MECHANICAL PROPERTIES OF PINEAPPLE LEAF FIBER REINFORCED POLYMER COMPOSITES FOR APPLICATION AS A PROSTHETIC SOCKET

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ABSTRACT

Biodegradable fibers derived from natural plants are abundantly available and are currently considered as waste. This study aims at investigating the mechanical properties of pineapple leaf fiber reinforced thermoset composites as possible alternatives to the above-knee glass fiber reinforced prosthetic socket. This study was carried out according to ASTM (2004) standards at temperature and relative humidity of 26 ± 3 °C and $51 \pm 2\%$, respectively. Continuous pineapple leaf fibers are treated with sodium hydroxide and acetic acid, and then added to epoxy and polyester at varying fiber loadings of 0, 20, 30, 40 and 50% to produce fiber reinforced composites using the hand lay-up method. The mechanical properties of glass fiber polyester composite (GFPC) were compared with pineapple leaf fiber polyester composites (PLPC) and pineapple leaf epoxy composites (PLEC). The results showed that PLEC, particularly at 40% fiber loading, had superior mechanical properties than GFPC and PLPC. The tensile, flexural and impact strengths of PLEC are 76.47 ± 3.85 MPa, 81.27 ± 1.77 MPa and 59.03 ± 0.99 k/Jm^2, respectively. These values are higher than those of PLPC with tensile, flexural and impact strengths of 62.09 ± 4.47 MPa, 53.02 ± 1.20 MPa 45.22 ± 1.10 k/Jm^2, respectively. The tensile, flexural and impact strengths of GFPC are also lower and are respectively 59.03 ± 0.99 MPa, 66.10 ± 1.88 MPa and 52.48 ± 1.77 k/Jm^2. Thus, PLEC has the potential to be further developed as a replacement for glass fiber in above-knee prosthetic sockets.

***KEYWORDS**: Pineapple leaf fiber; fiber; glass fiber; sodium hydroxide; thermoset; acetic acid; mechanical properties*

1.0   INTRODUCTION

Prosthesis, an artificial device that replaces missing parts of the body, is usually used in cases of disfigurement, accident and disease. Of all the major types of prosthesis, the above-knee prosthetic socket is the most difficult to maintain (Rosalam, Rahinah & Paridah, 2011). Above-knee, also called transtibial, amputees, according to Arvela, Albck, Aho, Venermo and Lepntalo (2010) require up to 80% additional energy to assume normal ambulation than a healthy person.

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Above-knee prostheses, as shown in Figure 1, can be classified into: the foot, used in ambulation; the suspension system, which enables the wearer to move at the desired degree; the pylon that connects the foot and the suspension system, which bears body weight; and the socket, an interface connecting the wearer and the prosthesis. An ideal socket must be lightweight, easily worn and removed, biocompatible, resist impact and stress in all directions, relatively cheap and easily available (James et al., 2009). Because it is constantly put on and taken off, the socket wears out easily and needs to be replaced periodically.

