Mechanical and Impact Characterization of Lake Tana Papyrus/Glass Fiber-Reinforced Hybrid Composites

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Abstract:

Lake Tana in Bahir Dar city of Ethiopia has a surplus amount of Papyrus plant, which has a great potential that can be used as natural fiber. Besides this fact, the contribution of papyrus plant on composite material and paper work sector of the city is negligible as compared to other countries. Moreover, due to an immaturity of awareness about this plant and unavailability of experimental tools, the performance and applications of Lake Tana natural fibers are not investigated before. Automotive industry is growing in our country Ethiopia, due to these the industry may need some materials that help to replace steel. This research tries to fill these needs by conducting software analysis and experimental test on impact strength of papyrus/glass fiber hybrid composite. The general objective of this research is to determine the impact strength of Papyrus/glass fiber Polyester hybrid composite. This is achieved by conducting different arrangement of the fibers and conducting experimental tests on the above-mentioned materials. The specific objective of this research includes Extraction of Papyrus fibers from Lake Tana Papyrus, Determination of fiber and matrix contents of the hybrid composite, Fabricating papyrus/fiberglass hybrid composite and conduct the Impact test, and Simulating using FEA software ANSYS to determine equivalent stress of papyrus/fiberglass hybrid composites. The present research is done by varying the percentage content of the natural fiber for papyrus composite and for PGFHC with fixed value of polyester. The other method is by changing the arrangement of the fiber glass and papyrus fibers in unidirectional, woven and random/Chopped/ manner. The Papyrus/Glass fiber hybrid composite is prepared manually by hand lay-up method. The samples were fabricated for each lamina and percentage content. The test pieces are cut according to ASTM standard. Tests are conducted on IZOD impact testing machine for low velocity. In addition to experimental work, samples were analyzed for equivalent stress with ANSYS. The maximum impact strength is observed in unidirectional fiber orientations and minimum values in chopped fiber orientations.

Keywords:
Lake Tana papyrus fiber, Glass fiber, Hybrid composites, Polyester matrix, Mechanical characterization, Impact strength, Fiber volume fraction, Hand lay-up technique.

