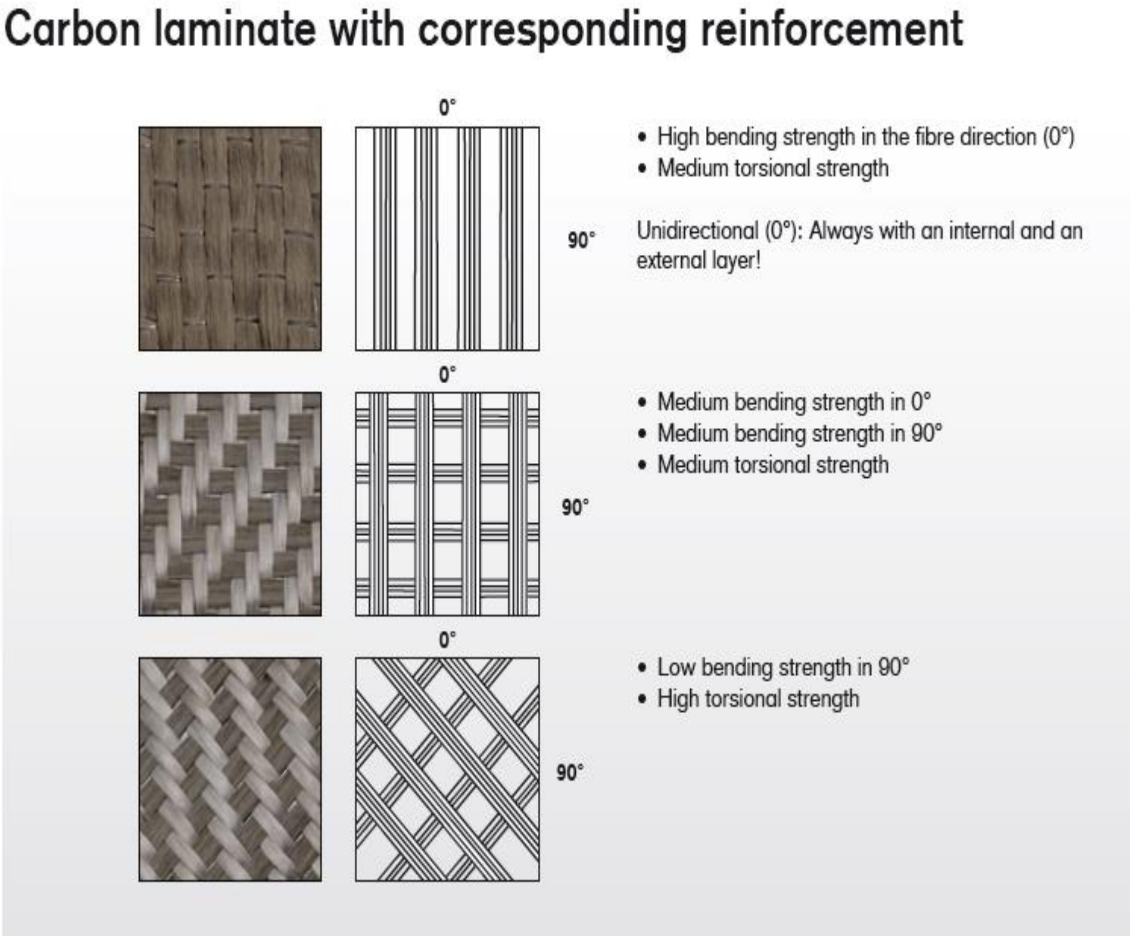


Figure 2.6 Fiber orientation in laminates (Klasson BL, 1995)

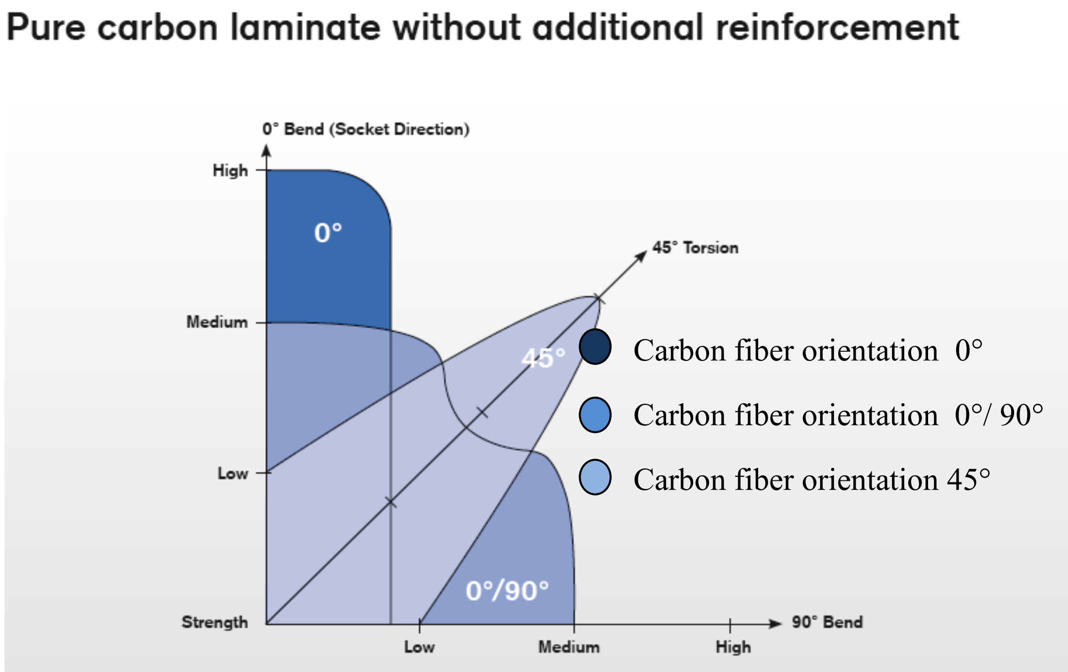


Figure 2.7 Force of carbon fiber orientation (Klasson BL, 1995)

The disadvantages of carbon fiber are low strain-to-failure, low impact resistance, and high electrical conductivity, which may cause ‘‘shorting’’ in unprotected electrical machinery. Their high cost has so far excluded them from widespread commercial applications. Orthotists are used mostly in the aerospace industry, where weight saving is considered more critical than cost.

Carbon Fiber Reinforced Polymers (CFRP) are characterized by the following properties: they are light weight, high strength-to-weight ratio, very high modulus elasticity-to-weight ratio, have good corrosion resistance, very low coefficient of thermal expansion, low impact resistance, high electric conductivity and high cost.

Glass fiber

Glass fiber properties vary somewhat according to the type of glass used. However, glass in general is well known as having several properties that contribute to its great usefulness as a reinforcing agent: glass fiber (glass fiber reinforced polymer matrix composites) is characterized by the following properties: it has high strength-to-weight ratio, high modulus of elasticity-to-weight ratio, good corrosion resistance, good insulating properties, low thermal resistance (as compared to metals and ceramics). Glass fiber materials are used for manufacturing boat hulls, marine structures, truck body panels, pressure vessels, aircraft wings, housings for radar systems, swimming pools and welding helmets.

2.3.2.2 Natural fiber

Bombyx mori woven natural silk (WNS) as a reinforcement is considered for its environmental and mechanical properties. It is among the strongest fibers produced in nature, with high specific-strength and high specific-stiffness (Bledzki A.,1999). Bombyx mori silk is better than Kevlar or steel in terms of elongation at failure. It has a good capacity to absorb energy and to dissipate this energy in a very controlled manner as the silk deforms (Perez-Rigueiro J et al, 2000).

2.4 Rehabilitation of Stroke Patients

2.4.1 Ankle foot orthoses

Ankle foot orthoses is a device worn on the lower leg and foot to support the ankle. They hold the foot and ankle to correct the deformed foot part and correct the foot drop. Ankle foot orthoses increase control and reduce pressure on the skin and increase weight bearing through the affected side during standing and walking. Ankle foot orthoses are resistance to plantar flexion and improve the ankle angle at initial contact and swing phase. Ankle foot orthoses designs are weight of the orthoses reduction, better on durability/weight ratio, easier to clean, cosmetic and can easily be change to different shoes.

Ankle foot orthoses (AFOs) are prescribed for stroke patients walking with a hemiplegic gait, and who have weakness, absence of plantarflexor and dorsiflexion and spasticity. **Table 2.6** (Richard Lehneis) While the patient is walking with the ankle foot orthoses, there are some biomechanical actions to prevent foot slap at heel strike, assist toe clearance in the swing phase, push-off in the stance phase, a control of inversion and eversion and provide extension moment at the knee to assist stability. These indications are applicable to patients with motor weakness of ankle dorsiflexors and plantarflexors, moderate medial-lateral instability and motor weakness of the knee extensor.

An orthoses which can assist in knee extension improves stance stability during a decrease of muscle tone (Pease WS et al, 1996). Ankle foot orthoses improve gait mechanics and efficiency by prevention of the active plantar flexion in swinging and stance phases (Garrison SJ et al, 2003). There is also less need for hip and knee flexion and pelvic elevation to gain foot clearance.

Table 2.6 Various ankle foot orthoses (AFOs) (Richard Leheis, orthoses Indications)

Device	Pathomechanical Condition	Degree of spasticity	Biomechanical Action
Posterior Leaf-spring AFO	Weakness of dorsiflexion	None to mild	- Prevents foot slap at heel strike. - Assists toe clearance in swing phase.
Spiral AFO	Weakness of dorsiflexion and plantarflexion	Mild to moderate	- Prevents foot slap at heel strike. - Assists toe clearance in swing phase and push-off in stance phase with control of inversion and eversion. - Provides extension moment at knee to assist stability.
Hemi spiral AFO	Equinovarus with rotation of foot	Moderate	- Prevents foot slap at heel strike. - Assists toe clearance in swing phase with control of inversion.
Posterior Solid AFO		Severe	- Immobilizes ankle in swing and stance phase.

The spiral ankle foot orthoses, (**Figure2.8**) provides spring resistance for dorsiflexion and plantar flexion. It is a shoe-insert orthoses for specific control of tibial rotation and subtalar joint motion and is useful for the patient. A totally flaccid foot can be free from dorsiflexion and plantarflexion in the neutral position. These spiral ankle foot orthoses have properties including the following items; being lightweight, having a strong structure under tension, strength under compression, flexibility to absorb torque, firmness to resist bending, shearing stress durability to resist fracture under impact, capability for resistance stress in all planes, low cost, and ease to apply a resin lamination with a composite material reinforcement by carbon fiber material (Rubin G; Dale A et al 1987).

Figure 2.8 Spiral ankle foot orthoses (Spiral AFOs)

(spiral ankle foot orthoses, http://www.cc-mfg.com/index.html)

The ankle foot orthoses have force through the anterior and the posterior in the aspects of the device which should fluctuate from being compressive (C) to be tensile (T) during the walking gait cycle due to rotation movement caused from ground reaction forces (Dale A et al 1987). **Figure2.9** shows the force acting on each step in the gait cycle. The heel strike phase compression force acts on the posterior of the ankle joint and the tensile force acts on the anterior of the ankle joint. The mid stances phase compression force acts on the posterior and anterior ankle joint. Toe off phase compression force acts on the anterior ankle joint and tensile force acts on the posterior ankle joint. Other forces on the ankle foot orthoses include the following: the stress of torque, impact, shear and design with direction of material reinforcement for absorption on the ankle foot orthoses.

In 10 years ago, the most notable reinforcing material for orthopedic use was carbon fiber (Evans, S. L. et al, 1998). Especially for lower limb prosthesis carbon composite lay-ups were very popular (Strike, S. et al, 2000). These composites were chosen because of their flexibility, energy storage and release properties (Strike, S. et al, 2000). The fibers can be fabricated in different ways such as being braided, knitted, woven, or laminated.

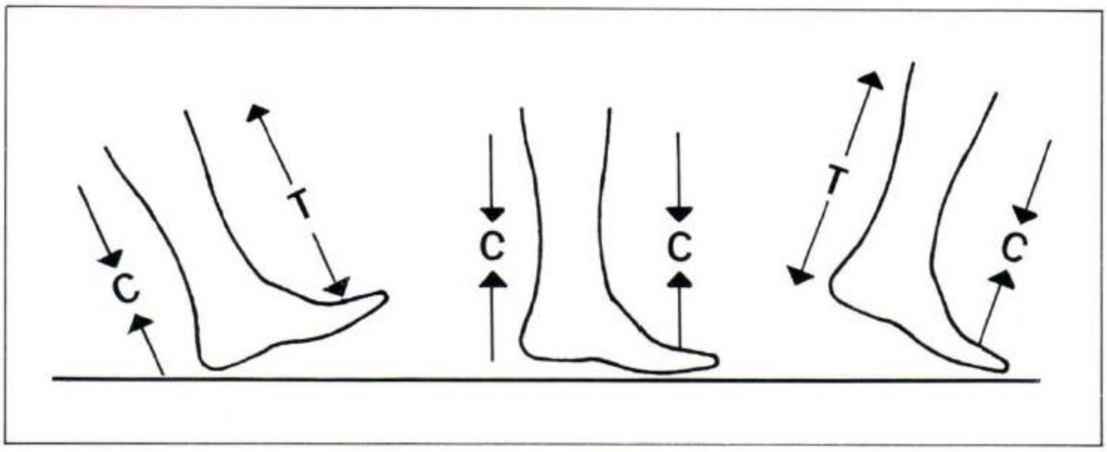


Figure 2.9 Force actions during gait cycle at heel stride, mid stances and toe off (Dale A et al 1987)

Fabrication of ankle-foot orthoses which use composite materials should concentrate on durability and lightness for return of energy. The composite materials should absorb the energy that is developed as there could be some deformities in dorsiflexion. It should be stored until the limb starts to unload in terminal stance to initial contact. The return of energy comes at push-off when the ankle-foot orthoses are completely unloaded at the swing phase. The materials that have good energy return properties are carbon fiber composites material laminated with epoxy resin (Eamer L et al 2008). Fiber reinforced plastics are laminated composites made by applying resin to one or more layer of fibers. The material properties of the resin and the fiber, the extent of bonding between the two and the "resulting structural architecture" determines the strength of the laminate (Phillips, S. L. et al, 2005).

2.4.2 Stroke Patients

Common diseases of a stroke are the result of the impairment of the nervous system, muscle weakness, loss of balance, spasticity and mobility impairment. The common problem from neuromuscular impairment is the patient's inability to swing the foot at the ankle joint. The foot is dropped while the patient is walking **(Figure2.10)**. Dropped foot is further characterized by an inability to dorsiflex the foot at the ankle joint. Therefore, the normal gait cycle is affected by the dropped foot syndrome (Wikipedia, 2012).

Stroke patients exhibit various deficits in perception, muscle strength, motor control, passive mobility, sensation, tone and balance (Yavuzer G et al, 2001) However, the patients with functional ambulation, who display very different gait patterns, compared with able-bodied persons, have an increase in the risk of falling. Marked variations in gait patterns across stroke patients have also been noted (Kramers de Quervain et al , 1996). Peripatetic gait is characterized by slow and asymmetric steps with poor selective motor control, delayed and disrupted equilibrium reactions, and reduced weight bearing on the paretic limb (Roth EJ 2000; Adams JM1984). Both smooth and symmetric forward body progression are impaired with large variations in gait patterns related to the degree of recovery (Sawner K et al, 1992). Well-controlled intra-limb and inter-limb coordination is replaced by mass limb movement patterns (synergies) on the paretic side which require compensatory adjustments of the pelvis and non-paretic side. The paretic limb has compensatory movement for ambulation to produce abnormal displacement of the gravity center resulting in an increase of energy expenditure (Esquenazi A et al, 1995).

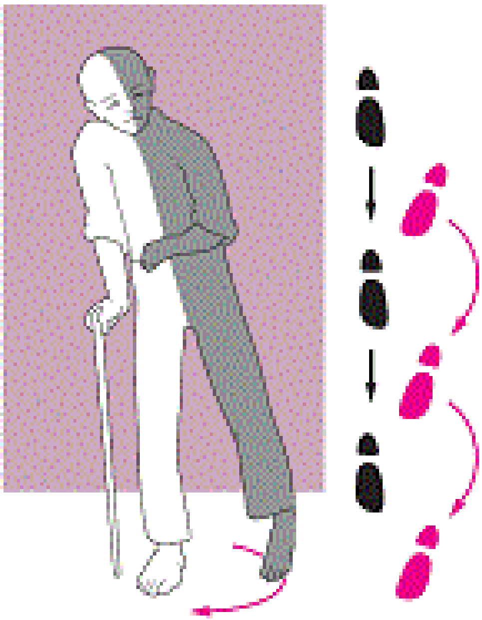


Figure 2.10 Foot drop and circumduction of stroke patient
(http://taibienmachmaunao.com, 2012)

The goal of stroke rehabilitation programs is to regain ability, to restore function and return to a productive and satisfying life. Rehabilitation can achieve these goals by either restoring the functions in the body, compensating for some body dysfunction, or a combination of both (Platz T, 2004). Walking ability is the most important function, because it is essential for community reintegration and social participation. Thus, gait training accounts for a large time proportion of what is spent for stroke rehabilitation. Some activity limitations may be due to the impairments of the different functions in the body, so that specific training about restoration of impaired body functions will have the highest chance to improve activity levels. If body functions cannot be regained, then various orthoses are prescribed for substitution and compensation for the loss of body functions (Matjacic Z et al, 2005).