Most imported prosthetic sockets are made from polymeric materials reinforced with synthetic fibers such as Aramid, carbon, fiber glass and silicon. These prosthetic sockets cost between $531 and $1,700 depending on the quality and aesthetic appeal (Kobayashi et al., 2010). This seems too expensive for most prosthetic users, especially in developing nations such as Nigeria. However, according to Highsmith, Carey, Koelsch, Lusk and Maitland (2009), 20% of the cost of a prosthetic leg is dependent on the cost of the socket, excluding the workmanship of the prosthetic leg. Therefore, if this 20% of the cost could be reduced, then it would greatly reduce the total production cost of the prosthesis. Hence, this study aims at fabricating a lower limb prosthetic socket from polymers reinforced with agro-biomass such as pineapple leaf fibers to replace the non-recyclable synthetic fibers reinforced prosthetic socket. This will relatively reduce the cost of production and will make the synthetic fibers more readily available, and environmentally and user friendly.
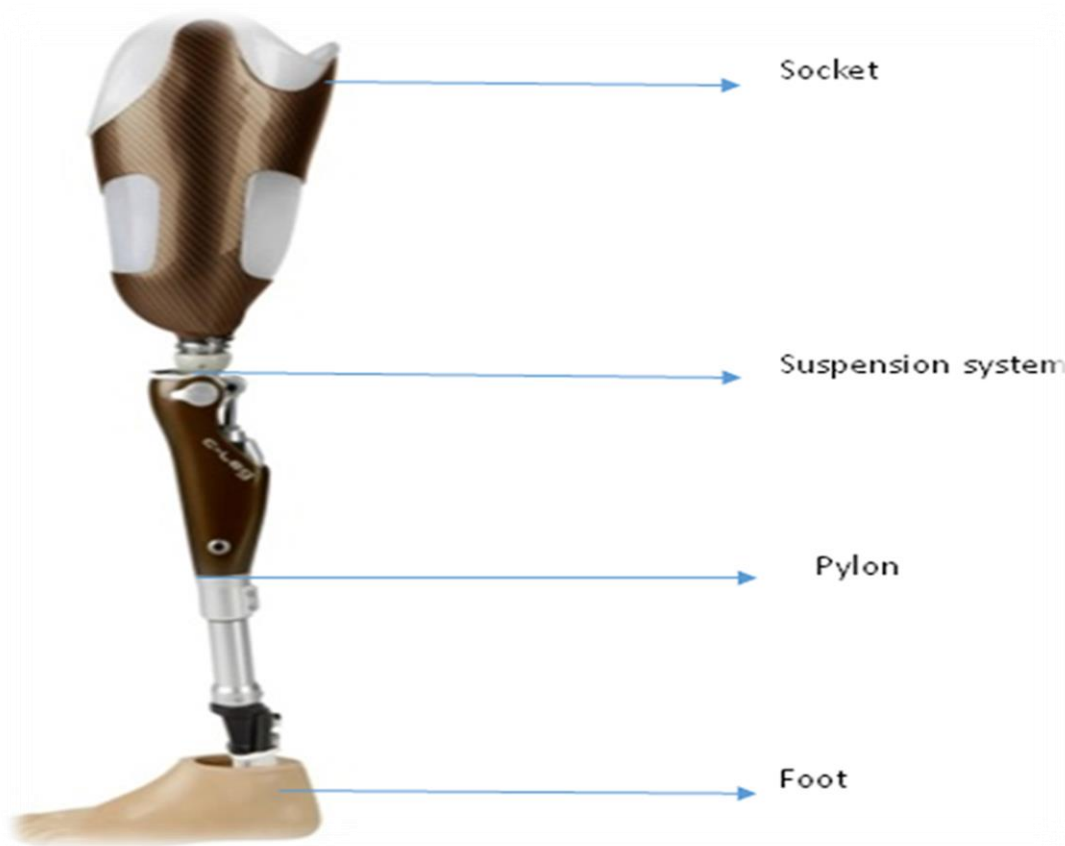

Figure 1. Above-knee prosthesis (ICRC, 2006)

Thermosets such as epoxy and polyester are cheap, offer high-impact strength, rigidity, and modulus of elasticity, and thus are extensively favored in orthotic and prosthetic industries. Although natural plant fibers are yet to parallel the strength of synthetics, plant fibers such as ramie, jute, bamboo and pineapple, which have a high cellulose content, have proved to be very successful, especially in low-strength applications. Moreover, compared with the non-renewable sources of synthetic fibers, natural fibers such as pineapple leaf fibers are readily available and are harvested yearly, making these sources renewable and inexhaustible (Begum & Islam, 2013).

According to the Food and Agricultural Organization (FAO) (FAO, 2005; IITA, 2014) pineapple contributes to 20% of the world production of tropical fruits, and, as a crop, is second only to banana as the most important harvest fruit. Nigeria produces 889,000 tons of pineapple fruits annually, which makes the country the top producer of the fruit in West African countries and the 6th largest global producer after Thailand, the Philippines, Brazil, China and India (IITA, 2014). After the pineapple fruit is harvested, the leftover leaves are often left fallow, burned or buried. This approach is not an accepted healthy means of waste disposal (IITA, 2014). This improper incineration presents an enormous environmental threat by increasing global warming through emission of poisonous gases such as carbon monoxide (CO), sulfur dioxide (SO_2), unburnt CH_4 and nitrogen oxide (NOx).

