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To cite this article: M H Nurhanisah *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **368** 012050

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Mechanical properties of laminated kenaf woven fabric composites for below-knee prosthesis socket application

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Abstract. Prosthesis is a process of creating artificial human body part. The primary function of below-knee prosthesis is controlling the leg during static and dynamic conditions. The aim of this study is to develop a prosthetic socket made from kenaf-glass fiber composite. The development of prosthetic socket with kenaf-glass fiber was carried out as an attempt to substitute prosthetic socket made from fiberglass polyester composites. Lamination method was adopted to fabricate the prosthetic socket. The laminates contain woven kenaf, glass silk knitted fabric and nylon knitted fabric. The effect of kenaf fabric layering sequence on the volumetric and mechanical properties were evaluated. The flexural and impact strength of 2 layers of kenaf fiber-based laminates are 7.11 MPa and 16.7 kJ/m^2 respectively which is higher than the single layer kenaf fabric-based composites. From the results woven kenaf fabric composites has the potential to replace the existing glass fabric-based polymer composites. It is a great initiative to fabricate a prosthetic socket which biodegradable, environmental friendly, locally available, lightweight, comfortable and psychosocially acceptable.

1. Introduction

Natural fibers as a reinforcement in composite materials gaining more attention among researchers and industries due to good mechanical strength, biodegradability, renewability, environmental friendly and cost reduction than synthetic fibers [1]. Natural fiber has a potential to be developed as an alternative t o replace the synthetic fiber composites. Natural fiber composites nowadays are getting acceptance in many medical device applications. For instance, Irawan et al. has developed the prosthetic socket mad e of ramie fiber reinforced epoxy composite [2]. Also the studies found bamboo fiber reinforced comp osites have the potential to replace with cotton and nylon composites in orthotic and prosthetic laminat ions [3]. In the other study [4], the authors revealed the opportunity to further development in rattan fi ber as above knee prosthetic socket.

Kenaf or Hibiscus cannabinus L. is plant that traditionally is used for twine, rope and coarse cloth [5]. Kenaf fibers are new type of economic crop and has gained a world attention in many application of eco-friendly assets such as automotive, furniture, sports industries and food packaging [6]. It has excellent fiber strength and great potential to be used as industrial materials and competing with hemp and flax in global market [7]. Since kenaf fiber has superior mechanical properties it could be a potential reinforcement in the polymer matrix instead of Glass. Also it is locally available, renewable, eco-friendly and low cost material [8].

The prosthesis is an artificial extension that replaces a missing body part, such as an upper or

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lower body extremity [9]. Therefore, the prosthesis must be comfortable to wear, easy to don and doff, cosmetically pleasing, light in weight, durable, function well and offer easy maintenance. Limb prosthesis characteristically has three main parts, which are interface, components and cover. As for the prosthetic legs, they consist of a socket, pylon and foot, which make up the main parts. The prosthetic leg socket is the uppermost part of a prosthesis that makes contact with the residual limb and transfers the forces of walking to the ground. Thus, the material of a prosthetic socket is the most important in determining the quality of fitting. Prosthetic socket basically made from glass fiber composite material. Fiberglass is a strong and lightweight reinforcement used in composites. However, few drawbacks have found in fiberglass due to disadvantages issues such as non-environmental friendly, expensive, and high hardness [10-11].

Previous study has mentioned that the incorporation of woven kenaf fibres in the lamination socket could improve the mechanical properties of prosthetic socket [12]. In this study, prosthesis socket has been made by laminated process with the different numbers kenaf layers in the composite. Therefore, the study was conducted by comparing two samples represent as composite A which has one layer of kenaf and composite B which composed of two layers of kenaf to determine the mechanical strength of woven kenaf fabric composite. The flexural and impact tests were conducted for this research. In determining the material's ability to resist deformation under load, the flexural tests were required due to the reason that prosthesis should be functioning exactly or at least emulate closely the missing limbs or body parts [13]. The flexural modulus is a measure of the resistance to deformation of the composite in bending [4]. The flexural strength analysis done for prosthetic socket to identify the strength needed to support the body weight and extreme movement when the patient walks with it [4].