The stroke patients uses rehabilitation program with ankle foot orthoses for stroke patients' walking to assist during stranded phase, promote weight durability, lateral weight shift, and improve the gravity center. The knee extension improved stability during period of decreased muscle tone when swing phase hip, improved knee flexion and pelvic elevation to gain toe clearance, increase walking speed, reduce energy expenditure and prevent contractures (Joan Leung et al, 2003; Rubin G et al).

CHAPTER 3

RESEARCH METHOLOGY

This study demonstrated that definitive laminated composite martial of silk fiber, carbon fiber and glass fiber with resin. This study is a research to seek for the optional choice for spiral ankle foot orthoses. Lamination resin techniques in spiral ankle foot orthoses are made by mixing two components (a resin and a hardener).The objectives of this study were to evaluate the morphology and mechanical properties; tensile strength, flexural strength, fatigue and hardness. The properties of the ankle foot orthoses materials were used as a guideline for othoses fabrication. Ankle foot orthoses were produced into fiber polymer composite by lamination technique. The orthoses study are compression on vertical and lateral force and test the complacency of a spiral ankle foot orthoses by some questionnaires.

3.1 Materials

I. Acrylic Resin

Name of product	: 617H55 C- Orthocryl Lamination Resin
Use of the substance/ preparation	: Lamination Resin for orthopedic procedures
Chemical characterization	: Solution of acrylic polymers in ethylmethacrylate, containing softener
Physical state	: Liquid
Color	: Colorless
Company name	: OttoBock HealthCare Deutschland GmbH&Co.KG

II. Hardening Powder

Name of product	: 617P37 hardening powder
Use of the substance/ preparation	: Curing agent
Chemical characterization	: Dibenzoyl peroxide with Dicyclohexyl phthalate
Physical state	: Powder, free flowing
Color	: White
Company name	: OttoBock HealthCare Deutschland GmbH&Co.KG

III. Perlon stockinet

Name of product	: 623T3 Perlon stockinet, white
Use of the substance/ preparation	: For lamination resin reinforcements
Color	: White
Company name	: OttoBock HealthCare Deutschland GmbH&Co.KG

IV. Silk fiber (Figure3.1 (a))

Silk fibers from the Bombyx silk worm have a triangular cross section with rounded corners. After Mulberry worms had fed for 45-55 days, they provided the fibers. The handicraft will keep together all the fibers and start to weave for the silk fiber. That means we can get silk cloth from Mulberry worms in the raw and pure condition **(Figure3.1 (a))**. The silk fiber property is 5-10 µm wide. Silk fabrics in medium weights are weight per unit area from 91 grams per square meter to 120 grams per square meter. Bombyx silk fibers have a linear density of 1.17(dtex) and a diameter of 12.9(µm)

Use of the substance/preparation	: carbon fibers for lamination resin reinforcements
Physical state	: solid
Color	: white up to yellowish up to light-gray
Procured from	: Queen Thai Silk Center of Narathiwat, Thailand.

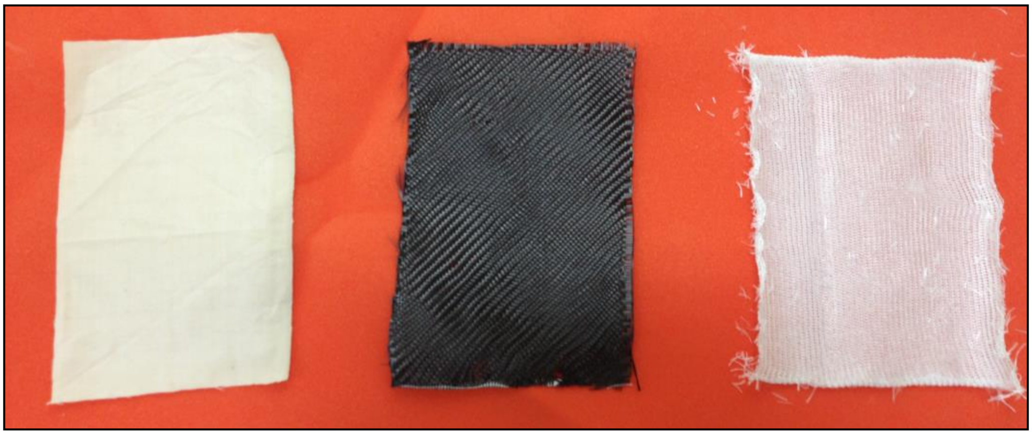
V. Carbon fiber (Figure3.1 (b))

Name of produc	: 616G12 Carbon Fiber Cloth
Melting point / melting range approx.	: 3500 ^{o}C
Ignition temperature	: 350 ^{o}C
Density: at 20 ^{o}C	: 1, 7-2 g/cm^{3}
Solubility in water: at 20 ^{o}C	: carbon fibers: insoluble
Thermal decomposition: Carbon fibers	: > 650 ^{o}C
Coating agent	: > 290 ^{o}C
Chemical characterization	: carbon fibers >95%
Use of the substance/preparation	: carbon fibers for lamination resin reinforcements
Physical state	: solid
Color	: black
Company name	: OttoBock HealthCare Deutschland GmbH&Co.KG

VI. Glass fibers (Figure3.1 (c))

Name of product	: G001 - Glass fibers textile material
Density	: Approx. 2, 6 g/cm^{3}
Water solubility	: Glass fibers: insoluble
Thermal decomposition	: Coating agent: > 200 ^{o}C
Chemical characterization	: Glass fibers-textile material >95% (Diameter fibers > 3 μm)
Use of the substance/ preparation	: Glass fibers for lamination resin reinforcements
Physical state	: solid
Color	: white up to yellowish up to light-gray
Company name	: OttoBock HealthCare Deutschland GmbH&Co.KG

Three fiber materials tested



(a) (b) (c)

Figure 3.1 Three fiber reinforcements (a) Silk Fiber, (b) Carbon Fiber and (c) Glass Fibers

3.2 Sample Preparation

Ankle foot orthoses are manufactured from the lamination technique with matrix and reinforcment. These are composite materials of resins with carbon fiber or glass fiber reinforcement. Carbon fiber and glass fiber are popular: they were fabricated from lamination technique (F.P. Gerstle et al, 2012). Composite materials are a family of high performance materials consisting of a matrix and fiber reinforced. The matrixes are thermosetting resin such as an epoxy, polyester and acrylic resin. The fiber reinforcement are aramid fiber, glass fiber and carbon fiber. The combination of a resin and a fiber results in properties of a quite different character than either constituent. These unusual properties are a result of the fiber being characterized by single crystal properties

From a plaster mold, laminations were performed under vacuum, within an inner and outer polyvinyl alcohol (PVA) bag at approximately 30 mmHg at room temperature. The laminations were done on one positive mold, rectangular cuboid in shape, with each face approximately 5 X 5 X 9 inches. (Sam L. et al 2005)

The resin and the hardener were mixed in the ratio 100: 1.5 parts by weight, respectively. The composites were prepared by layup lamination method (Rai Sppask et al, 2006). Advantages of lamination resin are that it is strong, easy on the patient's skin, and can be designed according to the areas that need the strength. Additionally, it is lightweight (Healthcare OB, 2007).

The lamination lay-up technique and composite materials should be within the final trim lines. The inner bag is positioned on the positive cast:

Layup 1 The inner bag has 3 layers of Perlon stockinet.

Layup 2 The inner bag has 1 layer of testing fiber. (Carbon fiber, Silk fiber, Glass fiber) **(Figure 3.1).**

Layup 3The inner bag has 3 layers of Perlon stockinet (Beffort O et al, 2000). The layup was ready for lamination. The resin was measured and mixed, the vacuum was turned on and the resin poured between the two PVA bags **(Figure 3.2)**. All samples in this part were tested and are characterized in sections 3.3 to 3.4.

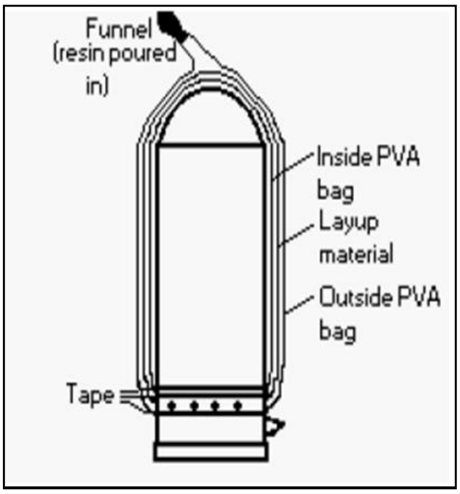


Figure 3.2 Process of lamination

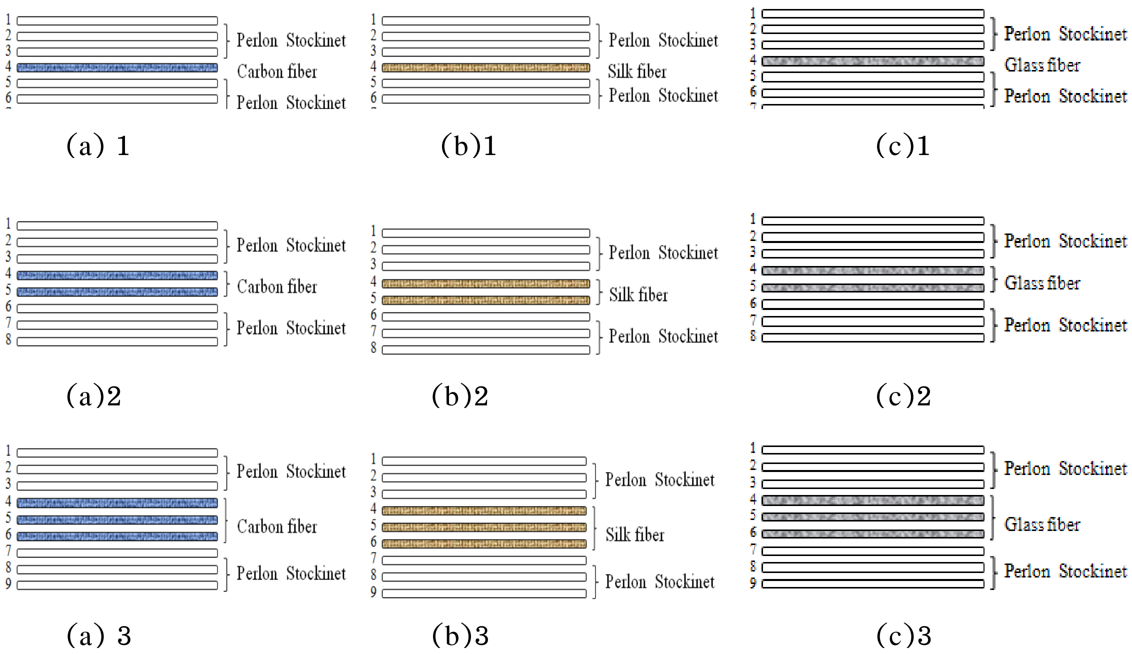


Figure 3.3 The layup material of lamination, Fiber composite (a)1 Carbon fiber 1 layer, (b)1 Silk fiber 1 layer, (c)1 Glass fiber1 layer. (a)2 Carbon fiber 2 layer, (b)2 Silk fiber 2 layer, (c)2 Glass fiber 2 layer. (a)3 Carbon fiber 3 layer, (b)3 Silk fiber 3 layer, (c)3 Glass fiber 3 layer.

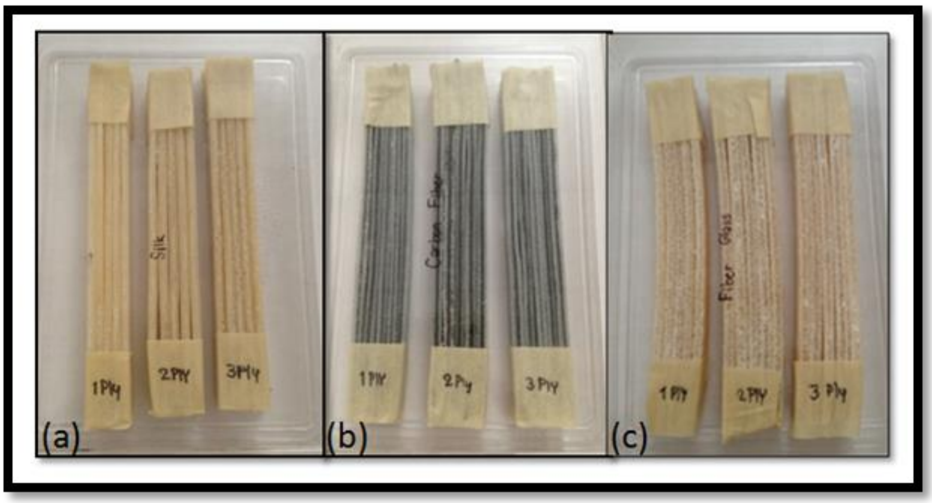


Figure 3.4 Fiber composite (AFOs); (a) Silk fiber (b) Carbon fiber and (c) Glass fiber

Fabrication of Laminate Composites

Sample preparation

1st **Testing material properties**

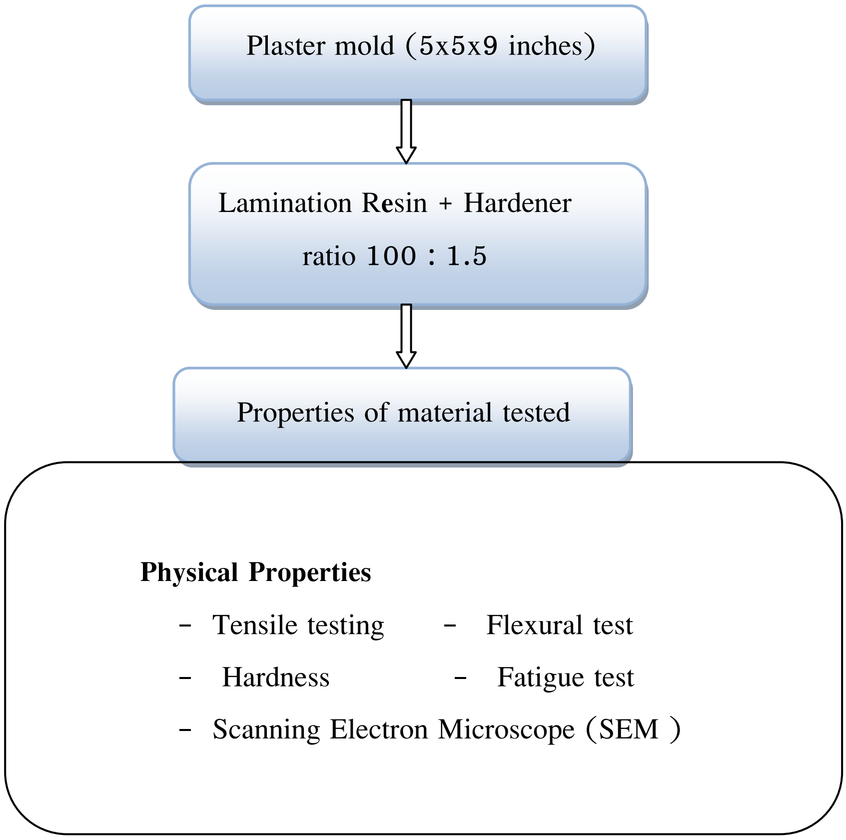
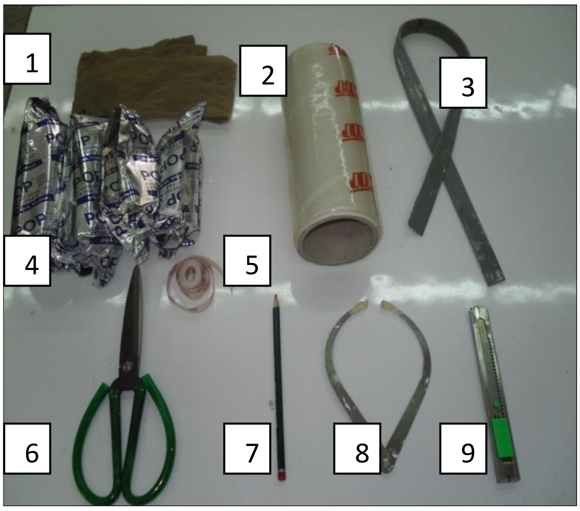


Figure 3.5 Flow chat of samples preparations and testing

3.3 Fabrication of spiral ankle foot orthoses

A medical doctor has to prescribe orthoses for a patient. This device cannot be bought in stores and is not mass produced. Following the prescription, the patient must consult with the orthotist in order to choose the best orthoses for his use. Some parts of the orthoses are manufactured in factories and can be custom made for each patient. The procedure starts with studying the affected leg. The orthotist makes an assessment and measures segments of the patient′s leg. The impression and the measurements are used to make a plaster cast of the affected leg.

Fabrication a Spiral Ankle Foot Orthoses



1 Stockinet	2 Plastic wrap
3 Rubber tube	4 Plaster of Paris bandage
5 Tape measure	6 Scissors
7 Indelible pencil	8 M-L, A-P (Caliper)
9. Cutter	

Casting Procedures

- For casting, foot-casting boards which correspond to the heel heights of the shoe to be worn are required.