With proper processing, these leftover leaves can be converted into something useful, such as through vermicomposting and by fibers being used as reinforcement for composite production (Navdeep, Khalid and Sona, 2012). Although the lingo-cellulosic nature of the plant fibers usually result in a poor adhesion between highly hydrophobic thermoset and hydrophilic plant fibers, this can be rectified with appropriate surface treatment such as alkalization and acetic acid. With chemical treatment, moisture absorption stops, cross linkage in the interface increases, fiber surfaces become rougher and, ultimately, a significant increment in mechanical properties parallel to the synthetic fibers can be obtained (Navdeep et al., 2012).

The present study focuses on using pineapple leaf fiber as reinforcement in thermoset composites using the low-cost hand lay-up method. Pineapple leaf fibers, which are eco-friendly and abundantly available at low cost, are being investigated to replace the expensive and non-environmentally friendly synthetic glass fiber currently being used for the production of above-knee prosthetic sockets. Hence, a less expensive and high-quality prosthetic socket using low-cost polymeric material reinforced with pineapple leaf fiber will be produced. This will be a huge relief to prosthetic seekers, especially in an emerging nation like Nigeria with income per capital as low as $1500 per year (News, 2014).

2.0   MATERIALS AND METHODS

2.1   Pineapple Fiber Preparation

Pineapple leaves were locally sourced at Oko-Oba village, near Ibadan, Oyo State, Nigeria. Polyester resin (methyl 2-methylpropenoate resin), cobalt naphthenate catalyst, and methyl ethyl ketone peroxide (MEKP) hardener were sourced from Ojota, Lagos, Nigeria. Sodium hydroxide (NaOH), acetic acid, Epoxy TKL-121 (a bisphenol resin

derived from organic compounds containing bisphenol A and di-glycidyl-ethers, BADGE) and hardener DETA (diethylenetriamine) were also obtained from Ojota, Lagos, Nigeria.

The fibers were separated from the matrix leaves using a specially decorticated machine in order to save time since more than 7 kg of pineapple fiber could be produced with the use of this machine (Das, Nag, Debnath & Nayak, 2009). The decorticating pineapple leaf fiber machine removed the waterproof outer layers before the fibers were passed through the retting stage. With retting, the fibers were soaked in clean water, constantly checked by hand-touching and were removed when the fibers perceptibly separated from the matrix after 14 days.

The fibers were washed thoroughly in water and subsequently sun dried. The pineapple leaf fibers (PALF) were immersed in a 5% alkaline solution. NaOH) prepared using a ratio of 1.5 liters to 100 g (liquid: fiber) for 30 minutes. To neutralize the effect of the alkali and further strengthen the PALF, a solution of 2% acetic acid solution was used to treat the PALF for 1 hr. After treatment, the pH of the solution was determined using a pH meter and the pH was found to be 4. The fibers were further washed thoroughly in water to remove embedded chemicals, sun dried, and subsequently dried in an oven at 70°C for 4 hours to finally obtain continuous pineapple leaf fibers, as shown in Figure 2.

2.2   Production of Composites

Continuous PALF, as shown in Figure 2, used in this fabrication were within the thickness and width range of 3 ± 0.4 mm with a symmetrical fiber orientation. The composite fabrication of the pineapple leaf polyester composites (PLPC) and pineapple leaf epoxy composites (PLEC) was produced by hand lay-up method with varying fiber compositions of 0%, 20%, 30%, 40%, and 50%. Recorded room temperature and relative humidity were 26.3°C and 57.5%, respectively. Epoxy resin and hardener were mixed in a ratio of 2:1, while ratio 10:1 was used for the polyester resin and its hardener. These mixtures were stirred thoroughly for 6 minutes for wetting and proper soaking before fabrication. However, 30% glass fiber was used for the glass fiber polyester composite (GFPC). To reduce voids, a load of 20 kg was placed on the mold during lamination and left for 6 hrs. Figure 3 shows a composite sample produced by hand lay-up method before being cut into various standards.