1.Introduction

A lot of work has been done on mechanical properties of glass fibre hybrid composite. Glass fibre is material mostly found in any construction material supplier shops, during processing makes the preferable one in hybrid composite material there are some research works carried out on this hybrid of fibre material by mixing with the base material polymers. The incorporation of several different types of fibers into a single matrix has led to the development of hybrid composites. The behaviour of hybrid composites is a considered sum of the individual components in which there is a more favourable balance between the inherent advantages and disadvantages. Also, using a hybrid composite that contains two or more types of fibers, the advantages of one type of fiber could complement with what are lacking in the other. As a consequence, a balance in cost and performance could be achieved through proper material design. The properties of a hybrid composite mainly depend upon the fiber content, length of individual fibers, orientation, extent of intermingling of fibers, fiber to matrix bonding and arrangement of both the fibers. Researchers Mohammad Javid et.al [1] concluded from their study that the addition of a very small amount of nanoparticle into a matrix can improve both thermal and mechanical properties significantly without compromising the weight or process ability of the composite. Hybridization [2] is a process of incorporating of two reinforcements either synthetic fibers/ Nano fillers/natural/ or metallic fibers in order to yield better properties such as (high mechanical strength, compressive strength, stiffness, thermal stability and lowered water absorption properties) which cannot be realized in conventional composite materials. Hybrid materials are very advanced composites materials [3] consisting of two or more different constituents at the molecular or nanometer level. Cyprus Papyrus is the largest member of the family. It has the capacity of growing very quickly, but needs fairly specific conditions. Temperature limits its range to tropical and sub-tropical regions, and it will not tolerate any shortage or irregularity in the supply of water (sensitive to water stress). Essentially it grows in slow flowing rivers, and lakes of low salinity, with stable water levels and shallow banks. It is native to Africa (parts) and Palestine [4]. Many studies were conducted to investigate the impact behaviour of fiber reinforced hybrid composites due to the increasing demand of these materials in the automotive, maritime, aviation, infrastructure, military, sport sector and petroleum. However, in order to obtain new properties, several researchers [5] studied on hybridizing fibers into polymer matrix. Impact resistant materials remain a concern to all types of military and civilian equipment manufacturers. The light weight fiber-reinforced composites have the capability to replace metals and traditional composites for high impact strength and vibration damping while providing good in-plane stiffness [6]. The study of various composite materials subjected to impact loading has not been given enough attention even though it should be a major design factor. The few published results on impact behaviour were obtained with a standard Charpy impact machine without any attempt to study the phenomena of impact. For a fiber reinforced plastic material, it is likely that the impact behaviour will be time dependent, i.e., dependent on the velocity of the hammer when striking the specimen. It has been shown that for a glass fiber reinforced plastic matrix, the ultimate strength increases as a function of the rate of loading in the fiber direction. Thus, in this impact study [7], the rate of loading during impact was used as one of the primary variables. It is naturally convenient to study [8] together the composites that have the same strengthening mechanism, which in-turn depends on the geometry of the reinforcement. The behaviour of hybrid composites is a considered sum of the individual components in which there is a more favourable balance between the inherent advantages and disadvantages. Also, using a hybrid composite that contains two or more types of fibers, the advantages of one type of fiber could complement with what are lacking in the other. As a consequence, a balance in cost and performance could be achieved through proper material design [9]. The impact strength of the hybrid composites increased with the addition of glass fibers. Addition of Kevlar fiber to glass fiber has improved the load carrying capability, energy absorbed [10]. Sisal fibers obtained from local sources and the chopped strand mat of glass fibers were used for the present study. Unsaturated polyester resin obtained as the matrix. An alkoxy [11] silane has been used as the coupling agent in order to enhance the adhesion characteristics between the fiber and the matrix. The sisal fibers were treated with a 2% solution of NaOH into a glass tray and the fibers were allowed to soak in the solution for 1 h. Preparation of Composites is done by hand lay-up and castings of different thickness were made from resin. In order to make the test specimens, the matrix system is poured into a mould made of glass plates. Unsaturated polyester and styrene are mixed in the ratio 100: 25 parts by weight respectively. Later, 1wt % methyl ethyl ketone peroxide and 1wt % cobalt naphthenate were added and mixed thoroughly. The impact specimens were cut as per ASTM D 256 specifications and the Izod impact tester was used. It is observed that the impact strength has been improved with increased glass fiber content and the total fiber content in the hybrid composite. In the study by Maneesh Tewari et.al [12] the properties of Palmyra/glass fiber composites at 55 wt. % fibers are investigated. Composites are prepared by varying both glass fiber and

Palmyra fiber content by keeping the overall fiber content constant. The impact strength of Palmyra fiber composite is 30.50 kJ/m2 which is comparable with results of other natural fiber composites. Increase in fiber content results in increase in fiber-to-fiber contact and hence matrix breakage becomes predominant failure mechanism. When the glass fiber is added to the Palmyra fiber the impact resistance is increased considerably. Evaluation of Mechanical Properties of Bagasse-Glass Fiber Reinforced Composite, in their research work natural fiber a bagasse-glass fiber reinforced composite material is developed, with 15 wt%, 20 wt%, 25 wt% and 30 wt% of bagasse fiber with 5 wt% glass fiber mixed in resin. The research was therefore initiated with the objective of studying the feasibility of manufacturing composite boards from a mix of fibrous bagasse particles with glass fiber by means of a flat press process and to show bagasse content, and pressure effect on selected board properties tensile and impact strength. Epoxy resin (CY230), hardener (HY951), bagasse fiber and glass fiber with different weight percentage were used. Different weight percentage (wt %) of bagasse fiber (15, 20, 25, 30 wt %), glass fiber (5 wt %) and epoxy resin were mixed by mechanical stirring at 3000 rpm. Finally, the investigation showed an improvement in the impact strength that has been observed due to addition of bagasse fibers. An increase of impact strength from 22.07 Nm to 27.01 Nm has been noticed due to addition of 30 wt% bagasse to the epoxy composite. From these observations it can be concluded that bagasse fiber improves the impact strength when added as filler material. Addition of fiber increases the modulus of elasticity of the epoxy. Mixing of bagasse with glass fiber also improves the modulus of elasticity. Bagasse and bagasse-glass fibers improve the impact strength of epoxy materials due to high elasticity properties of fiber as compared to pure resin. M. R. Sanjay and B. Yogesha, [13] conducted Study on Mechanical Properties of Jute/E-Glass Fiber Reinforced Epoxy Hybrid Composites, this paper deals with the hybrid effect of composites made of jute/E-Glass fibers. From the scientific literature, it is observed that nobody has carried out research on Papyrus which is abundantly available around 3000 km^2 in Lake Tana, Bahir Dar, Ethiopia. This Papyrus Fiber along with Glass fiber and Polyester resin are used to prepare the specimen.

