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Evaluating the Structural Integrity of Fibreglass for the Manufacture of Headgears

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Abstract

A composite material is made up of two phases, the matrix, and the reinforcing materials. The reinforcing material is embedded over matrix material. The reinforcing material works to make the matrix material harder. A fibreglass reinforced composite was developed using E-glass fibre reinforcement and epoxy resin matrix. The composites were produced using the hand lay-up technique with varying fibre percentage of 9%, 13% and 25% by weight percentage of fibreglass mat at orientations of 0˚, 15˚, 45˚, and 90˚ chosen at random. A 13% by weight percentage of chopped mat was also developed for purpose of comparison. The fabricated composites were subjected to tensile test, flexural test, impact test, punch shear test and hardness test to ascertain the appropriate fibre contents and orientation that is optimum for the manufacture of headgears. Analysis of Variance was carried out to determine level of significance and percentage contribution of the parameters. The results show that both fibre orientation and percentage of fibre content reinforcement of have significant influence on the strength and fracture energy of the composite .The fibre orientation has a higher impact on the strength of the composite (79.74%) while the percentage of fibre reinforcement has a lesser impact on the tensile strength of the composite (20.26%). However, the fibre orientation has a lesser impact on the fracture energy of the composite (24.54%) while the percentage of fibre reinforcement has a higher impact on the fracture energy of the composite (75.46%) The result from this study shows that the increase in fibre content increases flexural strength and impact toughness of the fibreglass reinforced composite. A fibre orientation of 90˚ and fibre reinforcement of 25% wt. was determined to be optimally suitable for the manufacture of headgears.

Keywords

Headgears, Fibre Glass, Fibre Orientation, Polymer Composites

1. Introduction

Over the years, protective head gear manufacturers have employed different materials in the production of cheap strong and effective head gears. This ranged from the use of steel, leather, aluminium, plastic, and Bakelite before fibre glass headgear production proved to be a worthy technology.

Fibreglass materials are of economic importance and its products are beneficial to safety engineering applications. Fibreglass generates rising, essential, and cost-effective products widely beneficial to the industrial spectrum either as one of many types of strengthening, as a fabrics or other products for acoustics, electrical, and thermal insulation, or more lately for fast insulation. Fortunately, in nearly unlimited supply, the raw materials are easily and economically acquired from commonly accessible inorganic indigenous ores. A large proportion of the world's fibre glass is used to strengthen plastics [1]. The types of fibreglass along with their various commercial products have wide applications, Fibreglass types can be differentiated by their various chemical compositions, physical properties, and the varying ASTM standards for each of the types [2]. The most common reinforcing material in the marine application (construction of ships, yacht and ferries) is still E-glass fibre, which has a good maximum tensile strength, about 2200 MPa, and an ultimate tensile strain of about 2.5% combined with outstanding resistance to moisture and chemical aggression. E-glass, due to its chemical composition has excellent electrical insulation properties. Glass fibres with high-strength glass are generally known as S-glass in the United States and R-glass in Europe. S glass has a higher content of SiO_2, Al_2O_3, and MgO than E-glass. Both the E-glass and the S-glass lose up to half their tensile strength when the temperature increases from the 70˚F (room temperature) to 1000˚F (approx. 540˚C), even if both fibre types still preserve a good resistance to corrosion [3] [4] [5].

Fibre-reinforced polymer composites can provide a much better strength-to-weight ratio than metals, sometime by 15%. The lower weight results in lower fuel consumption and emissions, enhanced aerodynamic efficiency, lower manufacturing costs. The aviation industry was the first attracted to such benefits and it was the manufacturers of military aircrafts who initially seized the opportunity to use composites characteristics to improve the speed and flexibility of their products. E-Glass fibres are majorly deployed in small passenger aircraft parts, radomes, and rocket motor casings while S-Glass are deployed in regions with high loadings because of its high specific strength, fatigue and corrosion resistance. Generally, fibre composites have a few drawbacks: some of the corresponding laminates display weak interfaces adhesion, yielding in poor resistance to out-of-plane tensile loads; susceptibility to impact-damage and strong possibility of some internal damages evolving unnoticed; moisture absorption and consequent degradation; occurrence of possible manufacturing defects [6].