2.3   Specimen Testing

Composite samples (GFPC, PLPC and PLEC) were in conformity with ASTM (2004) standards. That is, ASTM D 3039 – 76 for tensile testing, ASTM D790 – 03 for flexural test and D256 for impact test (ASTM, 2014). Before the tests were conducted, all the test samples were conditioned at room temperature of 23.2 ^{0}C with relative humidity of 50.5% for 24 hours.

Figure 2. Pineapple leaf fibers

Figure 3. Hand lay-up composite sample before being cut into various standards

2.3.1 Tensile Test

Tensile test samples were prepared according to the ASTM D 3039 standard, and the test was carried out using the Universal Testing Machine (Instron 5567). This machine was operated at a crosshead speed of 2 mm/min, room temperature of $26 \pm 3°C$, and relative humidity of $55 \pm 2\%$. The dimensions of the six specimens used for the tensile test are $150 \times 20 \times 3$ mm (length $\times$ width $\times$ thickness). The average values were

reported including standard deviations. Each sample was loaded to failure. From the tensile test results, tensile strength, Young's modulus and percentage elongation were calculated.

2.3.2   Flexural Test

Three-point loading system applied on a supported beam was utilized according to ASTM D790 – 03 standards. The load was applied midway between the supports with a crosshead speed of 1.7 mm/min. Test piece specimens were prepared with dimensions of 120 mm × 10 mm × 4 mm for the flexural test using the Universal Testing Machine (Instron 5567). Each sample was loaded to failure and the average values were thereafter reported including standard deviations.

2.3.3   Impact Test

Test method A (Izod type) according to ASTM D256 was used for testing (ASTM, 2014). Notching was done because it provides a stress concentration area that promotes a brittle rather than a ductile failure. Furthermore, notching also drastically reduces the energy lost due to plastic deformation. A few parameters were set according to the standard, for instance, Hammer Velocity = 3.46 m/s and Hammer Weight = 0.905 kg. Impact strength was calculated using Equation (1).

$$\text{Impact Strength} = \frac{\text{Energy of fracture in Joule}}{\text{Cross-sectional area in meter square}} \tag{1}$$

3.0   RESULTS AND DISCUSSION

It was observed that composite samples with fiber loadings of 20, 30 and 40% were easier to fabricate compared with the composite sample with 50% fiber loading. Flaws, crazing, void and delamination were observed at 50 wt.% fiber loading composite samples. From among the derivations of tensile properties, tensile strength, Young's modulus and percentage of elongation are directly relevant to prosthetic sockets (Philips et al., 2005), thus their results are discussed here.

As shown in Tables 1 and 2, the tensile properties, namely tensile strength, Young's modulus and percentage elongation of the composites, increased with fiber loading. In both epoxy and polyester composites, the optimum fiber loadings that yielded highest tensile strength were at 50 wt.% fiber loading. It was also observed that there was a slight increment between 40 and 50% in tensile properties, notably with Young's modulus.

Table 1. Tensile properties of pineapple leaf fiber and
glass fiber reinforced polyester composites

Composite	Parameter	Fiber loadings (wt.%)				
		0	20	30	40	50
Pineapple	Ultimate tensile strength	10.22 ± 1.93	30.15 ± 3.03	48.78 ± 3.90	62.09 ± 4.87	69.12 ± 5.20
	Young's Modulus	1.12 ± 0.02	2.43 ± 0.07	3.46 ± 0.05	4.81 ± 0.11	5.03 ± 0.10
	Elongation	0.98 ± 0.01	2.79 ± 1.10	3.11 ± 0.06	4.99 ± 0.13	5.44 ± 0.11
Glass fiber	Ultimate tensile strength	65.72 ± 3.30				
	Young's Modulus	7.33 ± 3.22				
	Elongation	7.76 ± 1.10				

There was no appreciable increase in modulus of elasticity from 40 to 50% fiber loading. Unlike the tensile strength and Young's modulus, which increased with fiber loading, some discrepancies were observed with some of the percentage elongation results.

A noteworthy exception was the pineapple leaf epoxy composite with a small difference of 12.6% between 30 and 40% fiber loading and a sharp decline from 8.93 ± 0.11 to 8.15 ± 0.22 induced from 40 to 50% fiber loading. Meanwhile, mechanical properties of GFPC samples were higher than all ratios of PLPC except at 50 wt.% fiber, while the mechanical properties of PLEC at 40 and 50 wt.% were higher than those of the GFPC samples.