- Indelible pencil are marked on the head of the fibula, the medial malleolus, the lateral malleolus, the base of the fifth metatarsal and any bony prominences on the foot.

- The lower limb is wrapped with plaster bandages on the foot.
- The foot is placed on the appropriate foot board and manipulated in such a way as to provide the proper toe-out, eversion-inversion control and forefoot alignment in a neutral position.
- The foot is held in this position until the plaster hardens. At the same time the shank should be aligned so that a vertical line connects the medial condyle of the knee with the medial malleolus.

Modification of the Positive Model

- Remove the negative model from positive plaster model before modification technique.

- The positive plaster model should add plaster at any bony prominences such as the head of the fibula, medial malleolus, lateral malleolus and base of the fifth metatarsal.

The positive plaster model should be prepared for lamination

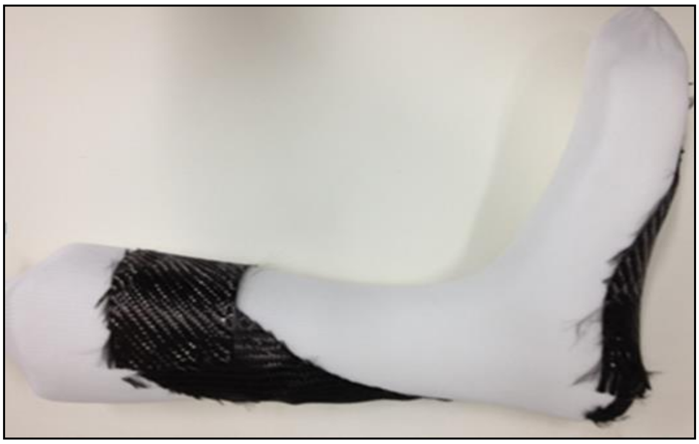
Lateral view

Posterior view

Lamination of spiral ankle foot orthoses

- A PVA bag is pulled over the positive plaster model to prevent resin from contacting the model

- A perlon stockinet is pulled tightly over the model on 3 layer.



- 2 layers reinforced are applied with adhesive tape on the foot part. (carbon-fiber cloth or silk-fiber cloth)

- A 3 layer perlon stockinet is pulled tightly over the model.

- A PVA bag is placed on the positive plaster model to prevent resin being in contact with the model. Vacuum is applied to the model to make sure that the PVA bag is tight.

- C-Orthocry lamination resin100 g. : hardening powder 1. g.

- The layup was ready for lamination. The resin was measured and mixed, the vacuum was turned on and the resin poured between the two PVA bags.

- A small amount of color is added to the C-Orthocry lamination resin mixture with 10% of hardener.

- The lamination resin was evenly and slowly distributed on the model and it is ascertained that the material is properly.

- Before removing the orthoses from the model, the brim course of the orthoses is marked and cut following the trim line.

- Orthoses is removed from the model and a trial fitting done.

- The orthotist fits the orthoses on the patient.

Statistical Analysis

Statistical analysis with unpaired t-test using Prism 5.0 for Windows (GraphPad Software, San Diego, USA) was performed to evaluate the percentage of carbon fiber, glass fiber and silk fiber differences, and the percentage of hardness and tensile strength . The statistical significance was $p \leq 0.05$.

3.4 Physical Properties Test

Physical properties were mean of weight ratio, thickness ratio and wide ratio of the three groups of fibers were calculated. The weights ratio were measured by the “Precision Balance Scale” with the repeatability of the thickness and width. Vernier calipers was measured of thickness and widths. The specimens of five samples were tested for measured three points of the thickness and width **(Figure 3.6)**.

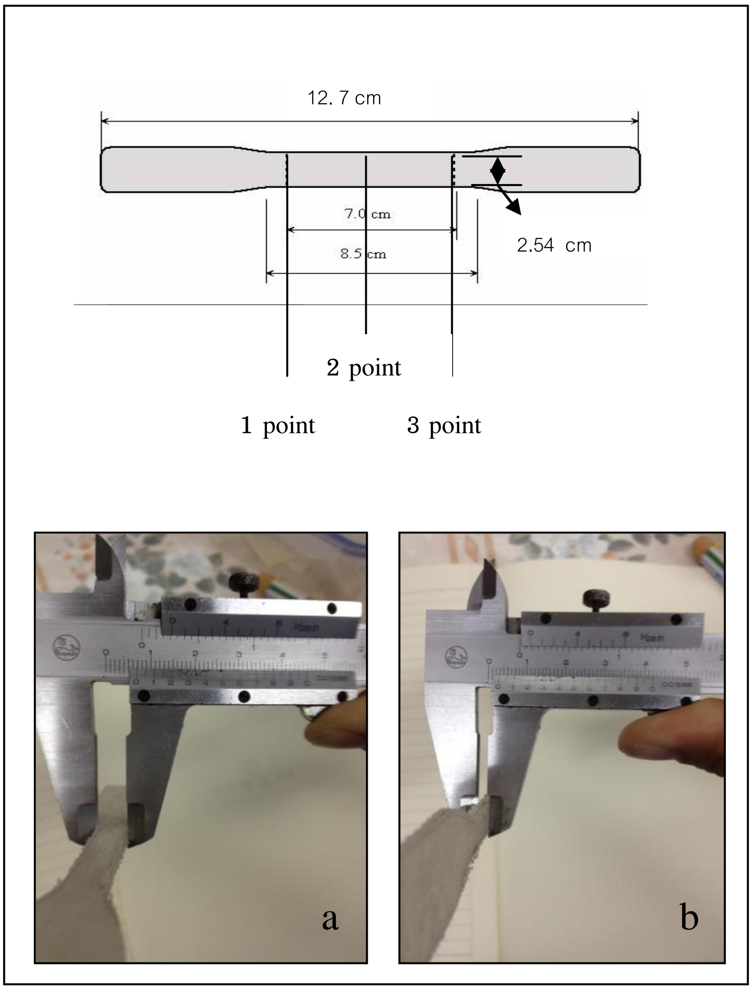


Figure 3.6 The condition of standard shape of sample for measuring (a) the width and (b) the thickness

3.5 Mechanical Properties

3.5.1 Tensile Test

Tensile properties were tested according to the INSTRON 5569 standard by using the universal testing machine. The specimen was tested per American Society for Testing and Material (ASTM) 3039. Standard ttest method for tensile properties of polymer matrix composite material. The specimens of five samples were tested for tensile testing. The average values were reported including standard deviations. Tensile strength of the sample was measured by the mechanical testing machine using a cross-head speed of 50 mm/min and 250 mm extensometer. The dimensions and tolerances of the dumbell-shaped specimens for tensile testing were a considerably larger gauge length (127 vs. 7.62 mm) and width (25.4 vs3.18 mm) shown in **Figure 3.7.**

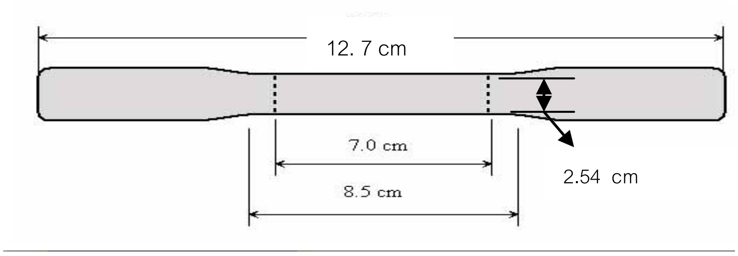


Figure 3.7 The condition of Standard shape of sample for measuring the tensile strength and elongation.

Tensile test is a mechanical test in which a machine is used to deform a specimen under gradually increasing tension load. Tension test can be used to plot a stress-strain curve and several mechanical properties can be obtained from this curve. Some of the most important mechanical properties that can be obtained from the stress-strain curve include yield strength, modulus of elasticity (Young's modulus) and ultimate tensile strength.

Tensile specimens consider the typical tensile specimen shown in Figure 3.8. It has enlarged ends or shoulders for gripping. The important part of the specimen is the gage section. The cross-sectional area of the gage section is reduced relative to that of the remainder of the specimen so that deformation and failure will be localized in this region. The gage length is the region over which measurements are made and is centered within the reduced section. The distances between the ends of the gage section and the shoulders should be great enough so that the larger ends do not constrain deformation within the gage section, and the gage length should be great relative to its diameter.

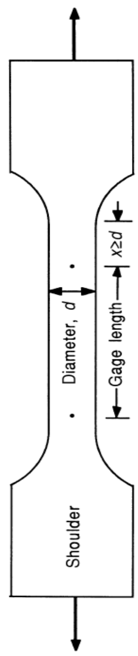


Figure 3.8 Typical tensile specimens, showing a reduced gage section and enlarged shoulders (Tensile Testing, Second Edition)

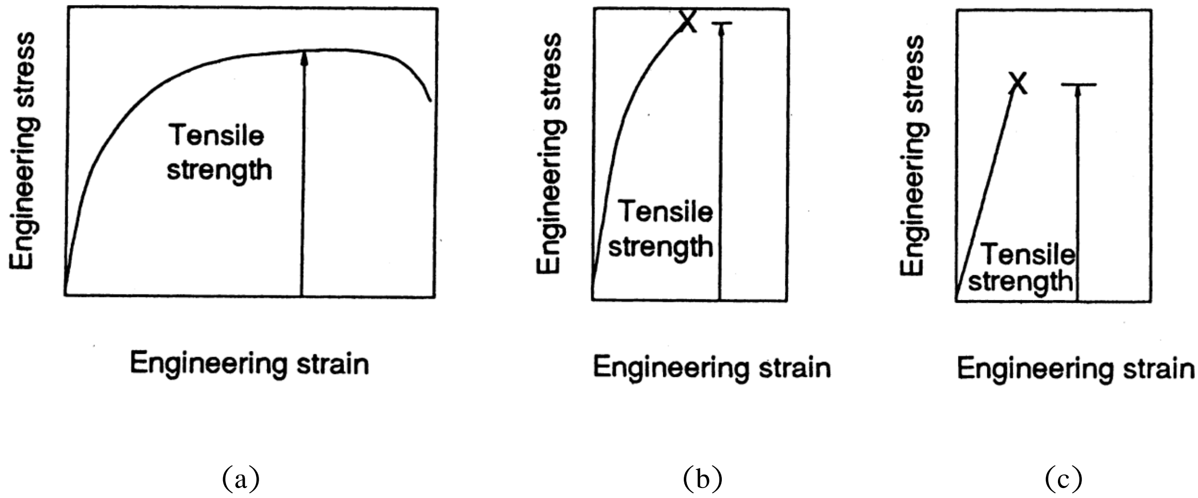


Figure 3.9 Stress-strain curves showing that the tensile strength is the maximum engineering stress regardless of whether the specimen necks (a) fractures before necking (b and c). (Tensile Testing, Second Edition)

The tensile strength (ultimate strength) is highest value of engineering stress (Fig. 3.9). Up to the maximum load, the deformation should be uniform along the gage section. With ductile materials, the tensile strength corresponds to the point at which the deformation starts to localize, forming a neck (Fig. 3.9a).Less ductile materials fracture before they neck(Fig. 3.9b). In this case, the fracture strength is the tensile strength. Indeed, very brittle materials(e.g., glass at room temperature) do not yield before fracture (Fig. 3.9c). Such materials have tensile strengths but not yield strengths.

Physical properties of individual layers in the lamination lay-up are important because they help determine the physical properties of the entire lamination. Important material properties are:

1. Stress is the amount of force applied over a given area.

$$stress \quad \sigma = \frac{load\ W}{area\ A}$$

2. Strain is the amount of deformation for a given length

$$strain \quad \varepsilon = \frac{increase\ in\ length\ \ x}{original\ length\ \ L}$$

3. Young's modulus or Stress/Strain is a measure of an elastic material the stiffness of and is a quantity used to characterize materials.

$$Y'oungs\ Modulus \quad E = \frac{Stress}{Strain} = \frac{W}{x} x \frac{L}{A}$$

or

$$Young's\ Modulus \quad E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

The tensile strength of the composites was measured with a universal testing machine in accordance with the ASTM D3039 procedure. Based on tensile testing, the results will be obtained for tensile strength and Young's Modulus of the ankle foot orthoses material (ASTM, 2002).

In this study, we use the Instron 5569 machine from department of polymer science and technology, faculty of science at prince of songkla university (**Figure 3.10**).

Figure 3.10 The Instron 5569 machine

3.5.2 Hardness Test

The hardness test measures the resistance of a material to an indenter or cutting tool. The indenter is usually a ball, pyramid or cone which is made of a material. It is harder than that being tested. A load is applied by slowly pressing the indenter at right angles to the surface being tested for a given period of time. An empirical hardness number may be calculated from knowledge of the load and the cross-sectional area or depth of the impression. Tests are never taken near the edge of a sample or any closer to an existing impression than the diameter of that impression for three times. The thickness of the specimen should be the depth of the impression at least ten and one-half times. The specimens of five samples were tested for hardness testing.

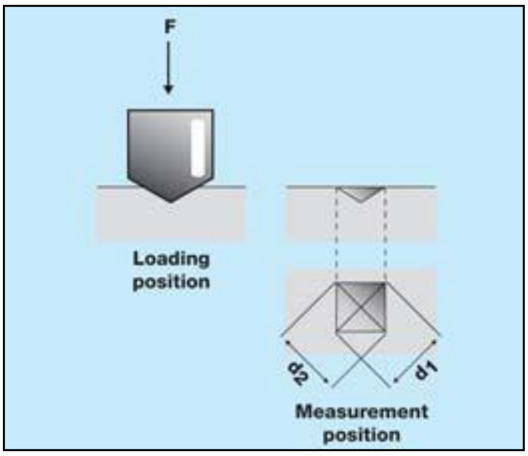


Figure3.11 Hardness testing (Vickers hardness HV)

Measured quantity

Vickers hardness HV. Lengths of both diagonals of residual test indentation measured.

Definition

$$HV = 0.102\ F/A$$
$$= 0.1891\ F/d^2$$

F = test load in N, A= indentation surface in mm2

d = arithmetic average value of diagonal lengths in mm

Hardness of the three separate specimens is reinforced. At this point, the residual penetration which is the hardness is measured. The three studied samples, which were carbon fiber, glass fiber and silk fiber composites, were tested for their hardness. Composite materials are determined by using Shore D hardness scales of Zwick Hardness Testing Machine. The hardness test was done with using a Zwick machine on minor load being 10 kgs and the major load 100 kgs. The specimen size which is used here was in the accordance with the ASTM D2583 procedure.

In this study, we use the Shore D hardness scales of Zwick Hardness Testing Machine from Department of Polymer Science and Technology, Faculty of Science at Prince of Songkla University **(Figure 3.12).**

Figure 3.12 The Shore D hardness scales of Zwick Hardness Testing Machine

3.5.3 Flexural Tests

The bending properties of composite materials are often characterized with simply supported beams under concentrated loads. The results from such tests are commonly based on homogeneous beam equations. For laminated materials, however, these formulas must be modified to account for the stacking sequence of the individual plies. The horizontal shear test with a short-beam specimen in three-point bending appears suitably as a general method of the evaluation for the shear properties in fiber-reinforced composites because of its simplicity. In the experimental part of this work, the shear strength of unidirectional-glass-fiber which was reinforced acrylic resin composites was determined in different fiber directions with the short-beam three-point-bending test (E. Sideridis et al).

Flexural testing is based on the bending of symmetrically loaded and supported beam and the monitoring of its centre point deflection as a function of load. Typical arrangements for point bending 3 and 4 shown in F**igure 3.13**

(a) **(b)**

Figure 3.13 Flexural Tests (a) Three point (b) four point bending

$$\text{Flexural strength} = \frac{3FL}{2Wh^2}$$

$$\text{Flexural modulus} = \frac{L^3F}{4Wh^3}$$

F = The axial load (force) at the fracture point

L = The length of the support (outer) span

W = Width

h = hickness

In this study, we use the Instron 5569 machine from Department of Polymer Science and Technology, Faculty of Science at Prince of Songkla University **(Figure3.10).** The three point flexural bend test was done in the standard ASTM D7264. The flexural strength and modulus were obtained from this test. The specimens of five samples were tested for flexural bending test.

Figure 3.14 The Instron 5569 machine

3.5.4 Fatigue Tests

In order to verify the models and approve the materials used to provide a given. Fatigue lifetime, an extensive testing has focused on design considerations. Only a few standards exist for measuring the fatigue performance of the composites materials. Fatigue as a specific failure mechanism that has been recognized .The Specimen was tested per American Society for Testing and material for tension-tension fatigue, (ASTM) D3479 Standard Test Method for Tension-Tension Fatigue of Polymer Matrix Composite Materials (W. Conshohocken, ASTM D3479) gives very brief guidelines for a tensile test specimen, with an axial tension-tension cyclic loading. This standard does not prescribe clamping procedures, frequencies or data reduction. Therefore, it has a little value in practical applications. This standard prescribes a rectangular shaped specimen with end tabs (Povl Brndsted at el, 2005) Fatigue tests were carried out according to ASTM 3479 and the stress ratios, Smax ($\sigma_{min}/\sigma_{max}$) was 0.1, where σ_{max} and σ_{min} are the maximum and the minimum applied stresses, respectively, and σ_{ult} is the ultimate strength of the composites.