Weight improvements and impact performance of air craft parts without compromising relevant properties have been studied, Qin *et al.*, (2018) [7] developed glassfibre reinforced polymers (GFRP) incorporating ferromagnetic microwires to improve the impact performance. Based on both the absorption and impact behavior, the study proposed a design of the microwire/GFRP composites to achieve best possible absorption and impact performance desirable for aeronautical structures and wind turbines.

In this study we will consider the mechanical and structural qualities of fibreglass and determine it suitability to produce head gears and possibly consider its eligibility for mass production. Fibreglass is light in weight, very durable and very powerful. Compared to metal, its bulk strength, stiffness and weight, hardness, transparency, chemical attack resistance, stability, and inertness, as well as desirable fibre characteristics such as strength, flexibility and stiffness are also very beneficial compared to metals [8]. The best part of fibreglass is its ability to get moulded into various complex shapes, used widely for the manufacture of structural composites, printed circuit boards and a wide range of special-purpose products (bathtubs, boats, aircraft, roofing, and other applications [9].

Studies had been carried out to investigate the necessary criteria for the successful manufacture of headgears. The tensile dynamic behaviour of a quasi-unidirectional E-glass/polyester composite was investigated for a non-unidirectional material composed of 5% fibre volume ratio of weft fibres. The weft fibres of 5% fibre volume ratio observed greater Young's modulus and improved the failure stress (40 MPa) [10]. The compressive and impact behaviour of discontinuous glass fibre reinforced epoxy composites with addition of fillers was investigated by Gupta *et al.* [11]. The result showed fly ash particles led to reduced compressive and impact strength of the composites compared to the calcium carbonate filler in the composites. The aspect ratio of the fibre increased the compressive strength and decreased the impact strength.

There is need to understand the head anatomy, anthropometry, biomechanics, fits, materials, manufacturing, and testing standards for headgears manufacture. Mamalis *et al.* (1996) [12] investigated the crashworthiness of the square frusta fibreglass composite material. The fibreglass was subjected to axial compression at various strain rate and the effect of the specimen geometry and the loading rate on the energy absorbing capacity of the fibreglass was experimentally documented. The mechanics of the axial crumbling process from macroscopic and microscopic points of view were also investigated theoretically and experimentally. The collapse modes at macroscopic and microscopic scale during the failure process were observed and analysed. The results showed theoretical models are also efficient in predicting the energy absorbing capacity of a collapsed shell.

Several tests had been developed for assessment of protective headgears. Hajiaghamemar *et al.*, (2015) [13] investigated the potential use of impact test procedure. The study represented the preliminary assessment of the test apparatus for use in development of protective headgear designed to prevent injury due falls considering linear, angular acceleration and collision velocity at impact conditions. Adekomaya *et al.*, (2017) [14] analyzed the effect of fibre loading and orientation on the tensile and impact strength of the polymeric composite materials. Series of experimental works were done to demonstrate the manufacturing of glass-fibre reinforced epoxy resin with special attention on the influence of oriented reinforced composite material. A significant improvement was discovered in the mechanical properties of oriented reinforced composite materials due to changes noticed in the impact strength.

The development of the fibreglass had been studied using different techniques by Wallenberger *et al.*, (2010) [15] and El-Wazery *et al.*, (2017) [16]. Series of experiments were conducted to demonstrate the manufacturing of glass-fibre reinforced epoxy resin with special attention on the influence of oriented reinforced composite material. El-Wazery *et al.*, 2017 [16] developed a E-glass fibre with random oriented reinforced polymer composite by hand lay-up technique with varying fibre percentages (15%, 30%, 45%, and 60% by weight percentage). The best mechanical properties obtained at 60 wt% of glass fibre of fabricated composites show good comparison to the standard requirement for the use of fibreglass in headgear production [17]. The various mechanical properties except the impact strength were improved with increase in fibre glass volume and that an important characteristic of fibreglass-polyester composite is high toughness. Also, significant improvement was observed in the mechanical properties for oriented reinforced composite subjected to dynamic form of loading [14].