Table 2. Tensile properties of pineapple leaf fiber reinforced epoxy composites

Composite	Parameter	Fiber loadings (wt.%)				
		0	20	30	40	50
Pineapple	Ultimate tensile strength	14.30 ± 2.21	35.88 ± 0.90	62.75 ± 2.10	76.47 ± 3.85	80.12 ± 2.23
	Young's Modulus	2.43 ± 0.19	5.42 ± 0.10	7.80 ± 0.08	8.93 ± 0.11	8.15 ± 0.22
	Elongation	2.56 ± 0.13	5.88 ± 0.20	6.92 ± 0.17	7.55 ± 0.31	8.24 ± 0.24

Figure 4 shows the flexural strength of pineapple leaf reinforced polyester and epoxy composites. The flexural strength of all the composites in this study increased with increase in fiber content. However, there was a slight variance in the flexural strength of the pineapple leaf polyester composites. A noteworthy exception experienced 3.5% decline in flexural strength from 0 to 20% fiber loading before following the normal

increasing trend. The impact test samples as shown in Figure 5 also witnessed successive increased impact strength with addition of fibers. However, GFPC, particularly at 30% fiber loading, had higher impact strength values than corresponding PPFC and PEFC. This is closely followed by PPFC and PEFC.
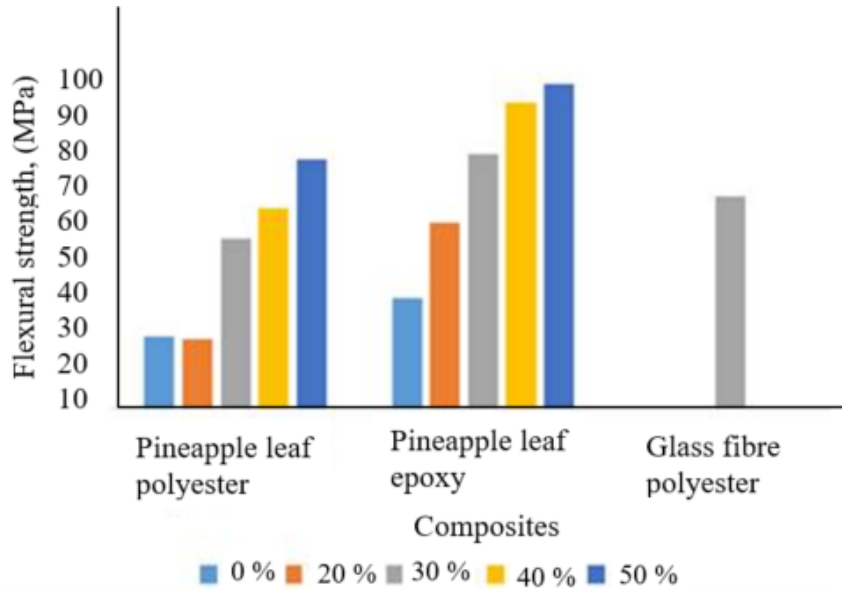

Figure 4. Flexural Strength of pineapple leaf fiber reinforced
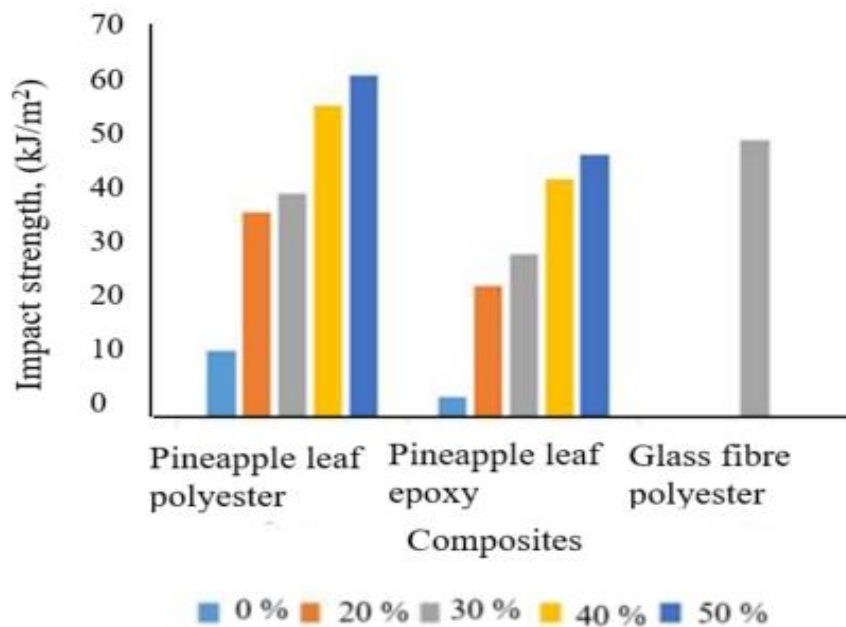in epoxy and polyester composites