2. Material and method

2.1 Materials

The kenaf woven fiber, with a linear density of 150 tex for its yarns, were supplied by Sri Jentayu Sdn. Bhd. (Kuala Lumpur). Glass-silk, helanca and polyvinyl alcohol (PVA) knitted fabrics were obtained from Endolite Sdn. Bhd. The acrylic resin and härterpulver UN 3106 hardener which also obtained from Endolite Sdn. Bhd. The hexagon mould was used as positive cast and the materials such as PVA film, helanca stockinette and glass silk stockinette were used in layering as same as laminated fabrication of prosthetic socket.

2.2 Fabrication of laminated composites

Kenaf woven composite laminates were produced using vacuum infusion in room temperature (25 – 30°C). The laminated composite is shown in Figure 1. Two PVA film are used as the first layer to form a separator between liner and mould, and the second is to enclose the whole layup and to hold the resin together in reinforcing materials [14]. The glass-silk knitted fabric provides strength to the socket and the helanca knitted fabric improves the elasticity of the composites. Two types of composites namely; composites A and B, with different kenaf fiber content were fabricated. The composite A was produced with 6 layers of different materials while the composite B was produced with 7 layers different materials included woven kenaf. The Figure 2 shows the arrangement of composites A and B. The vacuum processor with 60 kPa is used to remove the air trapped during the lamination process.

Figure 1. The laminated of woven kenaf composite in hexagon mould using vacuum infusion.

Composite A
Polyvinyl Alcohol (PVA)
Helanca Stockinette
Kenaf Woven
Glass Silk Stockinette
Helanca Stockinette
Polyvinyl Alcohol (PVA)

Composite B
Polyvinyl Alcohol (PVA)
Helanca Stockinette
Kenaf Woven
Kenaf Woven
Glass Silk Stockinette
Helanca Stockinette
Polyvinyl Alcohol (PVA)

Figure 2. The sequence of material layer in Composite A and B.

3. Characterization of the composites

3.1 Volumetric composition

Prior to analysis of the mechanical properties of the composite laminates, the precise volume determination of the reinforcement and matrix is important for further analysis of the mechanical properties. To this end, the weight fraction and accurate density of the compositions need to be measured. First of all, the aerial weight (i.e, mass) of the composites and compositions were measured.

The composites and compositions were cut in to the size of 23×4 cm^2 and weighed precisely (±0.0001 g). The aerial weight of the kenaf woven fabric was obtained from the data sheet of the supplier. In order to measure the aerial weight of the knitted reinforcements accurately, they have been stretched and cut into the required dimensions. The average aerial weight of the composite and constituents are given in Table 1. The mass of the matrix for each composite was calculated by subtraction of the total mass of the reinforcements from the mass of the composite.

Table 1. The aerial weight and density of the composites and constituents.

	Composite A	Composite B	Kenaf woven fabric	Glass silk stockinette	Helanca stockinette	PVA film	Matrix for composite A	Matrix for composite B
Aerial weight (g)	21.48	26.57	1.18	1.52	0.5848	0.9607	15.70	19.60
Density (g/cm^3)	1.23 (0.02)	1.25 (0.01)	1.51 (0.04)	2.88	1.12 (0.01)	1.18 (0.00)	1.18	1.18

By knowing the number of laminates, mass of the composites, and composite compositions, the weight fraction of the compositions can be calculated by dividing the mass of the constituents to the mass of the composite. The density of the composites, kenaf woven fabric, glass silk stockinette, helanca stockinete, PVA film, and cured matrix were measured by using the Mettler Toledo (XS205) density kit. It is important to note that glass silk stockinette is a spun yarn that made of glass yarn and silk yarn. During the sampling for density measurement the care should be taken into account in a way that the sample contains both glass yarn and silk yarn. Distilled water was used as an immersion liquid and its temperature was controlled before each measurement for correction of the distilled water density. For determination of the cured matrix density, first the acrylic resin mixed with hardener in the petri dish with the same ratio that used for fabrication of the composites, and then the mixture was put under the vacuum for 1 hr to remove the air bubbles inside the matrix. Minimum six samples with the size of 2×2 cm were cut for measurement of the density. Finally, the volume fraction of the compositions and void were calculated by using the following equations 1 and 2.

$$V_i = \frac{\rho_c}{\rho_i} W_i \qquad (1)$$

$$V_v = 1 - \sum V_i \qquad (2)$$

where, V_i is the volume fraction of the composition, ρ_c is the density of the composite, ρ_i is the density of the composition, W_i is the weight fraction of the composition, and $V_v$is the void volume fraction.