2. **Different materials and methods**

2.1 Materials: The raw materials in this research work, E-glass fibers, polyester resin with its hardener material are utilized directly for composite preparation. Lake Tana Papyrus fibre is extracted from papyrus stem taking from Lake Tana, which is then processed in AG FIBER factory, Bahir Dar, Ethiopia, finally the test was performed in Debre Tabor University.

2.1.1 Papyrus: In Lake Tana Papyrus is a weed that grew wildly along the banks more than 3000 km2 of the lake. Currently the people living around Lake Tana use papyrus to make baskets, sandals, mats, rope, blankets, tables, chairs, mattresses, and small boats called (Denkel). Truly, papyrus is important "gift of the lake Tana".

Figure 1. Typical view of Papyrus plant.

Fiber	Papyrus Fiber
Density (g/cm^3)	1.46
Elastic Modulus (E) GPa	4.2
Poisson's Ratio	0.029
Typical Diameter (μm)	70

Table 1. Properties of papyrus fiber. Source: (Nishino,Takashi/Hirao, Koichi/Kotera, Masaru, 2007)

Figure 2. a) Socked papyrus stem b) Manual extraction of fiber c) Extracted papyrus fiber

2.1.2 Glass fiber: Glass fiber is a material consisting of numerous extremely fine fibers of glass. Glass fiber is commonly used as an insulating material. It is also used as a reinforcing agent for many polymer products to form a very strong and light fiber-reinforced polymer (FRP) composite material called glass-reinforced plastic (GRP), popularly known as "fiberglass". Glass fiber has roughly comparable properties to other fibers such as polymers and carbon fiber. Although not as strong or as rigid as carbon fiber, it is much cheaper and significantly less brittle (Patil Deogonda1 et.al, 2013).

2.1.3 Unidirectional glass fiber: It is basically known as continuous glass fibres strand, or collection of individual fibres also known as a tow. The strands may be brought together to form an untwisted bundle of fibres called a roving. Both strands and roving can be woven into a variety of cloths.

Figure 3. Continuous E-Glass fiber

2.1.4 Chopped (random) glass fiber: Chopped strands are formed by cutting continuous strands into short lengths. Their length ranges from 3.2 mm to 12.7 mm. Chopped strand mat is manufactured from chopped strands, which are bonded together in a randomly oriented two-dimensional manner. This type of reinforcement is considerably cheaper than woven fabric when measured on a weight basis and is typically used as a reinforcing material in a laminate by itself or in conjunction with a woven fabric.