Figure 5. Impact test of pineapple leaf and glass fiber reinforced
in epoxy/polyester composite

The general observation of crazing, void, delamination, brittleness, and inability of the composites to form properly at 50% fiber loading may probably due to inadequate amount of matrix to effectively support the fibers, thereby leading to inhomogeneity of the composites. This inevitably led to flaws and crazing, thus creating a stress concentration area which lowered the stiffness of the composite. This phenomenon has also been reported by Philips and Craelius (2005).

For high-strength applications such as prosthetic sockets, higher tensile and Young's modulus need to be sought, whereas an increase in elongation, a function that determines the ductility of materials, is disadvantageous. Hence, a lower percentage of elongation is desirable for prosthetic socket materials, as reported by Irawan, Soemardi, Widjajalaksmi and Reksoprodjo (2010). Increase in tensile properties of the composites – tensile strength, Young's Modulus and percentage elongation – arising from fiber loading, as evident from Tables 1 and 2, is normal and has been reported by several authors (Fischer, 2010; Irawan et al., 2010).

The reversible behavior of Young's modulus often shows a linear relation between stress and strain. To minimize deformation, especially with a prosthetic socket that bears the weight of the body, a material with a large elastic modulus must be sought. This corresponds to the result in this study, as modulus of elasticity of the composite samples increased with increase in fiber loading. The slight increment between 40 and 50 wt.% in tensile properties, especially for tensile strength and Young's modulus, depicted that the polyester/epoxy composites were becoming stiff and could not withstand higher stress. This also could be attributed to the increase in stiffness of the polymer when fibers were added.

The treated fiber composites exhibit stronger bonding between the fiber and the polymer matrix, and this apparently affected the elasticity of the polymer (Augustinus & Sukaina, 2012). The fiber serves as reinforcement because the major share of the load has been taken up by the crystalline fibrils, resulting in extension of the helically wound fibrils along with the matrix (Phillips & Craelius, 2005). As for the percentage of elongation, the presence of the fibers in the matrix constrains the stretching of the matrix and reduces its elasticity. However, this lowers the extent of strain occurring within the polymer during loading. The small difference observed between 30 and 40% fiber loading and sharp decline from 8.93 ± 0.11 to 8.15 ± 0.22% induced from 40 to 50% fiber loading can probably be attributed to defects in the hand lay-up method of fabrication used in this study.

The tensile strength of the composite increased due to the chemical treatment, which induced greater adhesion between the polymer matrix and the fibers. The higher strength of the composites compared to that of the pure epoxy and polyester polymers suggest an efficient composite system is achieved, with better fiber-matrix adhesion. Continuous fibers such as pineapple leaf used in this study yield higher strength, while short fibers with discontinuity and irregularity in the polymer structure result in a weakened frame, as reported by Anyakora and Abubakre (2011).

Fiber ratio, chemical surface treatment and reaction between the matrix and fiber have been reported to have a tremendous effect on composites (Phillips & Craelius, 2005; Irawan et al., 2010). Fabrication techniques also strongly influence the strength of composites. Ramie Epoxy Reinforced Composite, RERC, fabricated using the filament

winding method (Irawan et al., 2010) displayed higher tensile strength and modulus of elasticity than Bamboo Epoxy Reinforced Composite (BERC) produced by hand lay-up (Irawan et al., 2010).