The fatigue test specimens were prepared from resin lamination. All the fatigue tests were performed according to the ASTM D3479M-96 test standard specifications (Povl Brndsted at el, 2005) using a 25 kn computer-controlled servo-hydraulic test machine. The following fatigue parameters were employed for the tests: stress ratio, R = 0.1, sinusoidal waveform and frequency, v = 1-3 Hz. It should be noted that it has been shown that higher test frequencies may induce thermal effects, and lead to reduced fatigue lives in composites (Mandell, J. F. et al, 1983; Staff, C. R. 1983; Sun, C. T. 1979) Therefore, the test frequency was kept below 3 Hz in the present studies.

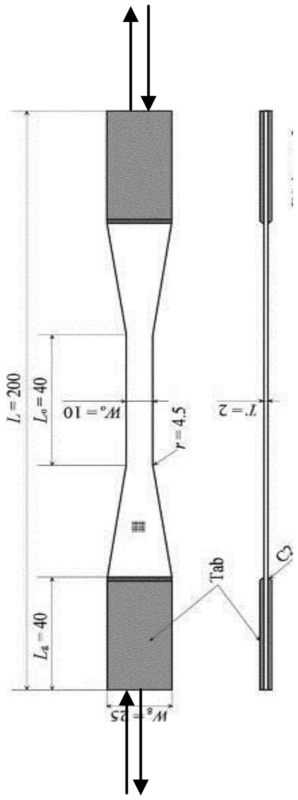


Figure 3.15 Speciment for Fatigue Tests (Yasuhide Shindo 2006)

$$\sigma_{max} = \sigma_f^1 (Nf)^b$$

The experimental data of stress vs. number of cycles to failure (S-N curves) for the bulk epoxies shown in Fig. 4 was ftted to Basquin's law where σ_f^1 is the fatigue strength coefficient (FSC), and b is the fatigue strength exponent (FSE).

In this study, we use the Instron 8872 machine from Department of Mechanical Engineering, Faculty of Engineering at Prince of Songkla University **(Figure3.16)**

Figure3.16 The Instron 5678 machine

3.6 Morphology Properties

Scanning Electron Microscopy

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with electrons in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image

A scanning electron microscope (SEM) studied the microstructure of composites samples, for the effect of fiber length on tensile properties of silk. Composite samples were left to settle at room temperature for one day and then removed from the mould. In this work, the main studies were carried out to investigate how fiber length of silk fiber reinforced the composite and affected fiber tensile strength. This section presents an experiment using the preparation of composites from raw materials by the silk fibers that were immersed in Liquid Nitrogen **Figure 3.17** (Pease WS, 1986).

Specimen preparation

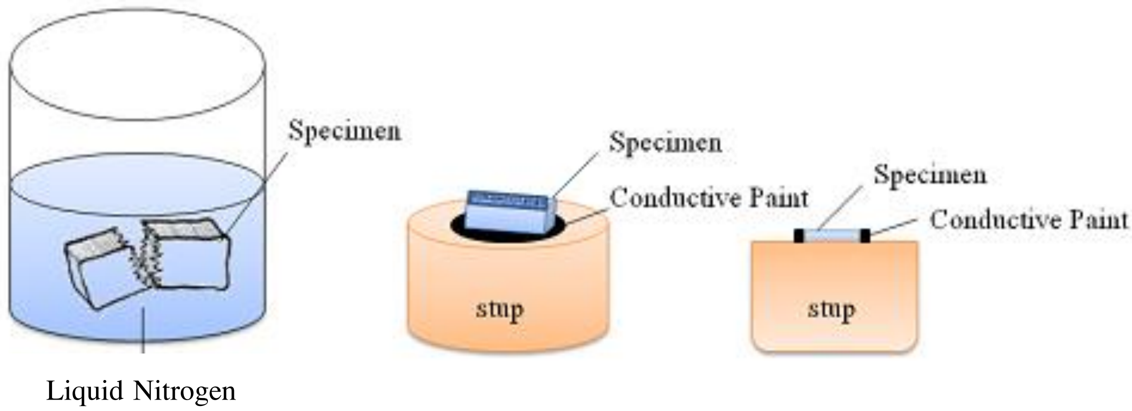


Figure 3.17 Immersed in Liquid Nitrogen and place on the stub

The SEM micrograph of the failure surfaces was used for the direct observation of the composite structure, and particularly to examine the resin fiber interface. A scanning electron microscopy (SEM) machine Model Quanta 400 FEI was used to study adhesion between fiber and resin in composite material in cross section SEM Photograph.

In this study, we use the scanning electron microscopy (SEM) machine Model Quanta 400 FEI from scientific equipment center at Prince of Songkla University **(Figure3.18).**

Figure 3.18 The scanning electron microscopy (SEM) machine Model Quanta 400 FEI

3.6 Properties material of Orthoses testing

3.6.1 Compression Testing

In this study, we use the Hounsfield Machine from Department of Mining and Materials Engineering, Faculty of Engineering at Prince of Songkla University **(Figure3.19)**

We have tested three different composite materials that are used to make the Spiral ankle foot Orthoses. The compression strength of orthoses was to choose considere a suitable orthoses for the patient. Importantly compression orthoses properties are during the patient walk forced through the anterior and the posterior in the aspects of the device which should fluctuate from being compressive (C).

Figure 3.19 Hounsfield Machine (test vertical force of othoses)

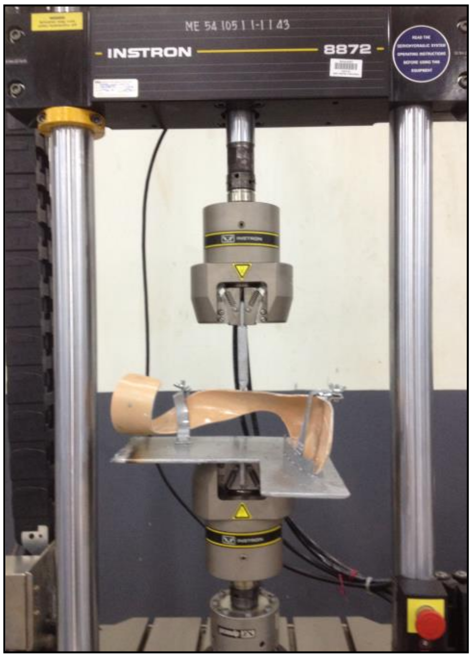


Figure 3.20 Instron 8872 Machine (test sagittal force of orthoses)

In this study, we use the Instron 8872 machine from Department of Mechanical Engineering, Faculty of Engineering at Prince of Songkla University (**Figure 3.20**). The different machine for compression testing on orthoses because not enough spaces of compression-head load. Compression testing of the spiral ankle foot orthoses was measured by the mechanical testing machine using a compression-head speed of 50 mm/min. The dimensions and tolerances of the spiral ankle foot orthoses for compression testing were a considerably direction and sagtital force of orthoses

3.6.2 Fatigue Tests of Orthoses

In this study fatigue of two composite materials was considered for selecting a suitable orthoses for patient. The fatigue tester, or cyclic machine as it is sometime know, was designed to test differing reinforcement composite material, it differs from the machine which is described within the ISO (International Standards Organization), in that it mimics the gait cycle more accurately. Subjecting a particular component to a fatigue test is a reliable way to determine the life of the material and the specification of loads that can be applied safely during the simulated gait cycle.

Failure definition for polymer composites under fatigue load is more complex than that of the metallic materials as it involves many damage modes such as matrix cracking, deboning, delimitation, fiber breakage, etc.

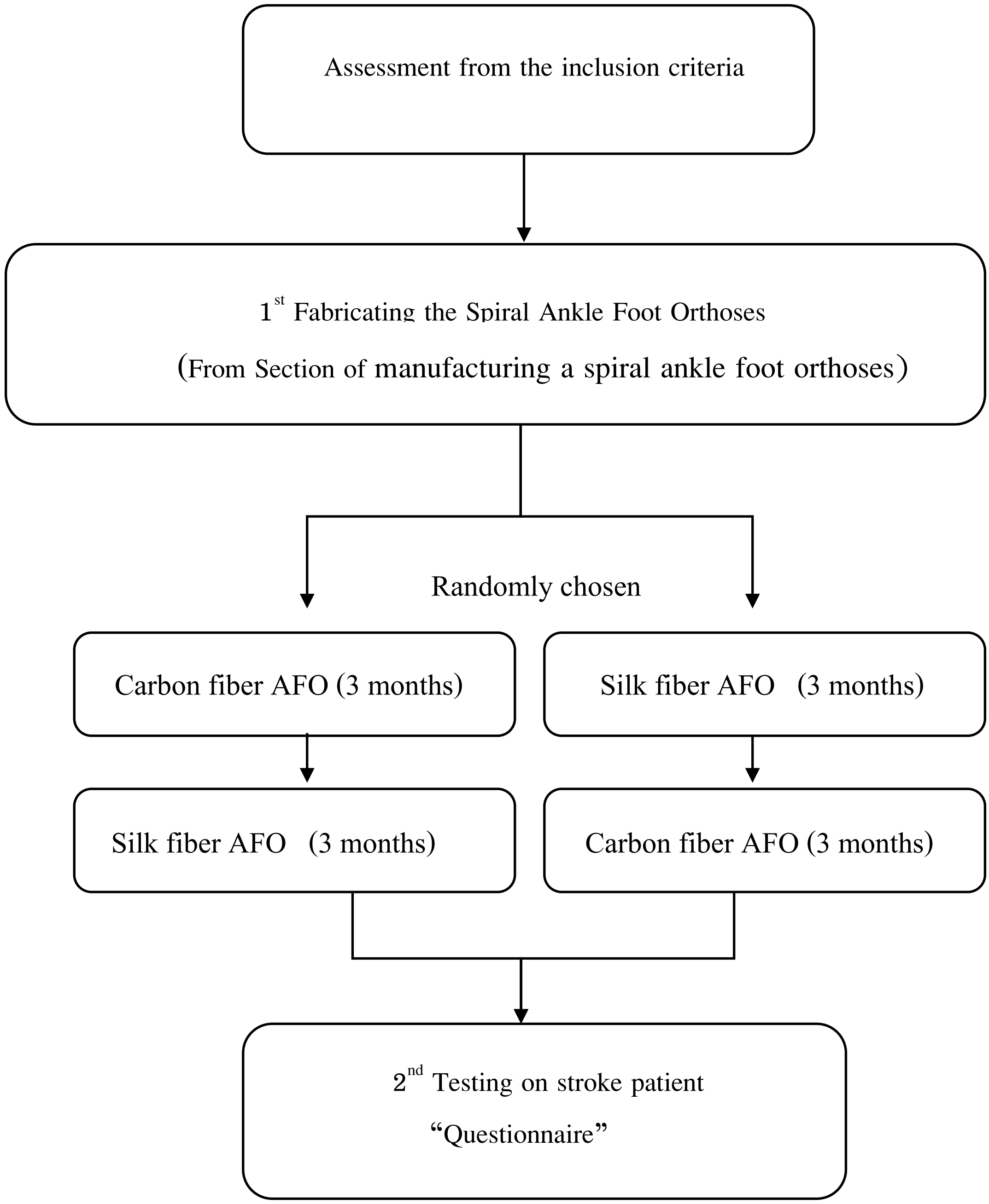
Figure 3.21 The fatigue cycle machine

In this study, we use the fatigue cycle machine from Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University (**Figure3.21**). For the cyclic test to be conducted the test sample must be correctly aligned within the testing equipment. Alternating force is then applied to the heel forefoot at a specified frequency of between 2 Hz (International Organization for Standardization, 1994) and applied force 1,500 N (International standard ISO/IEC 7498-1).

3.6 Participants

Ankle Foot Orthoses (AFOs) are devices often prescribed to improve gait performance for persons with impaired lower limb function as assistive or therapeutic devices. For the purpose of this study, to test the effectiveness of a spiral ankle foot orthoses by some questionnaires.

2nd Testing on stroke patient



There are 7 subjects that studied from rehabilitation in Physical Therapy Clinic at Songklanakarin hospital. All of subjects were diagnosed with unilateral hemiplegic caused by either hemorrhagic or ischemic stroke, the age range was 41-60 years. In this study, the study was accepted by the Ethics Committee, and every subject signed an informed consent for the study. This study is analyzed between June and January 2013.

The diagnosis, age, sex, affected side and onset time of hemiparesis were obtained from some patient interviews and medical charts.

The inclusion criteria

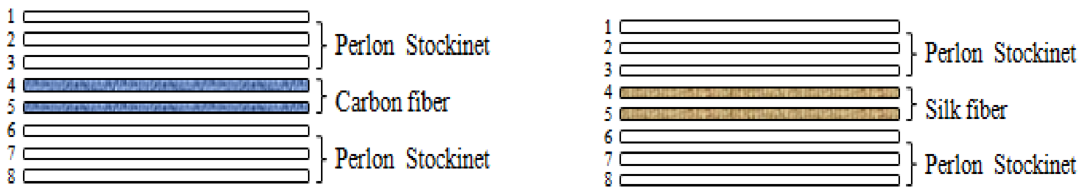
- For this study, Post stroke subjects with hemiplegic post 6 months.
- No pain during gait due to orthopedic problems.
- All patients underwent neuroimaging studies.
- Ability to understand and follow commands.
- According to the Scandinavian Stroke scale (SSS) score for lower extremity motor strength (Goutianos, S., et al,2007)

The exclusions criteria

- Visual impairment
- Inability to provide informed consent
- Significant cardiorespiratory or metabolic diseaseincluding untreated cardiac failure, diabetes, or uncontrolled hypertension

Subjects were then cast by an orthotist for a customized, Spiral AFOs design by lamination resin reinforcement with silk and carbon fiber, full length foot plate, set ankle at 90. and a dorsal ankle strap was attached to them to maintain proper foot alignment **(Figure 1.1)**. Footwear was tandardized for subjects with hemiplegia, with each participant receiving a pair of shoes, with zero centimeter difference in the sole height from heel-to-forefoot.

This study demonstrated that definitive laminated composite material silk fiber with resin had a higher specific tensile strength than carbon and glass fiber polymer composite. Hardness and elongation at break of is comparable to carbon and glass fiber polymer composite. Furthermore, the morphology of silk fiber composite showed that silk fibers adhere to resin better than carbon fibers and glass fibers. Therefore, in this study chose composite material fiber 2 layer reinforce **(Figure3.22)** of Carbon-Fiber and Silk-Fiber for Ankle foot Orthoses



(a) **(b)**

Figure 3.22 Layer of reinforcement (a) 2 layer of Carbon fiber, (b) 2 layer of Silk fiber

CHAPTER 4

RESULTS AND DISCUSSION

Materials and Orthoses

4.1. Physical Property Test

Physical properties were mean weight ratio, thickness ratio and width ratio of the three groups of fibers calculated. The weights ratios were measured by the "Precision Balance Scale" with the repeatability of the thickness and width. Vernier calipers measured thicknesses and widths. Five sample specimens were tested for three measured points of thickness and width.

In this study, physical properties, particularly mean weight and thickness ratios for choosing suitable materials for ankle foot orthoses were considered.

4.1.1 Weights

The weight of 1 ply glass composite is lower than carbon composite and silk composite. The weight of 2 ply silk composite is lower than carbon composite and glass composite. The weight of 3 ply carbon composite is lower than silk composite and glass composite **(Table 4.1)**. Interestingly, 2 ply silk composite has a low mean weight ratio. Such a result indicates that silk composite might be a suitable choice for ankle foot orthoses.

4.1.2 Thickness

Interestingly, the thicknesses of silk composite all ply are less thick than carbon composite and glass composite **(Table 4.1)**. Such a result indicates that silk composite might be a suitable choice for ankle foot orthoses.

Table 4.1 The physical properties of composite materials

Layer	Materials Type	Width (mm)	Length (mm)	Thickness (mm)	Weight (g/cm^2)
1	Silk composites	11.56±0.20	125.45±0.12	2.65±0.13	5.88±0.18
	Carbon composites	12.76±0.40	125.94±0.32	3.04±0.12	6.08±0.27
	Glass composites	12.54±0.32	125.09±0.40	3.14±0.22	4.76±0.25
2	Silk composites	12.04±0.25	125.83±0.13	3.15±0.31	6.04±0.30
	Carbon composites	12.58±0.32	125.08±0.32	3.45±0.18	7.17±0.28
	Glass composites	12.45±0.22	126.10±0.20	3.65±0.17	8.77±0.29
3	Silk composites	11.98±0.21	125.07±0.30	3.14±0.25	8.31±0.32
	Carbon composites	12.45±0.23	125.95±0.13	3.65±0.16	7.67±0.20
	Glass composites	12.68±0.14	126.05±0.13	3.84±13	11.83±0.13

4.1.3 Hardness Test

The hardness test measures the resistance of a material to an indenter or cutting tool. The indenter is usually a ball, pyramid or cone which is made of a material. It is harder than that being tested. A load is applied by slowly pressing the indenter at right angles to the surface being tested for a given period of time. In this study, hardness result for selecting a suitable material for ankle foot orthoses was also used.