3.2 Flexural properties

Figure 3 shows the set up for the flexural tests. Two types of composites were tested using the three-point bending test according to the the EN ISO 14125 standard by using the 5kN Instron 4201 Universal Testing Machine. The tests were done under the laboratory condition with temperature 23 ± 2 ºC and relative humidity of 50 ± 10%. The load was applied midway between the supports with a crosshead speed of 2.2 mm/min and each sample was loaded to failure. Based on the standard the dimensions of the specimens for flexural testing were cut into the size of 40 mm x 7 mm (length x width). Figure 4 shows the total of specimen for flexural tests. The average values were reported including standard deviations.

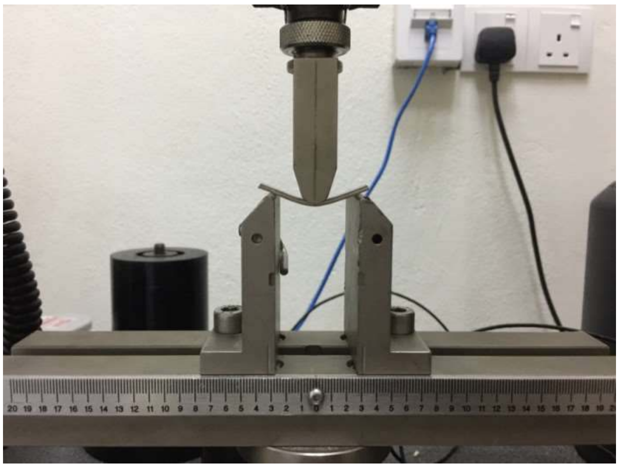

Figure 3. Flexural specimen tests

3.3 Impact properties
Impact specimens were tested using Instron CEAST 9050 Pendulum Systems (IZOD IMPACT TESTER) with 2.75 joules pendulum. Test samples were prepared based on ISO 180:2000 (E) which are 80 x 10 x 4 mm (length x width x thickness). The energy required to break the sample was divided by unit area of residual cross section of sample to obtain impact resistance value [15].Impact resistance was calculated by using the following equation 3:

$$^{a}\text{iN} = \frac{\text{Ec}}{h.b}\, x10^3 \qquad (3)$$

Where,

Ec = corrected energy, in joules, absorbed by breaking the test specimen;

h = thickness of the specimen (mm)

b = width of the specimen (mm)

3.3 Walking ability testing
Each prosthetic socket prototype was tested to determine the comfort level. Respondent was asked to use the prosthetic socket and evaluate the comfortability of each prosthetic socket. Test results were compared between one layer and two layer of laminated kenaf woven fabric composites.

4. Results and discussion

4.1 Volumetric composition
Table 2 shows the weight fractions and volumetric compositions of the composites A and B. The void content for composite A and B is 0.00 and 0.02 respectively. It indicates that the composites have good quality. In general, the composites with void content in the range of 0-2% considered as a high quality composites [16]. In addition, the 2% void content in composite A is due to its lower volume fraction of matrix compared to composite B. As can be seen in Table 2, the volumetric composition values for glass silk knitted fabric, Helanca knitted fabric and PVA film of composite B is less than composite A, eventhough same number of reinforcement layer were used for both composites. This is attributed to the higher total volume of the composites B due to using of high kenaf fiber content.

Table 2. The determined fibre weight fractions, density and volumetric composition of the manufactured composite A and composite B.