Kumar *et al.*, (2014) [18], constructed a fibreglass headgear using the fibreglass hand lay-up operation. They laid Emphasis on constructing the headgear with superior structural strength and stability over the polyethylene thermoplastic while also ensuring that the weight is kept as low as possible comparison with the polyethylene plastic headgear and ensuring that the product is economical. The fibreglass cloth was chosen keeping in mind various parameters concerning the weight and cost of the fibreglass reinforced glass headgear and ensuring that the mechanical properties were not compromised. Four layered glass specimens were tested for tensile strength, hardness and flexural strength and have been compared alongside the standard mechanical properties of a High-density polyethylene (HDPE) Industrial headgear. While the Fibreglass reinforced plastic (FRP) emerged as a clear winner over the HDPE Industrial headgear with respect to the structural properties, the study discussed the areas of research and need for improvement in design and in its economy.

2. Materials and Methods

2.1. Materials

2.1.1. Preparation of the Specimen

The fibreglass composite prepared contained epoxy resin matrix and E-glass variant reinforcement. The choice of the epoxy resin relies on its high chemical and solvent resistance, high Strength and good flexural strength, low cost and low toxicity, excellent adhesion to various substrates, low shrinkage, effective electrical insulation. The tensile strength of the resin ranges from 90 - 120 MPa and its modulus ranges from 3100 - 3800 MPa. The glass transition temperature range is from 150˚C - 220˚C. It has a bonding strength of about 2000 psi.

2.1.2. Test Equipment's

The mechanical tests were done on the specimen using the Universal Instron Machine, model 3369, maker (Instron), Monsanto Testing Machine for hardness and shearing and the Izod impact test machine.

2.2. Methods

2.2.1. Specimen Preparation

Three different combinations of composite specimen were prepared and cured at room temperature as tabulated in Table 1 using the hand-layup technique. The specimens were produced according to the ASTM standard, 200 × 30 sq·mm.

2.2.2. Hand Layup Technique

The moulds were prepared with the required dimension for the specimen using glass and plywood with smooth surface finish as shown in Figure 1. Release gel was sprayed on the mould surface to prevent sticking of the polymer matrix to the mould surface. Thin plastic (Perspex) sheets were used at the top and bottom of the mould plate to get a good surface finish for the product. The reinforcement was prepared in form of chopped strand mats (Figure 2) to fit in the mould and the epoxy resin in liquid form is mixed in suitable proportion with the curing agent at ratio 2:1. The mixture was spread in the mould and the process repeated for each layer of polymer and mat.

Figure 1. Specimen of mould.

Figure 2. Chopped mat of fiberglass.

Table 1. Specimen composition.

Composition and fibre orientation in the composite	Designation
9% wt fibre enhancement at 0˚ orientation	C_{11}
9% wt fibre enhancement at 15˚ orientation	C_{12}
9% wt fibre enhancement at 45˚ orientation	C_{13}
9% wt fibre enhancement at 90˚ orientation	C_{14}
13% wt fibre enhancement at 0˚ orientation	C_{21}
13% wt fibre enhancement at 15˚ orientation	C_{22}
13% wt fibre enhancement at 45˚ orientation	C_{23}
13% wt fibre enhancement at 90˚ orientation	C_{24}
25% wt fibre enhancement at 0˚ orientation	C_{31}
25% wt fibre enhancement at 15˚ orientation	C_{32}
25% wt fibre enhancement at 45˚ orientation	C_{33}
25% wt fibre enhancement at 90˚ orientation	C_{34}
13% wt chopped mat fibre enhancement at random orientation	C_{90}

2.2.3. Mechanical Test

The tensile strength test, punch shear test, impact test, flexural test and hardness test were conducted on the specimens. The tensile properties were obtained using the universal Instron machine. The ability of the composite to absorb shock and energy when subjected to dynamic loading was investigated using the impact test.