Figure 4. Chopped (Random) arrangement E-Glass fiber

2.1.5 Woven glass fiber: Glass fibers are also available in woven form. Woven roving is a coarse fabric and used in moldings and laminates to produce highly directional strength characteristics. A layer of woven roving is sometimes bonded with a layer of chopped strand mat to produce a woven roving mat. The woven forms are suitable for hand lay-up moldings (Mallick 1988)

Figure 5. Woven Arrangement E-Glass fiber

Table 2 Properties of E-Glass fiber

Fiber	E-glass
Typical Diameter (μm)	10
Density (g/cm^3)	2.54
Elastic Modulus (E) GPa	72.4
Tensile Strength GPa	3.45
Strain-to-Failure (%)	4.8
Poisson's Ratio	0.2

Source: (P.K Mallick, 2007)

2.1.6 Polyester Resin and Catalyst

The matrix material used in the present study was an **unsaturated polyester resin**, commercially known as **OCPOL 711 GP Resin**, manufactured by **ORGI CHEMIE FZ-LLC Development Corporation**. This resin was selected due to its favorable processing characteristics, including low viscosity, which facilitates rapid fiber wetting, and a high thixotropic index, which minimizes resin drainage on vertical surfaces during fabrication. As a general-purpose (GP) resin, it exhibits satisfactory mechanical and electrical properties along with good resistance to chemical degradation (Herakovich, 1998).

Unsaturated polyester resins are among the most widely used thermosetting polymers in composite manufacturing because of their availability, cost-effectiveness, ease of processing, and versatility across a broad range of engineering applications. Another significant advantage of polyester resin is its long storage life at room temperature, allowing it to remain stable for extended periods before use. Upon the addition of an appropriate catalyst, the resin undergoes curing and transforms from a liquid state into a rigid solid matrix within a relatively short period. Figure 8 illustrates the general-purpose polyester resin employed in this study.

Catalyst (Hardener)

The curing of polyester resin is achieved through the addition of a catalyst, commonly referred to as a **hardener**. The catalyst initiates a chemical reaction between the unsaturated polyester resin and the monomer components, leading to polymerization and cross-linking of the resin system. During this process, the resin changes from a liquid state to a solid, three-dimensional network structure, thereby providing the required mechanical strength and structural integrity to the composite material.

Although the catalyst facilitates the curing reaction, it is not consumed in the process and primarily serves to initiate and accelerate polymerization. When employed for this purpose, catalysts are often termed **catalytic hardeners**. The proper selection and proportioning of the catalyst are critical for achieving optimal curing conditions and ensuring the desired mechanical performance of the fabricated composite laminates.

2.2 Methodology

2.2.1 Fiber and Matrix Volume Content of the Composite

In the fabrication and analysis of composite materials, one of the most critical initial steps is the determination of the constituent proportions, namely the fiber and matrix (resin) contents within the laminate. The mechanical performance and overall characteristics of a composite are significantly influenced by the relative amounts of these constituents. Therefore, accurate determination of fiber and matrix fractions is essential for both composite design and performance evaluation. The resin-to-fiber ratio may be established based on either weight fraction or volume fraction. In the present study, the constituent proportions were initially determined on a weight basis and subsequently converted into corresponding volume fractions. The equations used for calculating the weight and volume fractions of the fiber and matrix constituents were adopted from the methodology reported by Hei-Lam et al. (2016). The fiber and matrix fractions represent fundamental microstructural parameters of composite laminates, as they directly influence the strength, stiffness, durability, and other mechanical properties of the composite material. Accurate evaluation of these parameters is therefore indispensable for the successful fabrication and characterization of composite laminates. The calculated weight and volume fractions serve several important purposes, including:

- Preparation and fabrication of composite laminates with the desired constituent proportions.
- Compliance with ASTM standards and specimen dimension requirements.
- Determination of laminate dimensions suitable for experimental testing.
- Development of finite element analysis (FEA) models for numerical investigations.
- Optimization and improvement of composite laminates through variation of constituent contents.
- Establishment of design guidelines by correlating constituent fractions with experimentally determined mechanical properties.

Consequently, the determination of fiber and matrix volume fractions provides a fundamental basis for composite fabrication, experimental evaluation, numerical analysis, and future material development.