Composite	Weight fraction					Volume fraction					
	Kenaf woven fabric	Glass silk knitted fabric	Helanca knitted fabric	PVA film	Matrix	Kenaf woven fabric	Glass Silk knitted fabric	Helanca knitted fabric	PVA film	Matrix	Void
A	0.06	0.07	0.05	0.09	0.73	0.04	0.03	0.06	0.09	0.76	0.02
B	0.09	0.06	0.04	0.07	0.74	0.07	0.02	0.05	0.07	0.78	0.00

4.2 Flexural Properties

The failure of the samples was observed under the flexural loading. The composites samples failed due to the failure in the tension side of the samples. Figure 4 shows the flexural stress-strain trend for composites A and B. Both composites showed ductile behavior. The considerable improvement in maximum stress and failure at ultimate strain can be seen in composites type B. Addition of 2 layers of kenaf layers in the composite B increases the bending resistance of the composite B.

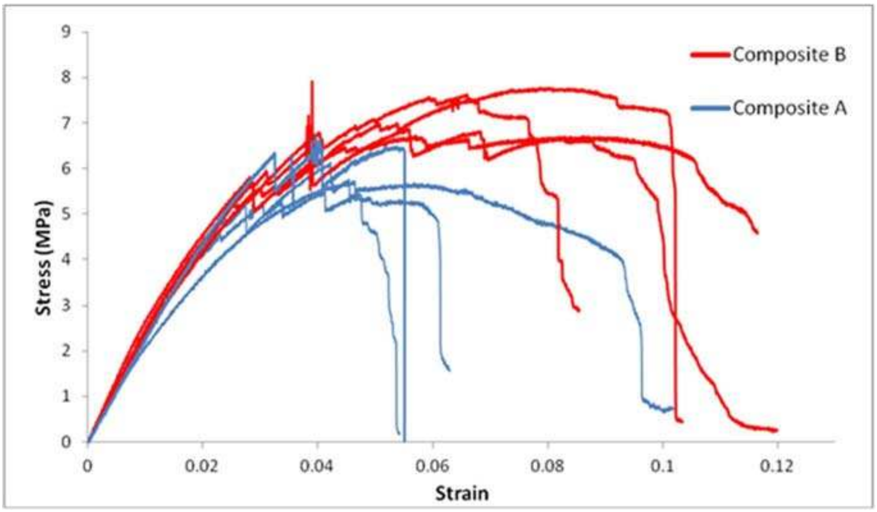

Figure 4. The flexural stress versus strain curves for composites A and B.

Figure 5 shows the flexural modulus for composites A and B. The flexural modulus for composite B (234.6 MPa) is slightly higher than composite A (229.6 MPa). It means that flexural modulus improved 2% by addition of 1 layer of kenaf fiber in composite B.

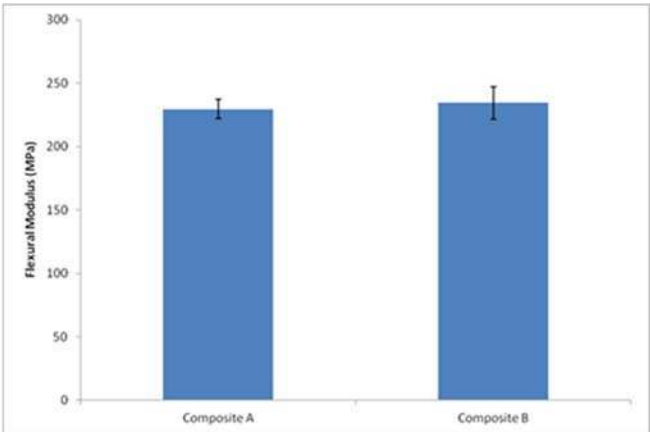

Figure 5. Flexural modulus of Composite A and B

Figure 6 shows the average values of the flexural strength of composite A and B. As can be seen the flexural strength of composite B (7.11 MPa) is 13.64 % higher than composite type A (6.14 MPa). This may be due to the fact that cellulose molecules in the kenaf fabric made a strong hydrogen bond with the matrix.