The tensile strength and modulus of elasticity values of RERC were also compared with the results in the present study (Table 3), and were found to also be higher, probably due to the hand lay-up method used here. Although the hand lay-up method of fabrication used in this study is simple and cost effective, it is labor intensive, non-homogenous and difficult to attain uniform thickness. The filament winding method, however, eliminates these deficiencies. Therefore, the strength of the RERC was higher than in this study due to the filament fabrication method used for the RERC (Phillips & Craelius, 2005).

Furthermore, this present study used NaOH and acetic acid to ameliorate the adhesion between resin and plant fibers by removing hemicellulose and lignin responsible for plant fiber hydrophilic behavior. However, in addition to NaOH and acetic acid, a silane coupling agent (amino-ethyl-propyl amino silane trimetoxy) was also used for treatment in fabrication of the RERC (Phillips & Craelius, 2005). Fiber pre-treated with NaOH for approximately half an hour before coupling with silane has been reported to generate more reactive sites by minimizing sensitivity to humidity and number of cellulose hydroxyl groups in the fiber-matrix interface (Irawan et al., 2010).

Table 3. Tensile strength and Young's modulus of socket materials (Taylor, Gilbert and Lautenschlager, 1992; Augustinus & Sukaina, 2012; and Phillips & Craelius, 2005)

Strength Range	Fiber Types	UTS Range (MPa)	Young's Modulus (GPa)
Low	Perlon, nylon, cotton, nyglass, spectralon.	18 – 42	1.8 – 5.1
Middle	Glass	67 – 109	5.0 – 17.3
	Rattan Epoxy	66.25 ± 0. 81	8.68 ± 0.68
	Ramie Epoxy	86 ± 6.07	9.40 ± 0.68
	Ramie Polyester	67 ± 5.11	7.45 ± 0.57
	Bamboo Epoxy	78.09 ± 1.97	8.96 ± 0.33
	Pineapple polyester	62.09±4.87	4.81 ± 0.11
	Glass fiber Polyester	65.72 ± 3.30	7.33 ± 3.22
	Pineapple Epoxy	77.47 ± 3.85	7.93 ± 0.11
High	Carbon	236 – 249	20.6 – 25.5

Thus, reactivity between the fibers and the resin greatly improves mechanical interlocking of the fibers in the matrix while also inducing a chemical linkage between

the cellulose and polymer chain (Ilomäki, 2012; Augstburger et al., 2011; Yaseer, 2009). This justifies the higher strength of Ramie composites compared to others, as shown in Table 4.

According to Phillips and Craelius (2005) and Augustinus, Tresna and Agus (2009), laminate composites used in prosthetics and orthotics can be classified into three categories as shown in Table 3. It is highly recommended to consider this classification when selecting a prosthetic socket. The results of this study showed that GFPC, 64 ± 4.20 MPa, was below the recommended middle-range strength while PLEC (77.47 ± 3.85 MPa) is classified as a middle-range strength material, which is in agreement with Augustinus and Sukaina (2012), Phillips and Craelius (2005) and Augustinus et al. (2009).

Flexural properties are very important in prosthetic sockets as the material used must be strong, elastic to support the body's weight, and able to receive dynamic load, which may happen in gaiting system (Phillips & Craelius, 2005). It was observed that the flexural strength of all the composite samples, except the 20% pineapple fiber epoxy composite, increased with fiber loading. This exception could probably be due to insufficient fiber loading. Phillips and Craelius (2005) reported increase in the flexural modulus and flexural strength to the increasing fiber to-fiber contact when the fibers were impregnated. And the higher strength of the epoxy composite compared to the glass fiber and pineapple polyester composites can be interpreted as the pineapple leaf fiber reinforced epoxy composites can withstand bending forces better than tensile stress due to their higher flexural and modulus strength. These observations prove that pineapple leaf, which has high strong crystalline content, can share the load applied in a matrix effectively due to the crystalline fibrils in it and can also withstand bending with various fiber loadings (Sumaila and Amber, 2013).

Compared with previous work on prosthetic and orthotic materials, Table 4 shows that Ramie epoxy composite clearly exhibit superior flexural strength which could be attributed to the use of filament winding method coupled with pre-treatment process of the fiber using silane coupling agent.