The composite weight Wc is the multiplication of the composite volume Vc and ρc

$Wc = Vc^{*}\, \rho c$

Glass fiber weight Wg: $Wg = Wc^{*}\, wg$

Papyrus fiber weight Wp: $Wp = Wc\, {*}wp$… Where: wg: the weight fraction of glass wp: the weight fraction of Papyrus fibers

wm: the weight fraction of matrix vg: the volume fraction of glass fibers vp; the volume fraction of Papyrus fibers vm: the volume fraction of matrix ρg: the density of glass fiber (g/cm3) ρp: the density of Papyrus fiber (g/cm3) ρm: the density of polyester resin (g/cm3) Wp: weight of Papyrus Fibre (g) Wm: weight of Matrix (g) Wg: weight of glass (g) Vp: Volume of Papyrus fibres, (cm3) Vg: Volume of Glass fibres, (cm3) Vm: Volume of Matrix, (cm3) Wc: weight of composite specimen (g) Vc: Volume of Composite specimen (cm3). Here, total fiber is the sum of Papyrus fibers and glass fibers.

Parameters	Value
Papyrus fiber density (ρp)	1.46 g/cm^3
Glass fiber density (ρg)	2.54 g/cm^3
Matrix Density (ρm)	1.399 g/cm^3

Table 4: Density values of materials

Sample ID	W_c (g)	W_p (g)	W_g (g)	W_m (g)	V_p (cm^3)	V_g (cm^3)	V_m (cm^3)	V_c (cm^3)	v_p (%)	v_g (%)	v_m (%)
PPU_1, PPW_1 and PPC_1	250	75	…	175	51.3	…	125.08	176.38	29.08	…	70.91

Table 5 The values in composites obtained from the above equation Composition of 30% Papyrus and 70% Polyester

Sample ID	W_c (g)	W_p (g)	W_g (g)	W_m (g)	V_p (cm^3)	V_g (cm^3)	V_m (cm^3)	V_c (cm^3)	V_p (%)	V_g (%)	V_m (%)
$PGPU_3$, $PGPW_3$ and $PGPC_3$	260.4	39.06	39.06	182.3	26.7	15.37	130.3	172.4	15.51	8.91	75.57

Table 6 The values in hybrid composites obtained from the above equation Composition of 15% Papyrus, 15% Glass and 70% Polyester

Sample ID	W_c (g)	W_p (g)	W_g (g)	W_m (g)	V_p (cm^3)	V_g (cm^3)	V_m (cm^3)	V_c (cm^3)	V_p (%)	V_g (%)	V_m (%)
$PGPU_4$, $PGPW_4$ and $PGPC_4$	260.4	26.04	52.08	182.8	17.83	20.5	130.7	168.99	10.55	12.13	77.3

Table 7 The values in hybrid composites obtained from the above equation Composition of 10% Papyrus, 20% Glass and 70% Polyester

Composite Manufacturing method

There are two types of manufacturing method for composite materials. Curing and lay up process. There are different types of lay-up process: hand lay-up/wet lay-up, spray lay-up, filament winding. Vacuum Bagging, Resin Transfer Moulding (RTM), Autoclave, Pultrusion are grouped under curing process (MILTON, 2004). In this research the manufacturing method used is manual hand lay-up method. This method is a reliable process, it is by nature very slow and labor-intensive.

2.2.2 Manual Hand Lay-Up Process

The **hand lay-up process** is one of the earliest and most widely used composite fabrication techniques and belongs to the category of **open-mould manufacturing methods**. Despite the development of advanced composite processing techniques, hand lay-up remains a preferred method due to its simplicity, low production cost, flexibility in component size, and ability to produce a good surface finish on one side of the laminate. In this process, the reinforcement material is manually placed onto a single-sided mould, and the resin system is subsequently applied to impregnate the fibers. The resin–fiber mixture is then consolidated using a hand roller to remove entrapped air and ensure uniform resin distribution throughout the laminate. The quality of the final composite largely depends on the operator's skill and experience, which is one of the primary limitations of the process. Another limitation is that only one surface of the component attains a finished appearance. However, the method offers the advantage of low capital investment and minimal equipment requirements.