Table 4.2 Hardness testing of composite material

Layer	Composite Type	Hardness testing
		Mean ± SD
1	Silk composites	70.33 ± 0.67
	Carbon composites	70.00 ± 2.00
	Glass composites	64.00 ± 2.00
2	Silk composites	76.33 ± 0.67
	Carbon composites	71.00 ± 2.00
	Glass composites	71.00 ± 1.00
3	Silk composites	78.33 ± 1.33
	Carbon composites	75.33 ± 2.33
	Glass composites	72.66 ± 1.33

According to the results in **Table 4.2 and Figure 4.1**, there were no significant differences of hardness in all fiber reinforcements. Hardness of the three separate specimens was reinforced. At this point, the residual penetration which is the hardness was measured. The three studied samples; carbon fiber composites, glass fiber composites and silk fiber composites were tested for hardness. Composite materials are determined by using shore D hardness scales of Zwick hardness testing machine.

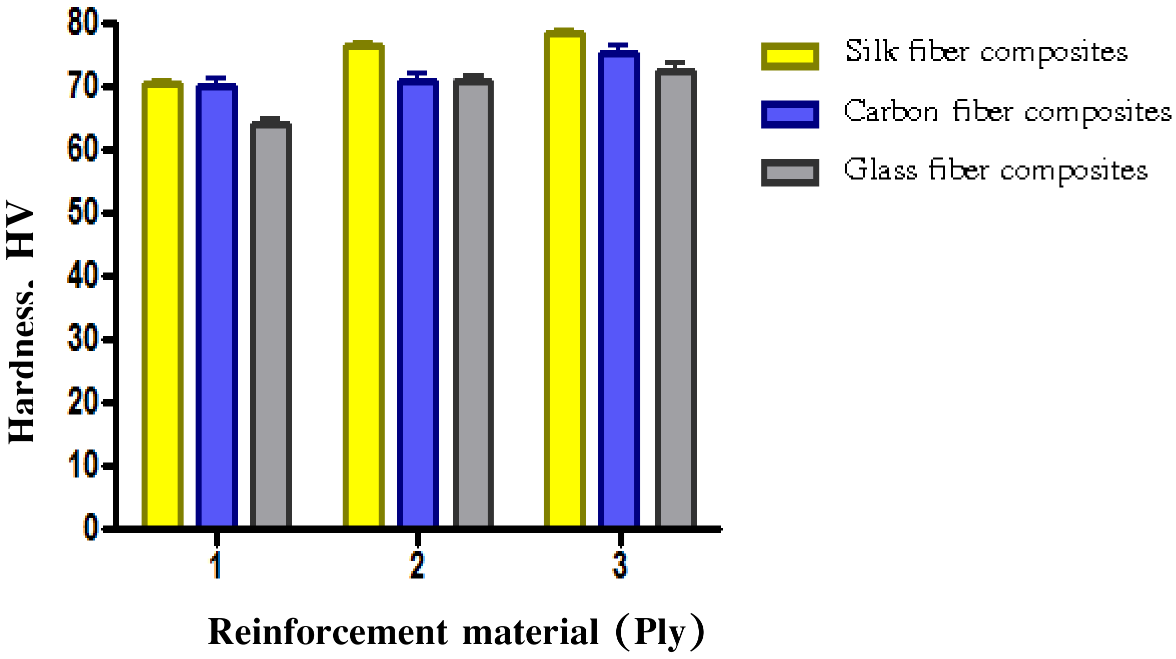


Figure 4.1 Hardness testing

As **Figure 4.1 and Table 4.2** show, the hardness of silk composite, carbon composite and glass composite are very similar, being tenths different, this result shows that silk composite can withstand deformation much more than the other two samples. Therefore in terms of hardness, silk composite would be the most suitable for lower limb orthoses applications.

The results indicate that silk fiber polymer composites have a higher hardness than carbon fiber polymer composites and glass fiber polymer composites, although they have provided different ratios of density. Concerning this result, it showed that silk composites might be used as materials for ankle foot orthoses that need scratch resistance.

4.2 Mechanical Properties

4.2.1 Tensile Test

Tensile strength is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking. Tensile strength is defined as a stress, which is measured as force per unit area.

In this study, we used tensile strength to select a suitable material for orthoses fabrication. The tensile strength of the composites was measured with a universal testing machine in accordance with the ASTM D3039 procedure. Tensile test was conducted on the three different types of composite samples under study, which were silk composite, carbon composite, and glass composite. The tensile test was done using the Instron machine on dumbbell shaped sample. For each material several tensile tests were conducted and the three most consistent results were selected for each type of material for analysis. The strain rate used for all the samples was 50 mm/min. Based on tensile testing; the results will be obtained for tensile strength and Young's Modulus.

Table 4.3 Mechanical properties of composite material

Layer	Composite Type	Tensile strength (MPa)	Young's Modulus (GPa)	Elongation at break (%)
		Mean±SD	Mean±SD	Mean±SD
1	Silk fiber	42.35±2.45	620.54±23.45	6.28 ± 1.05
	Carbon fiber	47.87±2.17	354.89±24.87	6.31 ± 0.58
	Glass fiber	38.12±5.64	548.00±50.98	4.61 ± 0.39
2	Silk fiber	52.10±2.30	956.46 ± 22.78	9.10 ± 0.35
	Carbon fiber	55.19±2.61	371.52±35.98	8.23 ± 0.69
	Glass fiber	50.33±3.53	589.94±30.87	7.72 ± 0.93
3	Silk fiber	55.27±1.87	1160.02±29.87	9.43 ± 0.54
	Carbon fiber	58.53±5.27	391.80±23.98	9.13 ± 1.71
	Glass Fiber	56.40±2.90	634.82±34.98	8.9 ± 0.74

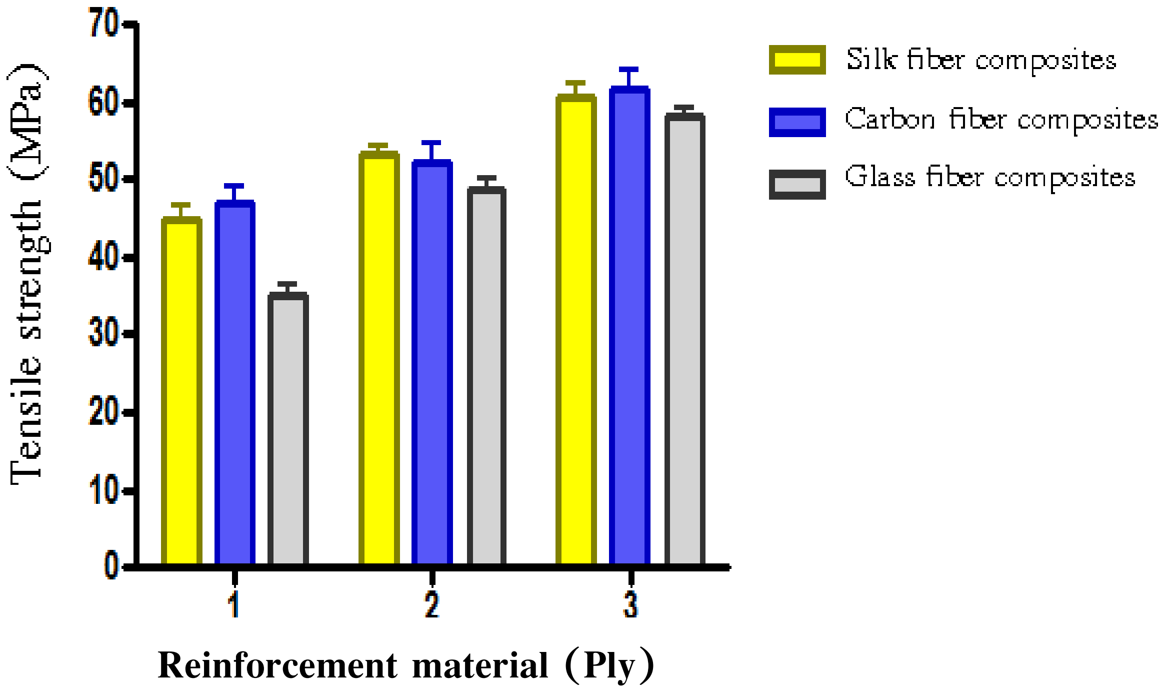


Figure 4.2 Average tensile strength of resin reinforced with fibers composite material.

Tensile testing results obtained from the tensile strength of the specimens were as shown in **Figure 4.2**: 1ply composite presented a tensile strength of silk composites. According to tensile strength, it indicates that there were significant differences of silk composites to compare with 1 ply glass fiber (P value = 0.0118).

Importantly, the result shows that tensile strength proportionally increases with the number of ply.

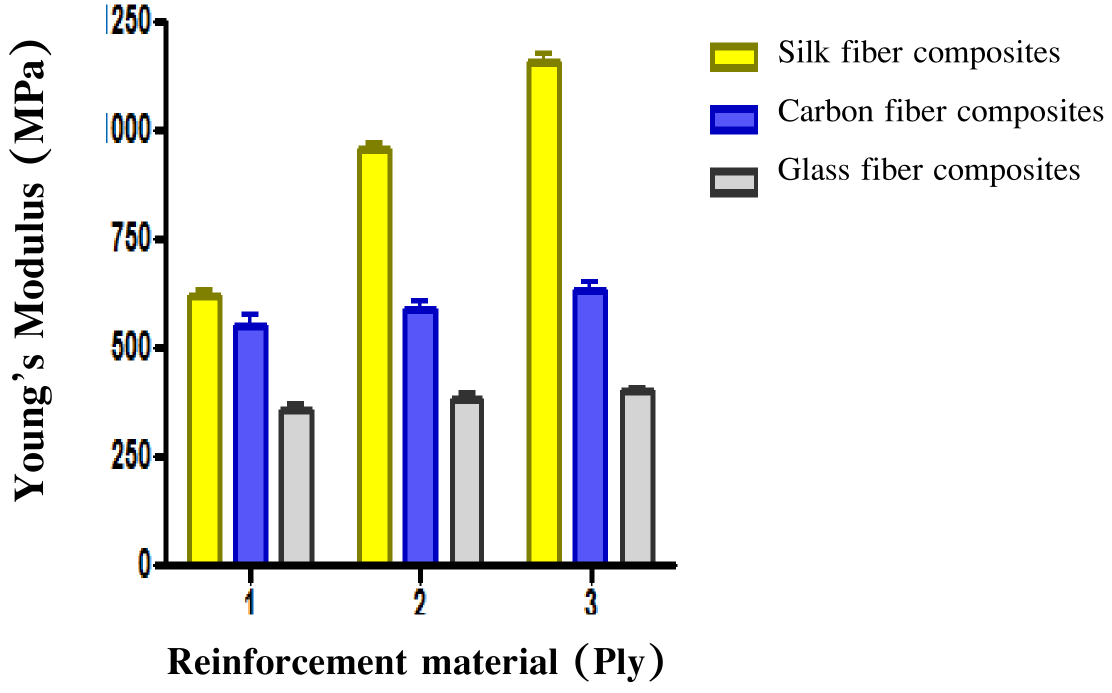


Figure 4.3 Average Young's Modulus of fiber reinforced (1 ply, 2 ply and 3 ply) with resin lamination composite material

Significantly, the result shows that Young's Modulus of silk fiber reinforcement all ply is higher than the others. (**Figure4.3**).

Elongation at break result, silk composite shows that elongation at break (ε) of 1 ply is significantly different in comparison to 1 layer glass fiber (P value = 0.0415) **(Figure 4.4)**.

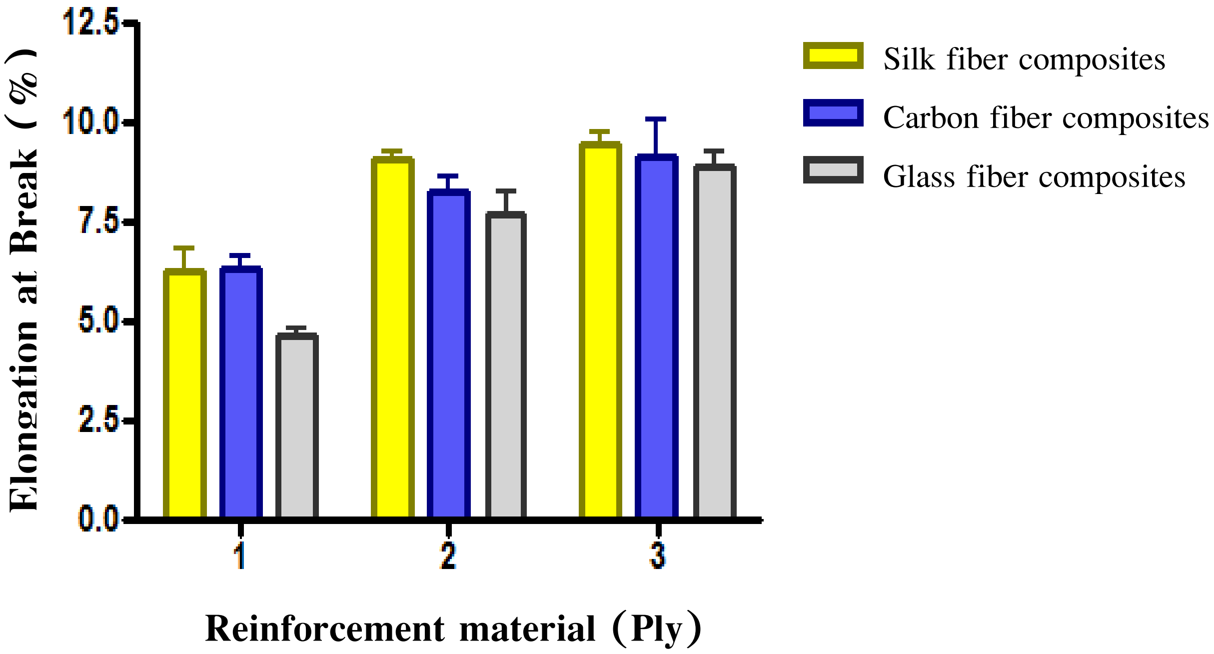


Figure4.4. Average elongation percentage at break of fiber reinforced (1 ply, 2 ply and 3 ply) with resin lamination composite material.

Interestingly, silk composite has a comparative tensile strength and elongation at the break to carbon composite. Fiber composites are the materials that are usually used for performance ankle foot orthoses. Furthermore, Young's Modulus of silk composite is higher than carbon composite and glass composite. Therefore, silk composite might be an alternative material for such orthoses. Furthermore, the elongation percentage of silk composite is higher than the carbon composite. According to this result, it showed that silk composite was more ductile than carbon composite, due to its toughness, had the feasibility to be used as a material for medical devices such as ankle foot orthoses and prostheses.

In this study, we considered the strength/weight of composite materials for choosing a suitable material for ankle foot orthoses.

Table4.4 The strength/weight of composite material

Composite material	**Layer**	**Tensile strength (MPa)**	**Weight (g)**	**Tensile strength / weight (MPa/g)**
	1	44.46±0.18	5.88±0.18	7.56 ± 1.43
Silk fiber	2	53.35±0.28	6.04±0.30	8.83 ± 0.25
	3	60.73±0.30	8.31±0.32	7.30 ± 0.28
	1	47.05±0.18	6.08±0.27	7.70 ± 0.03
Carbon fiber	2	52.05±0.19	7.17±0.28	7.30 ± 0.03
	3	42.75±0.16	7.67±0.20	5.57 ± 0.50
	1	35.16±0.18	4.76±0.25	7.40 ± 0.13
Glass fiber	2	48.85±0.27	8.77±0.29	5.57 ± 0.38
	3	58.00±0.15	11.83±0.13	4.90 ± 0.17

The strength/weight of composite materials is shown in **Table 4.4.** Fiber reinforcement 1 ply has silk composite 7.70 ±1.43, carbon composite 7.70 ±0.03 and glass composite 7.30 ±0.13. Fiber reinforcement 2 ply has silk composite 8.83±0.25, carbon composite 7.30±0.03 and glass composite 5.57±0.38. Fiber reinforcement 3 ply has silk composite 7.30±0.28, carbon composite 5.57±0.5 and glass composite 4.90± 0.17.