The resistance of the composite to plastic deformation resulting from indentation, abrasion and scratching and the stiffness of the fibreglass was investigated using the hardness test procedure. Also, the punching shear was designed to apply stress to the specimens for investigating the sliding failure of the material.

The flexural test exposes the flexural strength of the composite material specimens fabricated and it was carried out by using universal testing machine at 1000 kN full scale load capacity with a cross head speed of 5 mm/min according to ASTM standard D-790 (65 mm × 31.21 mm), thickness is 5.2 mm. Flexural strength of the composite's material was then obtained from the Equation (1).

$$\sigma_f = \frac{3FL}{2wt^2} \tag{1}$$

where F is the applied load (N), L is support span (mm), w and t are width and thickness of the specimen (mm), respectively.

2.2.4. Structural Integrity Test

The structural integrity measures the effectiveness and efficiency of the fibreglass in terms of its ability to withstand service loads without exceeding its allowable stress and deflection. The composites of epoxy E-glass (wet) and epoxy E-glass (UD) were both subjected to ANSYS software analysis to determine their various total deformation, maximum shear stress, maximum shear elastic strain, maximum principal stress, maximum principal elastic strain, equivalent stress, equivalent elastic strain, shear stress, deformation. The test piece was subjected to loading force of 2231.75278 N.

2.3. Data Analysis Technique

The randomized completely block design (RCBD) is probably the most frequent used technique. The fundamental idea of the RCBD is to group experimental material together into homogeneous blocks. The object of this grouping is to keep the errors within each group as small as possible [19]. The randomized complete block design is chosen for the following advantages:

1) Using blocks of more homogeneous experimental material usually results in more accurate results than if a completely randomized design is used.

2) Any number of treatments and any number of replicates (blocks) can be used. Whereas, In the complete block design, every treatment will have the same number of replicates.

The model for the Complete Randomized Block Design is defined as:

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}$$

where

y_{ij} is the random variable representing the response for treatment i observed in block j.

μ is a constant (which may be thought of as the overall mean)

τ_i is the additive effect of the i^{th} treatment ($i = 1, 2, 3, \cdots, k$)

ε_{ij} is the random error for the i^{th} treatment in the j^{th} block.

SS denotes Sum of Squares, MS denotes Mean of Squares, df denotes degree of freedom,

The blocks are the respective fibre enhancement percentage represented below

Block 1 = 9%, Block 2 = 13%, Block 3 = 25%

The treatments are the respective fibre orientation represented below

Treatment 1 = 0˚ Fibre orientation, Treatment 2 = 15˚ Fibre Orientation

Treatment 3 = 45˚ Fibre Orientation Treatment 4 = 90˚ Fibre Orientation

The yield are the respective outputs for each experiment *i.e.* (tensile strength, strain, flexural strength).

3. Results and Discussions

3.1. Tensile Properties

The mechanical test exposes the yield strength, ultimate tensile strength, and fracture strength of the material. The maximum tensile stress sustained by each of the variant fibreglass is as shown in **Figure 3** and **Table 2**. For 9% fibre reinforcement, a tensile strength of 40.5773 Mpa is recorded and it increased to 40.5981 Mpa, 47.0023 Mpa and 48.9894 Mpa as the fibre orientation is increased to 15˚, 45˚ and 90˚ respectively. The same trend is observed for subsequent levels of fibre reinforcement (13% and 25%) as it is observed that the increase in fibre orientation provides gives rise to increment in tensile strength of the

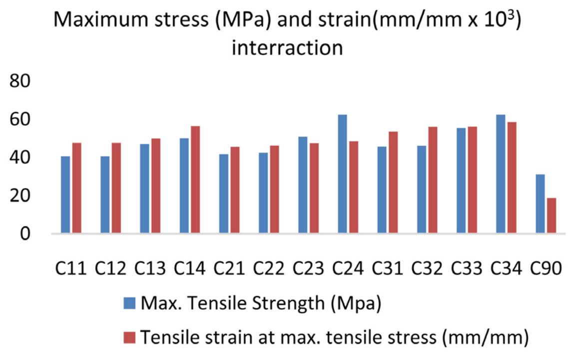

Figure 3. Maximum stress-strain evaluation for fibreglass reinforce composite.