The fabrication process may employ either a male or female mould. Prior to lay-up, the mould surface is coated with a suitable release agent to prevent adhesion between the mould and the composite. A gel coat may also be applied to provide a protective and aesthetically pleasing surface finish. The reinforcing fibers are then positioned within the mould, followed by the application of a liquid thermosetting resin mixed with an appropriate curing agent. The resin is distributed using brushes or rollers to ensure complete wetting of the reinforcement and effective fiber–matrix bonding. Polyester and epoxy resins are among the most commonly used matrix materials in hand lay-up fabrication. Curing is typically carried out at room temperature. The selection of the resin system is primarily governed by factors such as viscosity, wettability, and working time, which significantly influence the quality and performance of the fabricated composite (Schwartz, 1984).

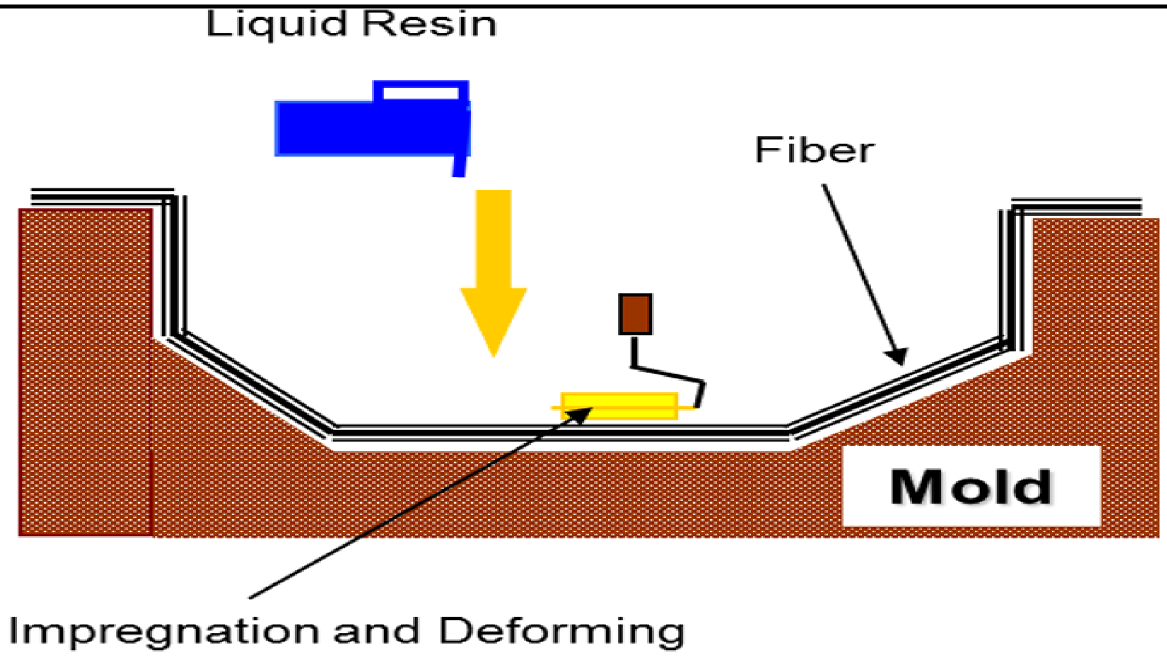

Figure 6. Hand Lay-up process

Figure 7. Mould made from rectangular wood

For Papyrus composite

Arrangement of fiber	Sample ID	Papyrus fiber %	Polyester resin %
Unidirectional	A1	30%	70%
	A2	20%	80%
Woven	A3	30%	70%
	A4	20%	80%
Chopped	A5	30%	70%
	A6	20%	80%

Table 8 Percentage composition for papyrus composite

For papyrus/glass fiber hybrid composite

Table 9 Percentage papyrus/glass fiber hybrid composite

Arrangement of fiber	Sample ID	Papyrus fiber %	Glass fibre %	Polyester resin %
Unidirectional	B1	15%	15%	70%
	B2	10%	20%	70%
Woven	B3	15%	15%	70%
	B4	10%	20%	70%
Chopped	B5	15%	15%	70%
	B6	10%	20%	70%