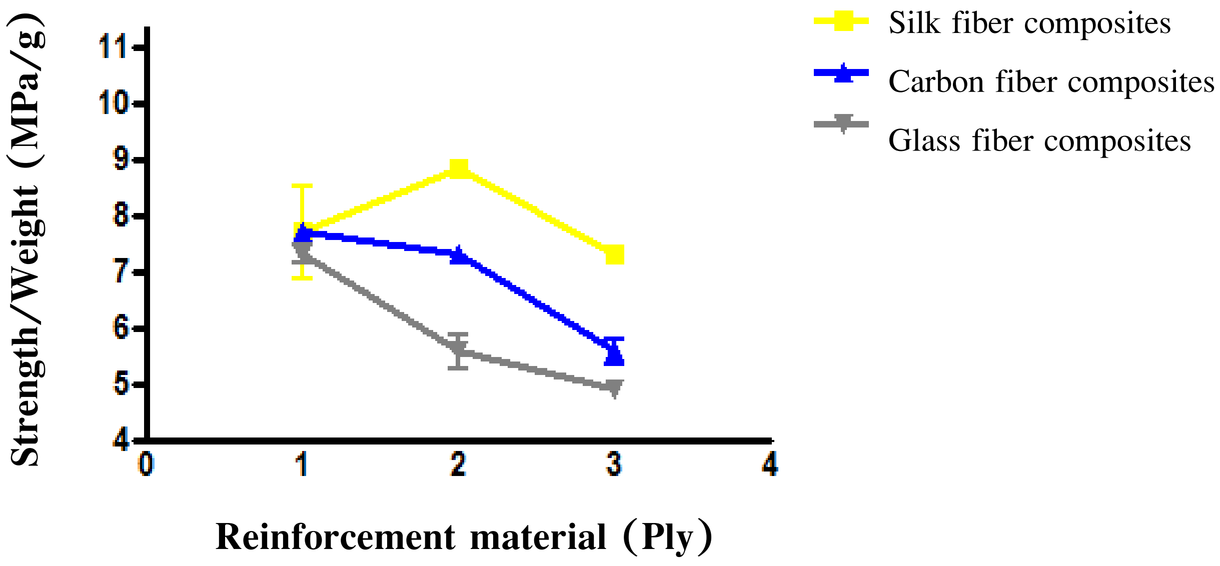


Figure4.5 Strength/weight of fiber reinforced (1 ply, 2 ply and 3 ply) with resin lamination composite material.

According to the results seen in **Figure 4.5**, strength/weight of reinforced 2 ply silk composite is the highest. Carbon composite and glass composite are decreased in the number of layers increases. Such results indicate that silk composite promises to be a good choice for use as a material for ankle foot orthoses because it is lightweight and has high strength.

4.2.2 Flexural Testing

The flexural test measures the force required to bend a beam under three point loading conditions. The data is often used to select materials for parts that will support loads without flexing. In this study, the three point flexural bend test was done in the standard ASTM D7264. The flexural strength and modulus were obtained from this test. The specimens of five samples were tested for flexural bending test.

Table 4.5 Flexural testing of composite material

Layer	**Composite Type**	**Flexural strength (MPa)**
		Mean±SD
1	Silk composites	42.75 ± 5.16
	Carbon composites	72.20 ± 2.17
	Glass composites	53.35 ± 5.64
2	Silk composites	50.70 ± 4.76
	Carbon composites	73.07 ± 7.33
	Glass composites	64.70 ± 11.54
3	Silk composites	53.55 ± 3.4
	Carbon composites	61.84 ± 11.66
	Glass composites	55.88 ± 4.10

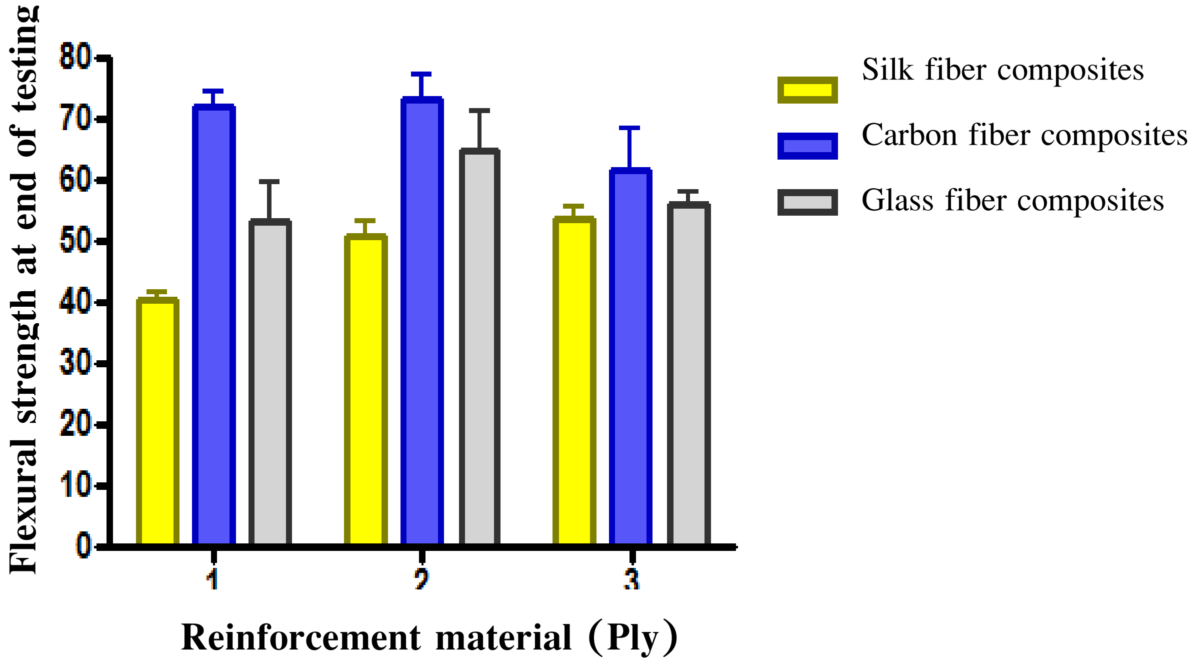


Figure4.6 Average Flexural strength of reinforced fiber

(1 ply, 2 ply and 3 ply) with resin lamination composite material

In this study, flexural behavior was characterized to consider in a suitable material for ankle foot orthoses. According to **Table 4.5 and Figure 4.6,** flexural testing, the result indicated that all samples of carbon fiber composites had higher flexural strength than the others. Interestingly, glass and carbon fiber composites broke during testing. However silk composite did not break until the end of testing. Such a result indicated that even at the end of testing, silk composite still had a good resistance of flexural strength. Therefore, silk composite might be a suitable choice for ankle foot orthoses.

4.2.3 Fatigue Testing

In this research, fatigue testing was also chosen preliminary results to select suitable materials for ankle foot orthoses. The specimen were tested per American Society for Testing and material for tension-tension fatigue, (ASTM) D3479 standard test method for tension-tension fatigue of polymer matrix composite materials (W. Conshohocken, ASTM D3479) gives very brief guidelines for a tensile test specimen, with an axial tension-tension cyclic loading. Tension-tension fatigue measurements (ASTM D 3479) were carried out in the controlled-load mode at a frequency of 2 Hz. Each data point refers to 5 samples. In this study three types of material were tested by fatigue testing. Such testing is a preliminary result to consider and a suitable material for ankle foot orthoses.

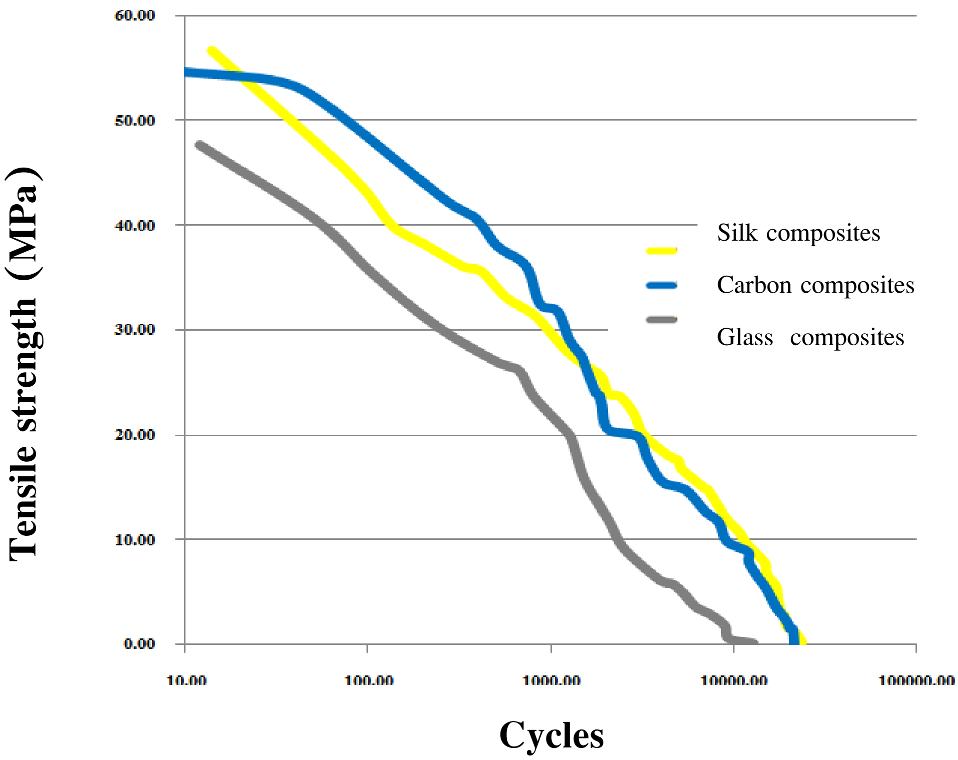


Figure 4.7 Average fatigue of fiber reinforced 2 ply with resin lamination composite material

Fatigue experiments, this test survived are failed in the centre of the silk composites specimen at 23,522 cycles. In addition, the carbon composites specimen failed in the centre at 21,429 cycles. The glass composites specimen failed in the centre at 12,827 cycles. During their fatigue life, all specimens showed a similar behavior. **Figure 4.7** shows the evolution of the maximum of the longitudinal stress during a 56 MPa at 2 Hz fatigue test. The fatigue experiment was stopped without failure or visible damage after around 20,000 cycles.

Importantly, the results showed that silk composite has good fatigue properties. Therefore, silk composite promises to be a suitable choice for ankle foot orthoses.

4.3 Morphology Properties

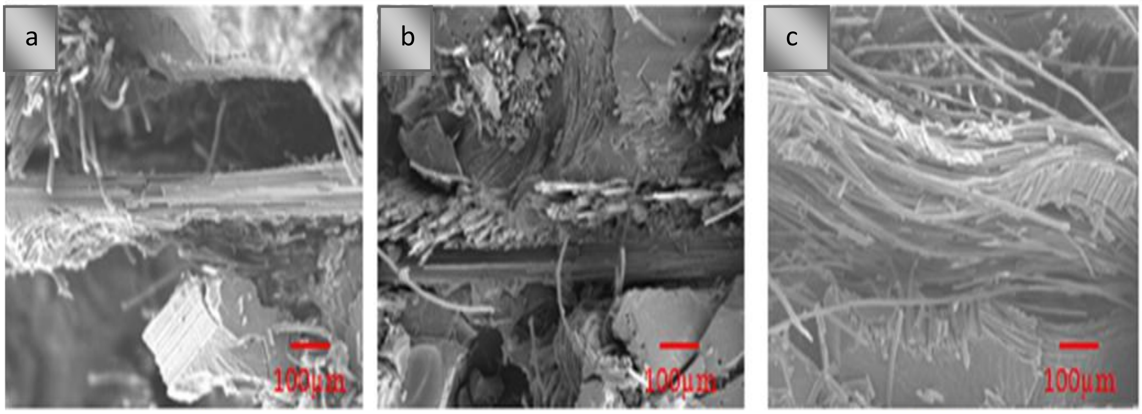
Scanning Electron Microscopy

A scanning electron microscope (SEM) was used to observe the morphology of composites samples. All broken samples from tensile testing were observed at cross-section area. Composite samples were left to settle at room temperature for one day and then removed from the mould.

Glass fiber composites | Silk fiber composites | Carbon fiber composites

Figure 4.8 Specimens prepare for SEM analysis : broken area of sample observed by SEM

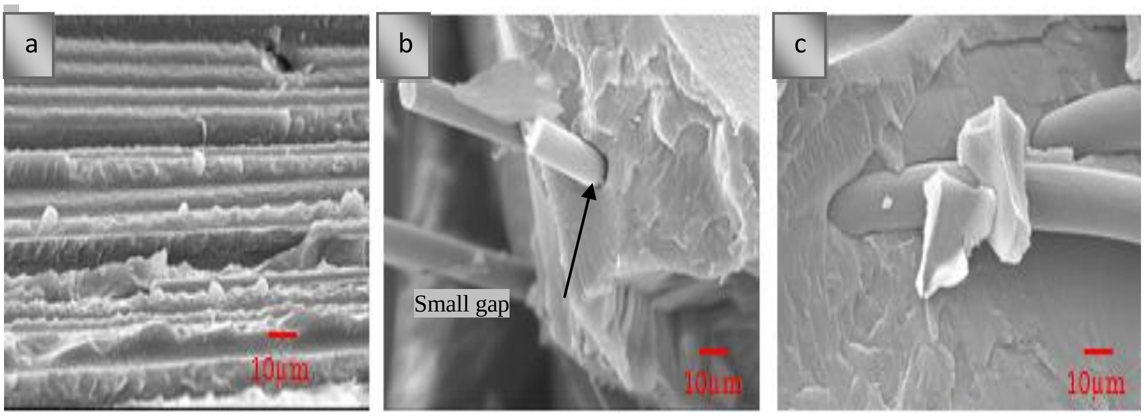
According to the morphology from **Figures 4.9** and **4.10**, the interfacial interaction between the fiber and polymer matrix phase can be seen. For the carbon composite, it is shown that no fiber was sticking on the polymer matrix, which means a poor adhesion between fiber and polymer matrix. For the glass composite, it is shown that there is a small gap between the fiber and the matrix, which means fairly good adhesion. For the silk composite, there is no such gap. Therefore, it indicates that silk fibers have a good adhesion with polymer matrix.



Carbon fiber composites Glass fiber composite Silk fiber composite

Figure 4.9 SEM micrographs (100µm)

of interfacial adhesion between fiber and matrix after tensile test.



Carbon fiber composites Glass fiber composite Silk fiber composite

Figure 4.10 SEM micrographs (10µm)

of interfacial adhesion between fiber and matrix after tensile test.

From such results, it might be deduced that good adhesion of silk composite is an important effect necessary to increase interfacial interaction between fibers and polymer matrix. Such good interfacial interaction might lead to enhance the comparative tensile strength of silk composite in carbon composite.

The aim of this project was to test and evaluate different types of reinforcement materials for spiral ankle foot orthoses in order to choose the most appropriate material in terms of performance and cost. Silk fiber reinforcement material was the material chosen for this project. According to results, it was indicated that silk composite has altercative physical and mechanical properties. It might be a suitable choice for ankle foot orthoses, especially the 2 ply fiber reinforcement material. The tensile and hardness results indicated that silk fibers have the highest tensile strength, strength/weight and hardness. Finally, for economic reasons, silk fibers were 10 times cheaper than carbon fiber and glass fiber. Therefore, this result show that 2 ply silk reinforcements might be a suitable choice for use in spiral ankle foot orthoses.

4.4 Properties material of orthoses testing

4.4.1 Compression testing of the spiral ankle foot orthoses (Vertical Force)

In this study three different composite materials that are used to make the Spiral ankle foot orthosis were tested. The compression strength of orthoses was to choose a suitable orthosis for the patient. Important orthoses compression properties are during the patient walk forced through the anterior and the posterior in the aspects of the device which should fluctuate from being compressive (C).

In this study, the Instron 8872 machine from the Department of Mechanical Engineering, Faculty of Engineering at Prince of Songkla University was used **(Figure 4.11).** Compression testing of the spiral ankle foot orthoses was measured by the mechanical testing machine using a compression-head speed of 50 mm/min. The dimensions and tolerances of the spiral ankle foot orthoses for compression testing were a considerably direction and vertical force of othoses.