Table 2. The tensile strength of varieties of fibre reinforcement with different fibre orientation.

Block (fibre enhancement)	Treatment (Fibre orientation)			
	1	2	3	4
1	40.5773	40.5981	47.0023	48.9894
2	41.5543	42.3216	50.7849	62.2472
3	45.5616	45.9989	55.3298	58.4000

composite. For same fibre orientation of 0˚, 15˚ and 45˚, an increase in in fibre reinforcement up to 25% increases the tensile strength. However, there is an exception for 90˚ fibre orientation as the strength increases to 62.2472 Mpa at 13% fibre reinforcement while a lesser strength is recorded at 25% fibre reinforcement.

Table 3 shows the two-factor Analysis of variance for the strength recorded which was dependent on the percentage fibre-reinforcement and fibre orientation. It is shown that both fibre orientation and percentage fibre reinforcement have significant influence on the strength of the composite at level of significance $\alpha = 0.05$ as the F-value of 15.557 and 5.929 exceeds the critical F value (Fcrit) of 4.757 and 5.143 for fibre orientation and percentage fibre reinforcement respectively. The percentage contribution of fibre orientation and fibre reinforcement to the tensile strength of the composite is 79.74 and 20.26 respectively, this implies fibre orientation is the most significant parameter as the composite is typically an anisotropic material which is greatly dependent on the orientation of fibre.

The relative comparison is a measure of the material deformation relative to the maximum stress. The relative comparison of the composites as shown in **Figure 4** reveals that the 13% wt chopped mat fibre enhancement at random orientation (C90) has the highest performance relative value of 1.66 followed by the 13% wt fibre enhancement at 90˚ orientation (C24) with relative value of 1.29.

The maximum energy at fracture sustained by each of the variant fibreglass is shown in **Figure 5** and **Table 4**. For 13% wt. and 25% wt. fibre reinforcement, as

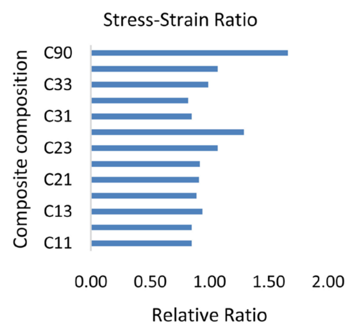

Figure 4. Relative values of composite maximum stress to strain.

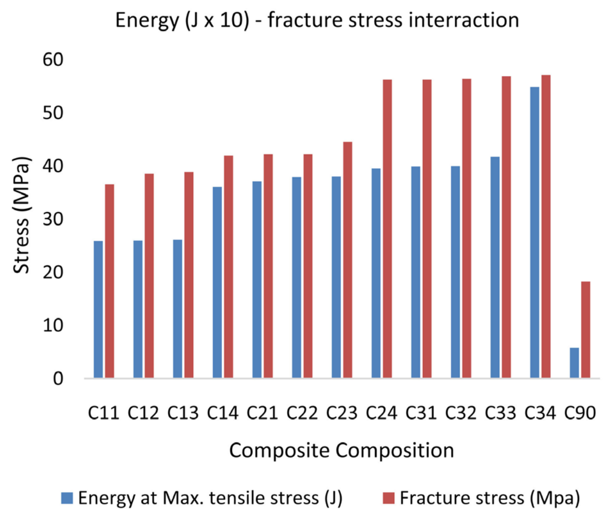

Figure 5. Energy and fracture stress properties of the composite material.