For papyrus/glass fiber hybrid composite

Table 10 Calculated amount of the various ratios for papyrus/glass fiber hybrid composite

Percentage % (Papyrus/polyester/ glass respectively)	Sample ID	Weight of Papyrus 30% (gm)	Weight of Glass fiber (gm)	Weight of polyester 30% (gm)
15%/15%/70%	B1,B3 and B5	31.5	31.5	147
10%/20%/70%	B1, B3 and B5	21	42	147

Simulation Method In this work, ANSYS version 15 software is used to calculate the flexural strength of Papyrus/Glass fiber hybrid polyester composite of different angle arrangement of fibres. For this material, the nine independent elastic constants are Exx, Eyy, Ezz, Gxy, Gxz, Gyz, vxy, vxz and vyz required to characterize material property as inputs for ANSYS program and then the results are obtained for the given data.

3.RESULTS and DISCUSSION

3.1 Experimental Results

Papyrus–Glass Hybrid Polymer Composites (PGHPCs) were fabricated with different fiber and matrix volume fractions using three laminate configurations: **unidirectional, woven, and chopped (random) fiber orientations**. For both the papyrus fiber composites and the papyrus/E-glass fiber hybrid composites, four different composition ratios were considered. The papyrus fiber composites were prepared with fiber-to-matrix ratios of **30%/70%** and **20%/80%**, while the hybrid composites were fabricated with **15%/15%/70%** and **10%/20%/70%** volume fractions of papyrus fiber, glass fiber, and polyester resin, respectively.

A total of **twelve composite samples** were manufactured, representing the various material compositions and laminate orientations. For each sample, **three test specimens** were prepared and evaluated, resulting in a total of **thirty-six specimens** for the experimental investigation. To ensure the reliability and consistency of the results, the measured values obtained from the three specimens corresponding to each sample were averaged, and the average value was used for subsequent analysis and discussion.

For 15% Papyrus, 15% Glass fiber and 70% Polyester Hybrid composite

Experimental result Table 11 Experimental result 15% Papyrus, 15% Glass fiber and 70% Polyester Hybrid composite (Absorbed Energy).

Lamina	Sample ID	Test 1 (U_c) (J)	Test 2 (U_c) (J)	Test 3 (U_c) (J)
Unidirectional	B1	21	21.6	21.6
Woven	B3	19.8	19.5	18.8
chopped	B5	18.8	19.8	18.3

Simulation Result of Equivalent (von-Mises) Stress for 15%/15%/70% unidirectional Lamina Papyrus/Glass fiber hybrid Composite.