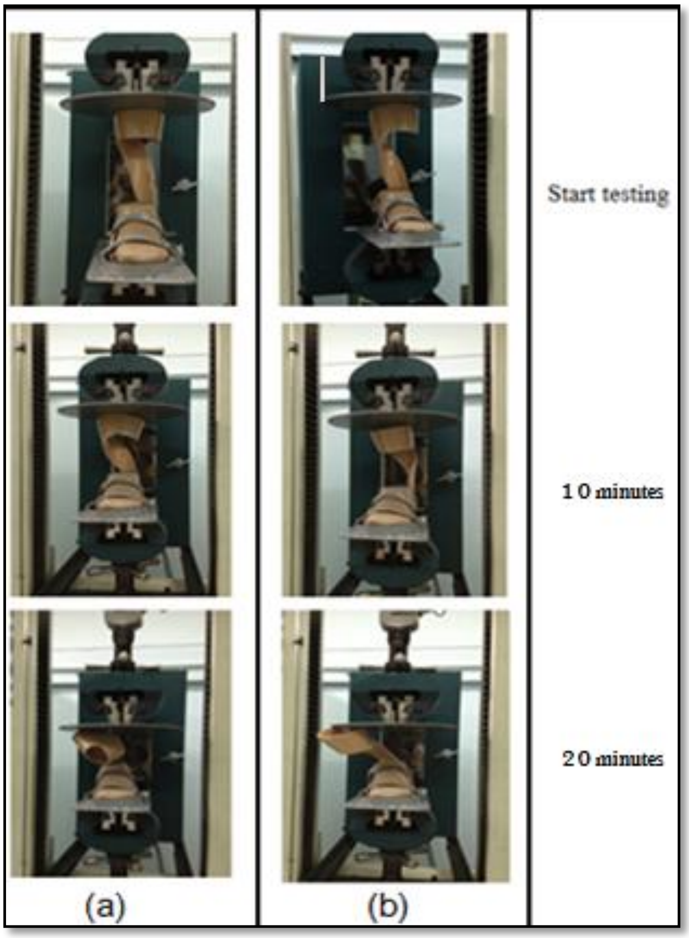


Figure 4.11 Compression load; (a) Spiral ankle foot orthoses with carbon fiber reinforcement, (b)Spiral ankle foot orthoses with silk fiber reinforcement

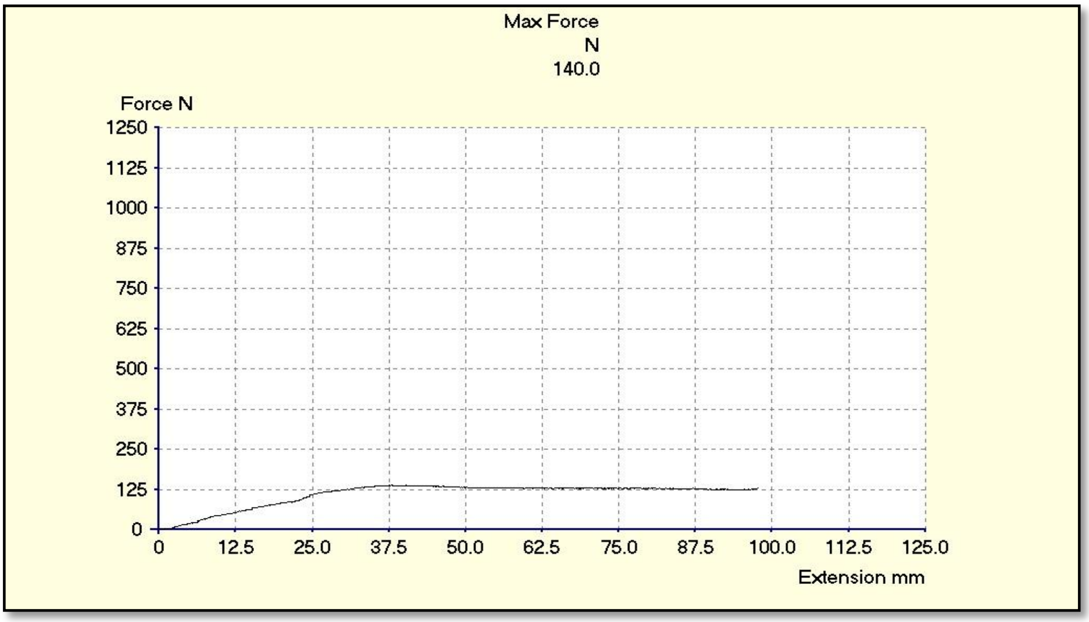


Figure 4.12 Force with extension of spiral ankle foot orthoses

with carbon fiber reinforcement

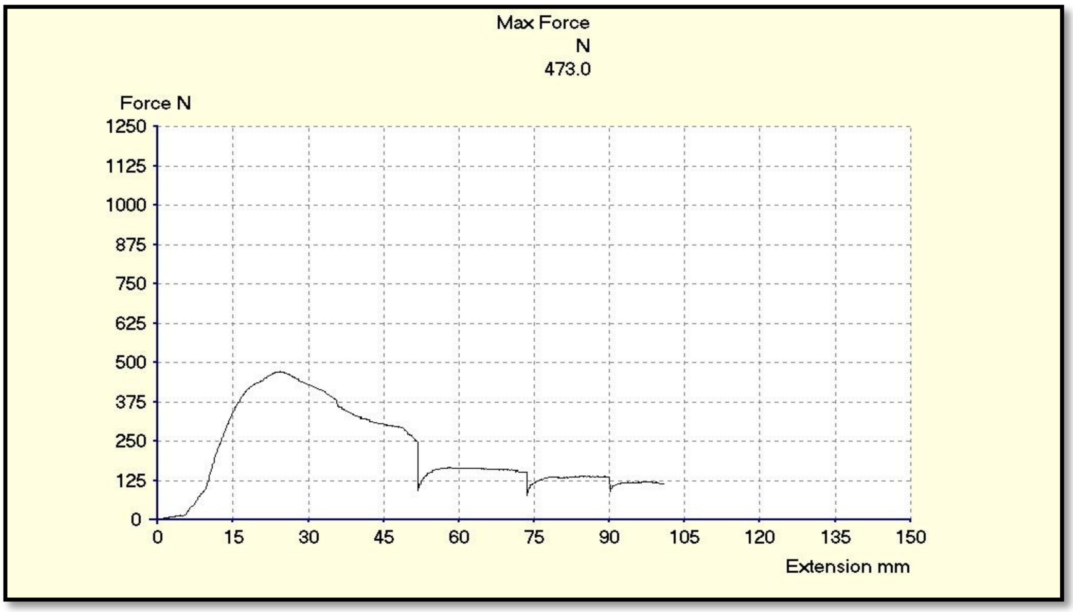


Figure4.13 Force with extension of spiral ankle foot orthoses
with silk fiber reinforcement

For spiral ankle foot orthoses with carbon fiber reinforcement 2 layers in maximum load 140 N, spiral ankle foot orthoses short term to 25 mm can return to the original form. The spiral ankle foot orthoses with silk fiber reinforcement 2 layer in maximum load 473 N. The spiral ankle foot orthoses ankle foot orthoses short term to 28 mm can return to the original form **(Figure4.12 and 4.13)**. Spiral ankle foot orthoses with carbon fiber reinforcement have about 2.5 cm. space. The spiral ankle foot orthoses with silk fiber reinforcement has a space of about 2.8 cm **(Figure4.14)**. The spiral ankle foot orthoses with carbon fiber reinforcement can return to its original shape more than the one with silk fiber reinforcement.

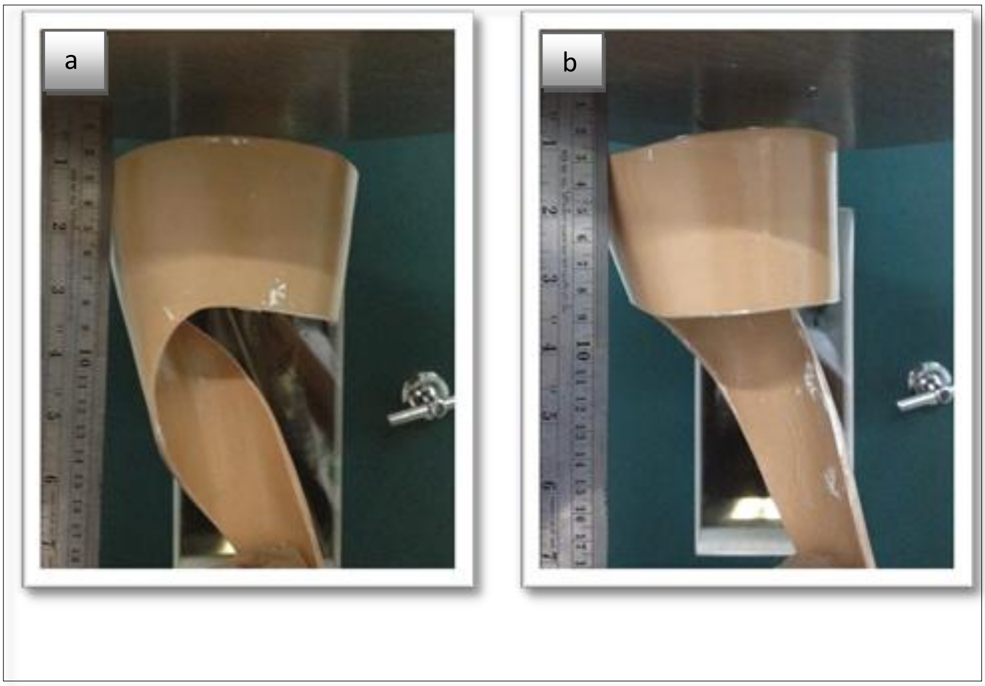


Figure 4.14 Reshaped extension of spiral ankle foot orthoses

(a) Spiral ankle foot orthoses with carbon fiber reinforcement and

(b) Spiral ankle foot orthoses with silk fiber reinforcement

Interestingly, ankle foot orthoses with silk fiber reinforcement had higher ultimate strength than ankle foot orthoses with carbon fiber reinforcement.

4.4.2 Compression testing of the spiral ankle foot orthoses (Lateral Force)

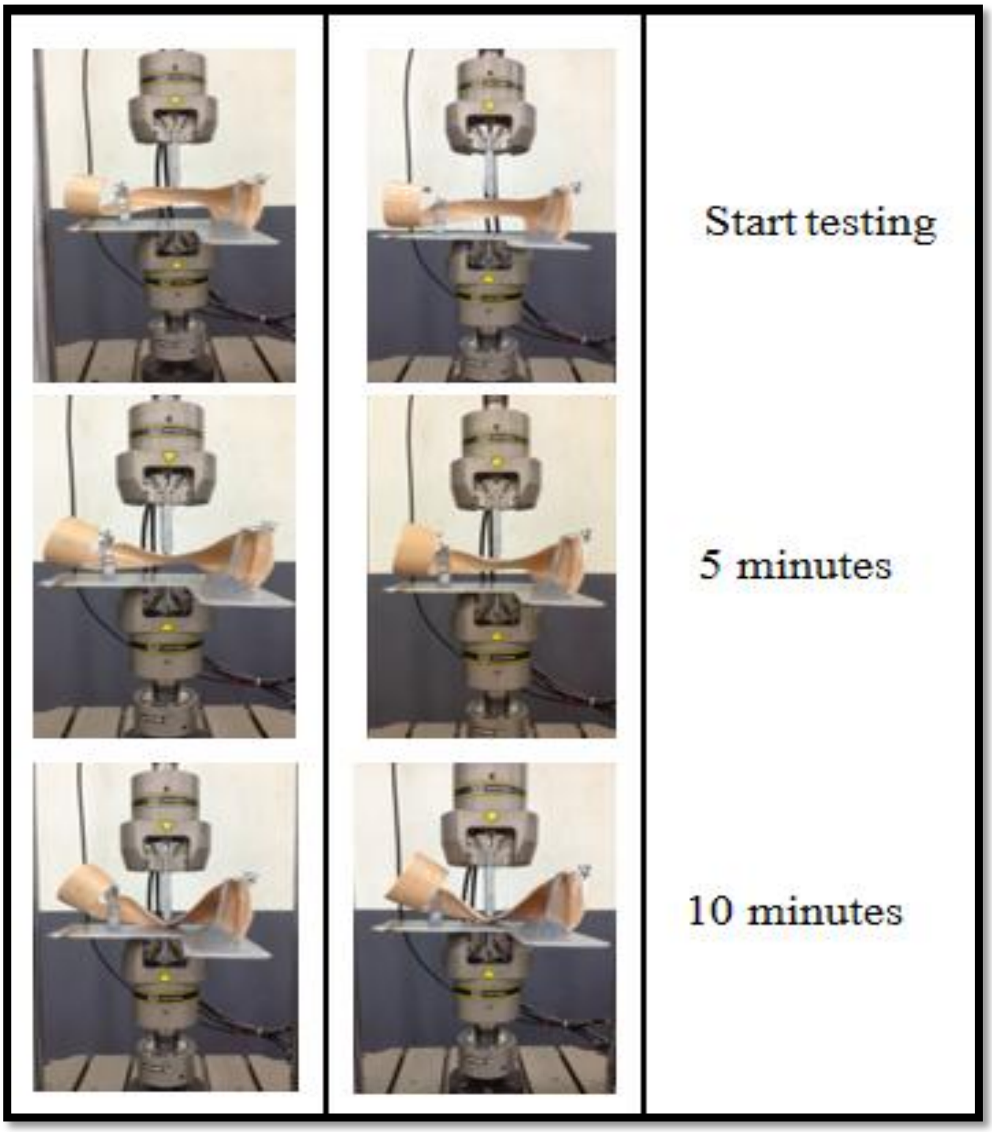


Figure4.15. Compression load; (a) Spiral ankle foot orthoses with carbon fiber reinforcement, (b)Spiral ankle foot orthoses with silk fiber reinforcement

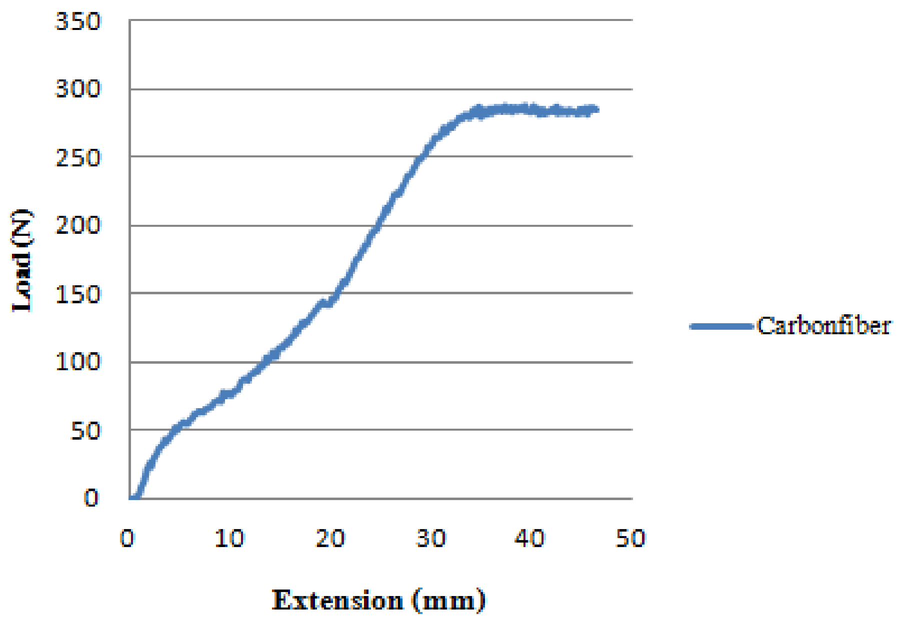


Figure 4.16 Force with extension of spiral ankle foot orthoses with carbon fiber reinforcement

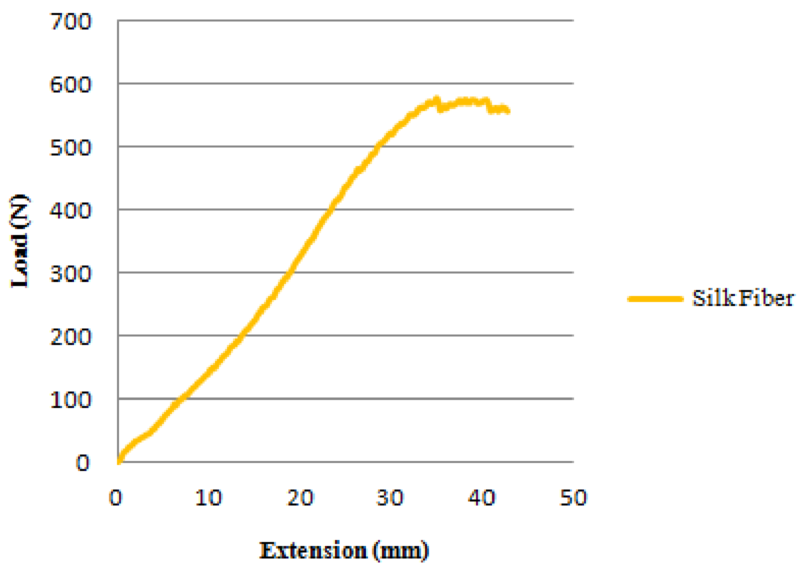


Figure 4.17 Force with extension of Spiral ankle foot orthoses with silk fiber reinforcement

Spiral ankle foot orthoses made with 2 layers carbon fiber reinforcement in a maximum load 300 N. They are reshaped at an extension of 33.56 mm. The spiral ankle foot orthoses made with 2 layers silk fiber reinforcement in a maximum load at 550 N **(Figure4.16 and 4.17)**. The spiral ankle foot orthoses with carbon fiber reinforcement has a space of 15.59mm. The one with silk fiber reinforcement has a space of 14.28 mm **(Figure4.18)**. The spiral ankle foot orthoses with carbon fiber reinforcement can return to shape more than the one with silk fiber reinforcement.

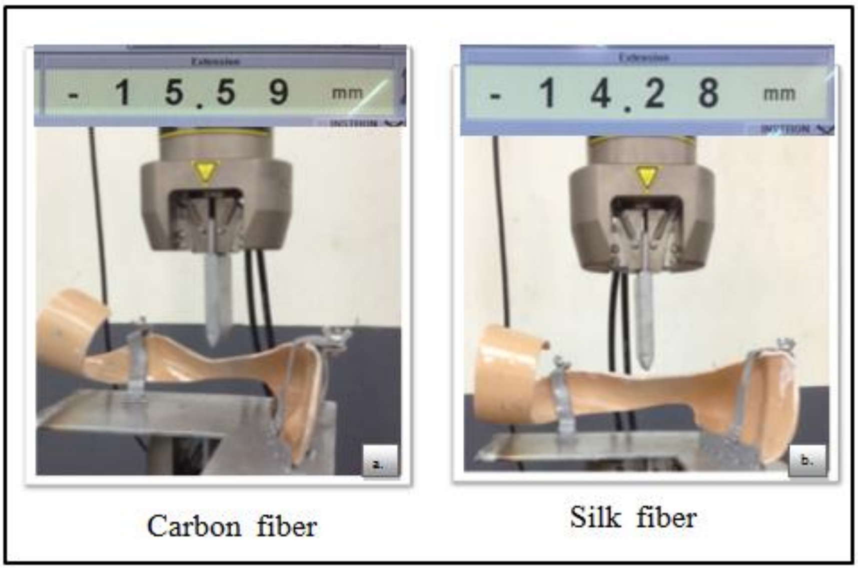


Figure 4.18 Reshaped extension of spiral ankle foot orthoses
(a) Spiral ankle foot orthoses with carbon fiber reinforcement
(b) Spiral ankle foot orthoses with silk fiber reinforcement

Interestingly, from **Figure 4.16 and 4.17**, the graph compares the load and extension of the spiral ankle foot orthoses from composites. The result was expressed that ankle foot orthoses from the natural bombyx silk fiber polymer composites had a greater load resistance than the synthetic carbon fiber polymer composites.