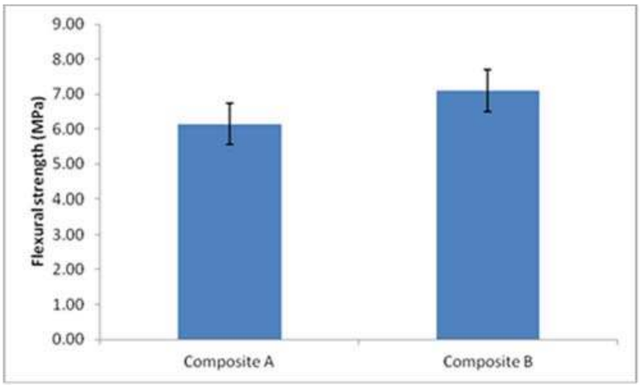

Figure 6. Flexural strength of Composite A and B

4.3 Impact properties

The impact strength of kenaf fiber woven composite is presented in Figure 7. The impact strength of composite A is 15.39kJ/m^2 whereas for composites B it is 16.7 kJ/m^2. Therefore, the results showed that two layers of kenaf woven composite provide better impact for prosthetic socket material. Addition of 2 kenaf layers in the composite B enhances the dissipation of kinetic energy. The prosthesis socket material needs to have an excellent ability on impact force which provides safety and unbreakable material while having impact load from the residual limb[4].

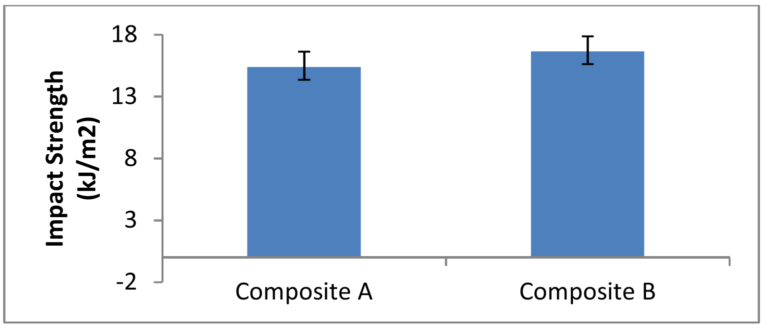

Figure 7. Impact strength of Composite A and B

4.4 The prosthetic socket ability testing

Figure 8 shows the prosthetic socket made from kenaf woven fabric composite has been attached with a human leg. The Ability of the artificial prosthetic socket has been evaluated during static and dynamic conditions. The patient felt that this prosthetic socket is more comfortable and easy to remove and refit. The feedback from the patient showed that prosthetic socket has great ability to donning by patient.

Figure 8. Patient donning the prosthetic socket made from kenaf woven fabric composite

4.5 The significance of incorporating single and double layer of kenaf in laminated composite for prosthetic leg socket

Based on result of volumetric, flexural and impact testing, the incorporation of double layer of woven kenaf fiber has shown better mechanical properties than single kenaf layer based composites. The mechanical properties are required in determining the material for prosthetic socket fabrication which should to be works as following the missing body parts [13] which expected to replace the function of lost leg.

Flexural strength is used to determine the mechanical properties of restorative materials [17]. It is important to determine the material design and flexural properties [18], due to the ability of the composite to withstand bending forces and rapture in surface of composite. The suitable material composite needs to provide an ability to endure bending forces from body weight of wearer which some activities might causes the breaking part of prosthetic socket. Therefore, the result for this study shows good properties by incorporating two layers and it could increase the ability on resist breaking by energy load at the prosthetic socket surface.

The durability of material is highly concerned in prosthetic leg socket because the physical capability of wearer might be limited due to their condition and a better impact strength could provide a benefit to active wearer as well. Thus, in composite B, which provide 2 layers of kenaf shown the better impact properties which provide resist fracture under stress applied in any stress and resist breaking under a shock load [19].

5. Conclusion

Kenaf fiber based prosthetic socket showed better mechanical properties and comfort. Therefore, kenaf woven fabric composite has the potential to develop below knee prosthetic socket as an alternative material to the existing pure glass fiber based prosthetic socket. The kenaf woven fabric composite offer good strength, environmental friendly and improves the aesthetic value of the product.

Acknowledgement

The authors gratefully thankful to Ministry of Higher Education for providing Exploratory Research Grant Scheme (ERGS) - 5527184.

IOP Conf. Series: Materials Science and Engineering **368** (2018) 012050 doi:10.1088/1757-899X/368/1/012050

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