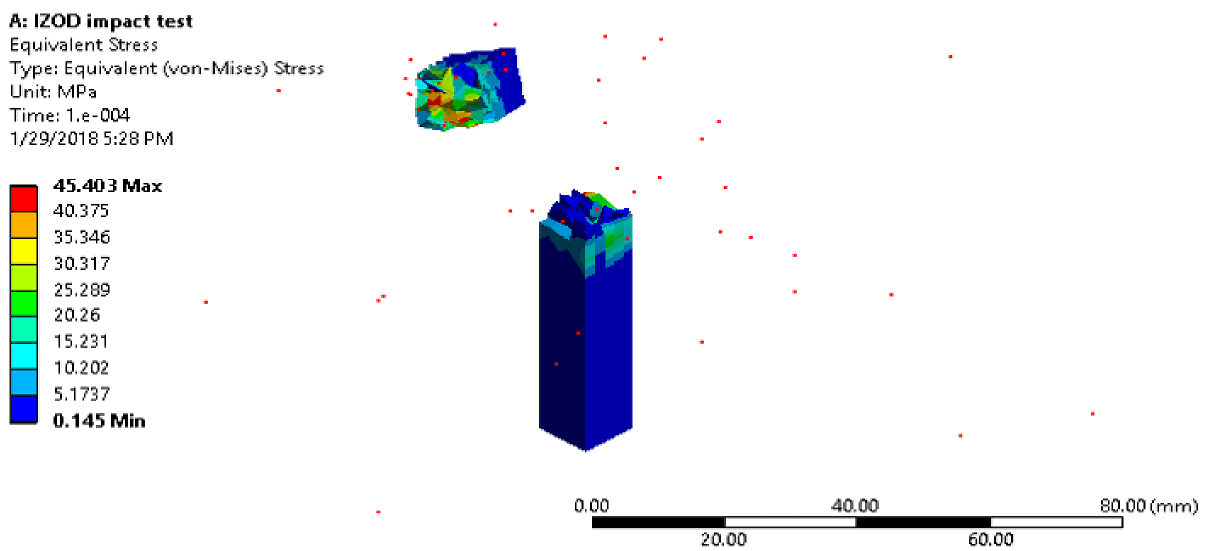

Figure 8 Simulation Result of Equivalent stress for unidirectional lamina.

The experimental results revealed that, among the papyrus fiber composites, the unidirectional laminate with a composition of 30 wt.% papyrus fiber and 70 wt.% matrix exhibited the highest average impact strength of **22.84 kJ/m²**, outperforming the woven and chopped laminates. Furthermore, the 30 wt.%/70 wt.% papyrus composite demonstrated superior impact strength compared to the 20 wt.%/80 wt.% composition across all laminate configurations.

Similarly, the results presented indicate that the unidirectional hybrid composite containing **15 wt.% papyrus fiber, 15 wt.% glass fiber, and 70 wt.% matrix** achieved the highest average impact strength of **28.53 kJ/m²** among all the hybrid composite laminates investigated. In addition, the hybrid composite with a composition of 10 wt.% papyrus fiber, 10 wt.% glass fiber, and 70 wt.% matrix exhibited higher impact strength than the composite containing 10 wt.% papyrus fiber, 20 wt.% glass fiber, and 70 wt.% matrix for all laminate orientations.

During impact testing, the unidirectional hybrid composite with a composition of **15 wt.% papyrus fiber, 15 wt.% glass fiber, and 70 wt.% matrix** did not undergo complete fracture; instead, it exhibited a hinge-like failure mode. Examination of the fractured surface revealed extensive fiber pull-out, indicating significant energy absorption during crack propagation. The superior impact strength of this composite may be attributed to the combined effect of fiber pull-out mechanisms and the balanced reinforcement provided by equal weight fractions of papyrus and glass fibers (15 wt.% each), which enhanced stress transfer and improved resistance to impact loading.

4. Conclusions and Recommendations

The present study investigated the impact strength characteristics of papyrus fiber composites and papyrus/glass fiber hybrid composites. Based on the experimental results, the following conclusions can be drawn:

1. The impact strength of composites reinforced with unidirectional fibers was found to be significantly higher than that of composites reinforced with woven and chopped fibers. This observation was further supported by the fracture patterns exhibited by the tested specimens.
2. Two categories of composites, namely papyrus fiber composites and papyrus/glass fiber hybrid composites, were successfully fabricated and evaluated. The results demonstrated that the incorporation of glass fibers into the papyrus composites enhanced their impact strength.
3. The impact strength of the hybrid composites increased with increasing glass fiber content. The maximum impact strength was achieved when the papyrus fiber and glass fiber contents were equal, corresponding to 15 wt.% papyrus fiber and 15 wt.% glass fiber.
4. The presence of voids within the composite structure adversely affected the impact performance, resulting in a noticeable reduction in impact strength.
5. Within the scope and limitations of the present investigation, the composite containing 15 wt.% papyrus fiber and 15 wt.% glass fiber exhibited the highest impact strength. This composition is therefore considered the optimum reinforcement ratio for effective load transfer and improved impact resistance.

Recommendation: Future studies may focus on optimizing the manufacturing process to minimize void formation, investigating different fiber surface treatments, and evaluating additional mechanical and durability properties to further enhance the performance of papyrus/glass fiber hybrid composites for engineering applications.

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