4.4.3 Testing of the spiral ankle foot orthoses

In this study fatigue of three composite materials was considered for selecting a suitable orthosis for a patient. The fatigue tester, or cyclic machine as it is sometimes known (**Figure 4.19**), was designed to test differing reinforcement composite materials. It differs from the machine which is described within the ISO (International Standards Organization), in that it mimics the gait cycle more accurately. Subjecting a particular component to a fatigue test is a reliable way to determine the life of the material and the specification of loads that can be applied safely during the simulated gait cycle.

Failure definition for polymer composites under fatigue load is more complex than that of the metallic materials as it involves many damage modes such as matrix cracking, deboning, delimitation, fiber breakage, etc.

For the cyclic test to be conducted the test sample must be correctly aligned within the testing equipment. Alternating force is then applied to the heel forefoot at a specified frequency of between 2 Hz (International Organization for Standardization, 1994) and applied force 1,500 N (International standard ISO/IEC 7498-1).

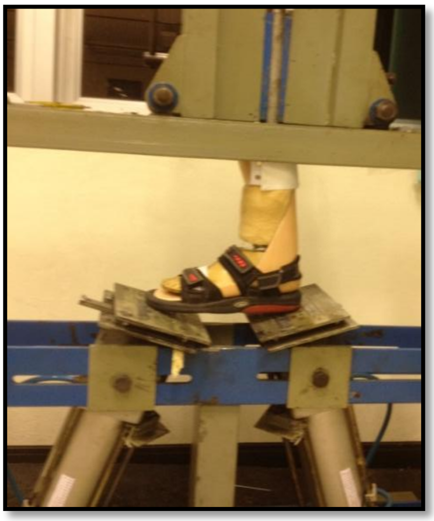


Figure 4.19 The fatigue cycle machine

The average walking activity of a patient with a well-functioning AFO was close to 2 million cycles/years. The walking activity of women was no different than that of men for this information. (Mauricio Silva 2002)

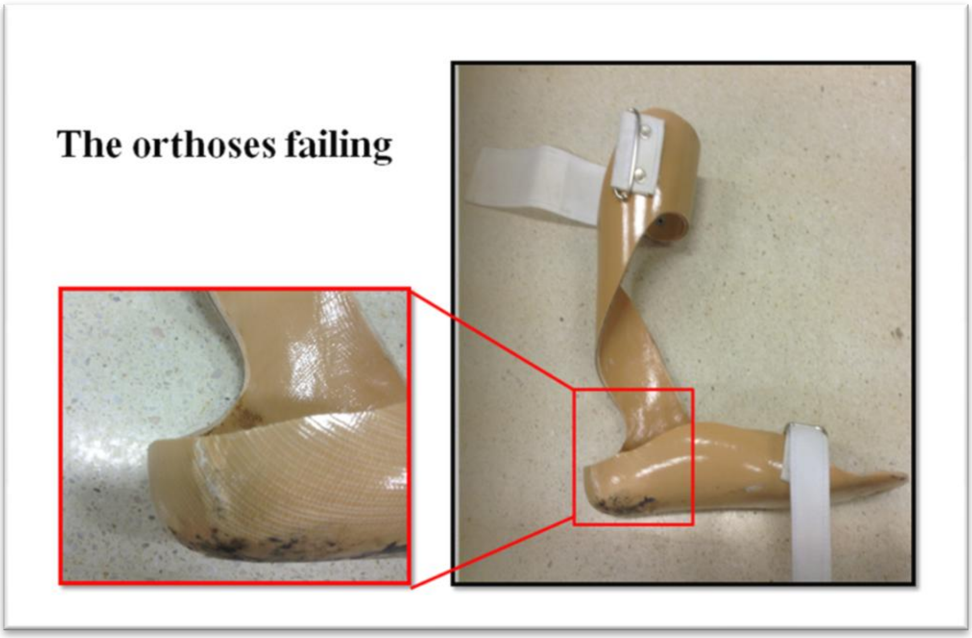


Figure 4.20 The orthoses failing

The fatigue characteristics of the spiral ankle foot orthoses have been analyzed by the cyclic tester. The failure or decay of mechanical properties after repeated applications of stress. Fatigue tests give information on the ability of a material to resist the development of cracks, which eventually bring about failure as a result of a large number of cycles.

Table 4.6 The time of orthoses (Years)

Spiral AFO	**Figure test (Cycles)**	**Time of Orthosis Years**
Carbon fiber reinforcement	482,351	0.24
Silk fiber reinforcement	386,527	0.19
Average Patient Walking Activity Approaches 2 Million Cycles / Year		

In this study, spiral ankle foot orthoses was fiber failure at the heel. The fatigue characteristics of spiral ankle foot orthoses made from 2 ply reinforced carbon fiber testing without shoes the shoes had 482,351 cycles = 2.88 months. spiral ankle foot orthoses made from 2 ply reinforced silk fiber testing without shoes had 386,327 cycles = 2.28 months.

Table 4.7 The time of orthoses with the shoes (Years)

Spiral AFO	**Figure test (Cycles)**	**Time of Orthosis (Years)**
Carbon fiber reinforcement	1,983,283	0.99
Silk fiber reinforcement	1,972,435	0.98
Average Patient Walking Activity Approaches 2 Million Cycles / Year		

The fatigue characteristics of Spiral ankle foot orthoses made from 2 ply reinforced carbon fiber testing without shoes the shoes had 1,983,283 cycles = 11.88 months. Spiral ankle foot orthoses made from 2 ply reinforced carbon fiber testing without shoes the shoes had 1,972,435 cycles = 11.76 months.

This study demonstrated that definitive laminated composite material silk fiber with resin had a higher specific tensile strength than carbon and glass fiber polymer composite. Hardness and elongation at break is comparable to carbon and glass fiber polymer composites. Furthermore, the morphology of silk fiber composites showed that silk fibers adhered to resin better than carbon fibers and glass fibers did. There were no significant difference in the fatigue characteristics of Spiral ankle foot orthoses between 2 ply reinforced carbon fiber and silk fiber.

4.5 Participants

A sample of 6 participants (4 males; 2 females) met the inclusion criteria of the study. The mean age was 58.16 years (range 48-65) and the mean time since stroke was 26.83 months (range 10-52). The mean Body Mass Index (BMI) was 22.18 years (range 26-16). Right hemiparesia was identified in 3 participants, whereas 3 presented left hemiparesia. Scandinavian Stroke scale (SSS) score for lower extremity motor strength (Lindenstrem, E , 1991), subjects had to have strength in lower limbs of at least 4, raise leg with flexion in knee (moderate paresis) to 5, raise leg straight but with reduced strength (mild paresis). Subject's characteristics are shown in Table 4.8.

Figure 4.21 Spiral Ankle Foot Orthoses
(a) Frontal view, (b) Lateral view, (c) Median view, (d) Posterior view

Table 4.8 Subject characteristics

Subject No.	Sex	Age (yrs)	BMI	Time since stroke (months)	Affected hemisphere	Stroke type	SSS	Use of Assistive Device	Prior AFO Use
1	M	48	25	25	Right side	Ischemic	5	No	Y (Rigid - AFO)
2	F	63	26	20	Right side	Ischemic	5	No	Y (Rigid - AFO)
3	F	65	16	10	Right side	Ischemic	4	No	Y (Flexible-AFO)
4	M	56	24	27	Left side	Ischemic	4	No	Y (Rigid - AFO)
5	M	60	24	52	Left side	Hemorrhage	4	No	Y (Rigid - AFO)
6	M	57	18	27	Left side	Hemorrhage	4	No	Y (Rigid - AFO)

Abbreviations: F=Female, M= Male, Y=Yes, SSS= Scandinavian Stroke scale

Table 4.9 The satisfaction score of spiral ankle foot orthoses with carbon fiber reinforcement

Subject	Number of assessment items								
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	2.1	2.2
1	4	4	4	4	4	4	4	4	4
2	4	3	4	3	4	3	3	3	4
3	4	3	3	3	3	3	4	3	3
4	3	3	3	3	4	3	3	2	3
5	4	2	4	3	5	4	3	3	3
6	4	4	4	3	4	4	4	4	3
MEAN	3.83	3.17	3.67	3.17	4.00	3.50	3.50	3.17	3.33
S.D.	0.41	0.75	0.52	0.41	0.63	0.55	0.55	0.75	0.52

Table 4.10 The satisfaction score of spiral ankle foot orthoses with silk fiber reinforcement

Subject	Number of assessment items								
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	2.1	2.2
1	5	5	5	5	5	5	5	5	5
2	5	5	4	4	4	4	4	5	4
3	4	4	5	4	5	5	5	5	4
4	4	4	4	5	4	4	5	5	5
5	5	5	5	5	5	4	5	5	3
6	5	4	4	4	5	5	5	5	4
MEAN	4.67	4.50	4.50	4.50	4.67	4.50	4.83	5.00	4.17
S.D.	0.52	0.55	0.55	0.55	0.52	0.55	0.41	0.00	0.75

Table 4.11 Mean and SD score of the satisfaction of spiral ankle foot orthoses

Assessment items	Carbon fiber			Silk fiber		
	Mean	SD.	Result	Mean	SD.	Result
1. Product						
1.1 The quality and standards of the orthoses.	3.83	0.41	Average	4.67	0.52	Good
1.2 The weight of the orthoses.	3.17	0.75	Average	4.50	0.55	Good
1.3 The suitability of the material used for orthoses.	3.67	0.52	Average	4.50	0.55	Good
1.4 Comfort during use of orthoses.	3.17	0.41	Average	4.50	0.55	Good
1.5 Ensured safety during use of orthoses.	4.00	0.63	Good	4.67	0.52	Good
1.6 The strength of the orthoses.	3.50	0.55	Average	4.50	0.55	Good
1.7 Satisfaction of use in everyday life.	3.50	0.55	Average	4.83	0.41	Good
2. Price						
2.1 Orthoses price compared to quality.	3.17	0.75	Average	5.00	0.00	Excellent
2.2 Maintenance cost of the orthotic.	3.33	0.52	Average	4.17	0.75	Good

Satisfaction of spiral ankle foot orthoses

This study's secondary outcome was to compare satisfaction of spiral ankle foot orthoses with silk fiber reinforcement and with carbon fiber reinforcement. A questionnaire was used as the tool in this research. The samplings were the 6 patients in rehabilitation at the Physical Therapy Clinic at Songklanakarin Hospital. The investigation and analysis took place between June and January 2013. Data was analyzed by using SPSS program. The statistics used were, namely, percentage, mean and standard deviation (S.D).

Table 4.12 The satisfaction of spiral ankle foot orthoses

Assessment items	**Carbon fiber**					**Silk fiber**				
	5	**4**	**3**	**2**	**1**	**5**	**4**	**3**	**2**	**1**
1. Product										
1.1 The quality and standards of the orthoses.			/				/			
1.2 The weight of the orthoses.			/				/			
1.3 The suitability of the material used for orthoses.			/				/			
1.4 Comfort during use of orthoses.			/				/			
1.5 Ensured safety during use of orthoses.			/				/			
1.6 The strength of the orthoses.		/					/			
1.7 Satisfaction of use in everyday life.			/				/			
2. Price										
2.1 The orthoses price compared to quality.			/			/				
2.2 Maintenance cost of the orthotic.			/				/			

5= Excellent, 4= Good, 3= Average, 2= Below average, 1= Poor

The results found were that there were 6 males (66.67 %) and 2 females (33.33%) in rehabilitation in the Physical Therapy Clinic at Songklanakarin Hospital. The patients′ satisfaction of admission and evaluation of spiral ankle foot orthoses with silk fiber reinforcement was reported as being highly satisfied. The highest mean score were on the orthoses price compared to quality.

In silk fiber reinforcement, there was high satisfaction on "the orthoses price compared to quality". All subjects appeared to compare the reinforcement of spiral ankle foot orthoses, which was found to have an excellent silk fiber reinforcement. They were similarly satisfied on "the strength of the orthoses" and " maintenance cost of the orthotic" when comparing silk fiber reinforcement with carbon fiber reinforcement. Most gave a higher score to silk fiber reinforcement than carbon fiber reinforcement.

The result of comparing spiral ankle orthoses satisfaction between silk fiber reinforcement and carbon fiber reinforcement was different at more than 0.05 level of no difference significance.

4.6 Economic Justification

Table 4.13 Economic Justification

Material	Price	
	Carbon Composite AFOs	Silk Composite AFOs
Plaster Powder	50 Baht	50 Baht
Resin	800 Baht	800 Baht
Hardener	30 Baht	30 Baht
PVA Bag	300 Baht	300 Baht
Perlon Stockinet	300 Baht	300 Baht
Fiber Reinforcement	1,000 Baht	100 Baht
Total	**2,480 Baht**	**1,580 Baht**

When the price of spiral ankle foot orthoses was compared between carbon fiber composite and silk fiber composite, it could be seen that the fabrication of silk fiber had a low cost when compared to other synthetic fibers. Specifically, silk fiber reinforcement was 10 times cheaper than carbon fiber reinforcement.

Composite material of silk fiber with resin had a higher specific tensile strength than carbon and glass fiber polymer composites. Hardness and elongation at break were comparable to those of carbon and glass fiber polymer composites. Furthermore, the morphology of silk fiber composites showed that silk fibers adhere with resin better than carbon fibers and glass fibers do. So, silk composite material is the choice for ankle foot orthoses.

CHAPTER 5

RESEARCH CONCLUSION

5.1 Material properties

Silk fiber with resin has lightweight physical characteristics. It has a higher specific tensile strength when compared with fiber glass and carbon fiber. Hardness and elongation at break are similar for the three types in the same number layer of fiber reinforcement.

In this study, it was determined that the mechanical properties of silk fibers indicate that such a material has the potential to be a replacement for carbon fiber and fiber glass on resin lamination. Furthermore, silk fiber is a material that is recyclable, potentially abundant, more environmentally friendly and low cost when compared with synthetic fibers. Therefore, using silk fiber composites results in improved durability and reduced overall weight. The Bombyx silk polymer composites are natural composites that are very high-quality and can be the alternative choice for prosthetics and orthotics. Moreover, the low price and the fact that they are not harmful to patients are important reasons. Therefore, silk fiber composite reinforcement material is a promising material for medical applications.

Silk fiber reinforcement can be the alternative choice for prosthetics and orthotics. The properties of silk composites materials in all ply are that they have higher thickness than synthetic fibers, Young's Modulus, hardness, elongation at break and specific tensile strength. 2 ply Silk fiber composites have the highest tensile strength and fatigue of any material. As for the morphology of materials, the silk fiber composites adhere with resin better than carbon fibers and glass fibers do.

5.2 Ankle foot orthoses properties

The ankle foot orthoses with silk fiber reinforcement have maximum force in the result of compression force on vertical force and lateral force. However,the spiral ankle foot orthoses with carbon fiber reinforcement can return to shape more than the the ones with silk fiber reinforcement can. In this study, The fatigue characteristics of spiral ankle foot orthoses with carbon fiber reinforce had cycles more than 2 ply silk fiber reinforce in no shoes.

5.3 Participants

The subjective feedback provided by the subjects produced some interesting results. In question 2.1 “The orthoses price compared to quality” all subjects appeared to compare the reinforcement of the orthoses, which was found to have an excellent silk fiber reinforcement. All silk fiber reinforcement question scores were higher than those for carbon fiber reinforcement.

The price of the orthoses with silk fiber composites was much lower than that of the ones with carbon fiber composites. Silk fiber reinforcement was ten times cheaper than carbon fiber reinforcement.

RECOMMENDATION AND FUTURE STUDY

A limitation with our study was that our sample size was small (n=6). General characteristics of the study population are presented in Table 4.8. The findings and conclusions of this thesis were limited to the population who used ankle foot orthoses and had the ability to walk without some gait aid. The fatigue tester was not exactly the normal gait cycle (fatigue machine), however it gave a good indication of the load that can be applied to the affected limb and the type of breakdown that can occur.

The dissertation presents critical content regarding the method of development of Bombyx silk fibers to replace carbon fiber and fiber glass on resin lamination and to test the effectiveness of spiral ankle foot orthoses on patients. Further research on this subject may be extended into two steps. Firstly, there is a need to study the morphological, physical and mechanical properties performed in vitro mechanical and biological tests to ensure sufficient biomechanical performance using finite element method. Secondly, the animal model should be performed after the in vitro test to validate the possibility of gait analysis on a patient.

In this study, comparisions were made of fiber reinforcements in ankle foot orthoses. Gait analysis testing appropriate more than useing in a questionnaire.

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