Table 3. Analysis of variance for tensile strength obtained from varieties of fibre reinforcement with different fibre orientation.

Source of Variation	SS	Percentage Contribution	df	MS	F	P-value	F crit
Fibre Reinforcement	104.240	20.259	2.000	52.120	5.929	0.038	5.143
Fibre Orientation	410.295	79.741	3.000	136.765	15.557	0.003	4.757
Error	52.746		6.000	8.791			
Total	567.281	100	11.000				

Table 4. The fracture energy of varieties of fibre reinforcement with different fibre orientation.

Block (fibre enhancement)	Treatment (Fibre orientation)			
	1	2	3	4
1	25.9120	25.9960	25.1150	36.0010
2	37.1111	37.9040	38.0000	39.5303
3	39.9240	39.9670	41.7630	54.8800

the fibre orientation is increased to 15˚, 45˚ and 90˚ the energy absorbed before fracture increases. However, there is an exception for the 9% wt. fibre reinforcement as the energy increases from 0˚ to 15˚ fibre orientation while it decreases from 15˚ to 45˚ fibre orientation. Table 5 shows the two-factor Analysis of variance for the fracture energy recorded which was dependent on the percentage fibre-reinforcement and fibre orientation.

It is shown that both fibre orientation and percentage fibre reinforcement have significant influence on the strength of the composite at level of significance $\alpha = 0.05$ as the F-value of 5.559 and 24.358 exceeds the critical F value (Fcrit) of 4.757 and 5.143 for fibre orientation and percentage fibre reinforcement respectively. The percentage contribution of fibre orientation and fibre reinforcement to the tensile strength of the composite is 25.54 and 74.46 respectively, this implies the percentage of fibre is a more significant parameter on the fracture energy of the composite.

The test reveals that the 25% wt fibre enhancement at 90˚ orientation (C34) has the maximum energy compared to others but also undergoes the highest form of deformation as seen in Figure 6 shows the absorbed energy of the composites. The relative stress-strain value for C34 is 1.07 and of same value with C23 as shown on Figure 4, however energy absorbed by C23 (13% fibre reinforcement at 45˚ orientation) is lower. The C24, C31, C32, C33, and C34 composite were observed to have the highest range of Moduli indicating elasticity

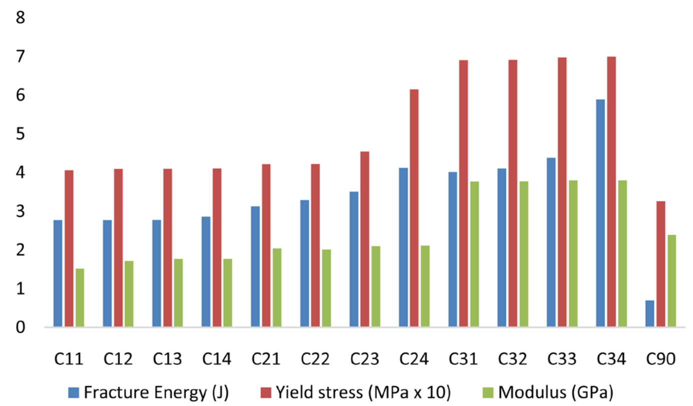

Figure 6. Absorbed energy and failure chart for fibreglass reinforced composite.

Table 5. Analysis of variance for Fracture energy recorded from varieties of fibre reinforcement with different fibre orientation.

Source of Variation	SS	Percentage Contribution	df	MS	F	P-value	F crit
Fibre Reinforcement	514.243	**74.462**	2.000	257.121	24.358	0.001	5.143
Fibre Orientation	176.369	**25. 538**	3.000	58.790	5.569	0.036	4.757
Error	63.337		6.000	10.556			
Total	753.949	100	11.000				

characteristics of the composites. These range of the composite also have the highest values of yield strength showing their ability to undergo large plastic deformation before fracture.