Table 4. Flexural strength of prosthetic socket material (Augustinus & Sukaina, 2012)

Socket materials	Flexural strength (MPa)
Ramie Epoxy	103 ± 15.62
Ramie Polyester	84.8 ± 6.93
Pineapple Polyester	53.02 ± 1.20
Polyester Glass fiber	66.10 ± 1.88
Pineapple Epoxy	81.27 ± 1.27

Impact strength of a material is defined as the material's ability to absorb applied energy, and is directly related to its overall toughness. Area under the stress-strain curve is proportional to the toughness of the material. Nevertheless, impact strength is a measure of toughness. Impact strength is required for prosthetic socket materials. The quality of prosthetic socket materials also depends on the impact strength necessary to

provide safety, and that they are not easily damaged when receiving impact loads (Phillips & Craelius, 2005). This greatly affects the user's sense of safety when using a prosthetic socket product. Based on the foregoing explanation, the results of this study that increased with fiber loadings also agreed with the study of Augustinus and Sukaina (2012), as shown in Figure 6. Higher impact strength values of epoxy composites compared with polyester composites are probably an indication of better matrix-fiber interaction assisted by chemical treatment, of the former.
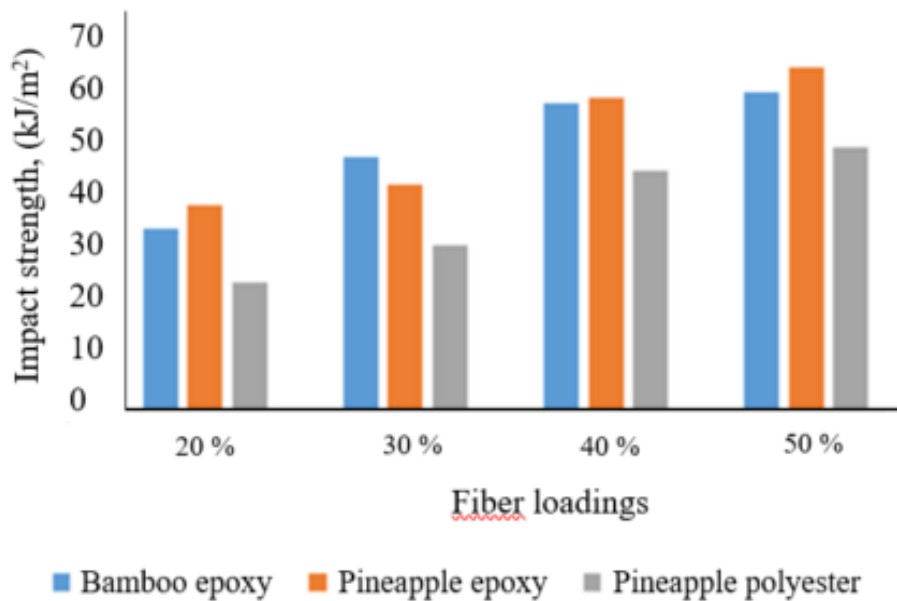

Figure 6. Impact strength of bamboo epoxy (Irawan et al., 2010),
pineapple epoxy and pineapple polyester

4.0   CONCLUSION

From the experimental results, the following can be concluded:

i. Pineapple fiber reinforced epoxy composites had better flexural, impact and tensile properties than fiber glass and pineapple fiber reinforced polyester composites.

ii. Chemical surface treatment was responsible for the good adhesion between epoxy and pineapple leaf fiber than pineapple leaf fiber and glass fiber polyester composites.

iii. 40% fiber loading was the best and is preferred to the higher value of 50% fiber loading, ostensibly because there are fewer voids, and less crazing, delamination and complexity during fabrication.

iv. Overall, GFPC composites exhibit most prominent strength in comparison to those of the PLPC and PLEC composites. However, this is not the case for the 30 wt.% GFPC composites.

v. Finally, the results of this study showed that PLEC has the potential to be further developed as a substitute for fiber glass polyester prosthetic sockets, particularly for above-knee ones, where higher strength is required. Pineapple leaf fiber is locally available, bio-mechanically appropriate, as lightweight as possible, comfortable and psychosocially acceptable.

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