3.2. Flexural Properties

The related properties to the flexural rigidity of the fibreglass composite is as expressed in Figure 7. The analysis shows that the flexural strength of the composite increases with increasing percentage content of the fibre. The influence of the fibre orientation is more pronounce in the 13% fibre content composite (C_{21} - C_{24}). At a higher fibre content, the influence of the orientation of the fibres within the composite content is lesser as exposed in composite compositions C_{31} - C_{34}). A sustainable composite fabrication between C_{24} and C_{34} is favoured from this study for the manufacture of the headgear.

3.3. Impact Toughness

The variation of impact Toughness with the glass fibre content of glass fibre reinforced polymer composites is as shown in Table 6. The impact resistance of the composite improves with the content of the fibre reinforcement. The impact resistance is considered low due to resins brittle nature. However, results showed that reinforcing it with glass fibres improves the impact resistance.

3.4. Selection Criteria for Headgears

Table 7 shows the ranking of the composite based on desireable mechanical properties for headgear manufacture. A rank of 1 shows the composite has the most suitable property while a rank of 12 indicates the composite has the least suitable property. It is seen that C34 (25% wt. fibre reinforcement at 90˚ fibre

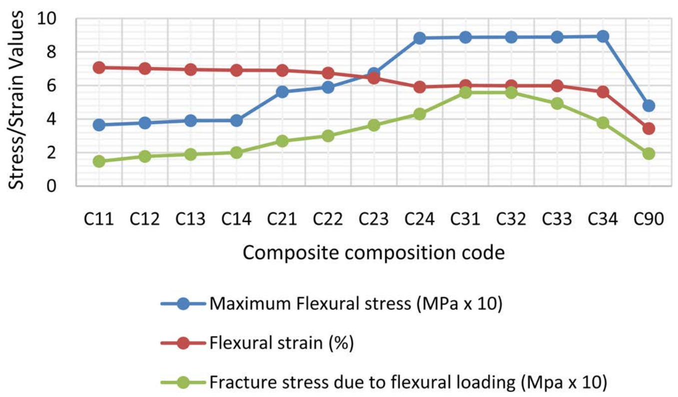

Figure 7. Flexural rigidity analysis chart.

Table 6. Variation of impact Toughness with the glass fibre content of glass fibre reinforced polymer composites

Designation	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{31}	C_{32}	C_{33}	C_{34}	C_{90}
Impact Toughness (J)	8.3	8.3	8.4	9.1	8.7	8.7	9.0	10	9.1	9	10	11	9.6

Table 7. Ranking of composite based on desireable properties for headgear manufacture.

Composite	Rank			
	Tensile Strength	Impact Toughness	Energy at fracture	Flexural Strength
C11	12	11	12	12
C12	11	11	11	11
C13	10	10	10	10
C14	9	4	9	9
C21	8	8	8	8
C22	7	8	7	7
C23	6	6	6	6
C24	1	2	4	5
C31	5	4	5	4
C32	4	6	3	3
C33	3	2	2	2
C34	2	1	1	1

orientation) possesses the highest impact toughness, Highest Ffracture energy and Highest flexural strength. Hence, it is optimally suitable be used in the fabrication of headgears.

4. Conclusions

This study experimentally investigated the structural integrity of fibreglass in a composite that makes it fit for the local manufacture of headgears. The mechanical characteristics of the various composite produced were investigated. The percentage of the fibreglass in the composite and the fibreglass orientation while ensuring that the mechanical properties were not compromised. The investigations were carried out by subjecting the samples to various mechanical tests. The results show that both fibre orientation and percentage of fibre content reinforcement of have significant influence on the strength and fracture energy of the composite .The fibre orientation has a higher impact on the strength of the composite (79.74%) while the percentage of fibre reinforcement has a lesser impact on the tensile strength of the composite (20.26%). However, the fibre orientation has a lesser impact on the fracture energy of the composite (24.54%) while the percentage of fibre reinforcement has a higher impact on the fracture energy of the composite (75.46%). The result from this study shows that the increase in fibre content increases flexural strength and impact toughness of the fibreglass reinforced composite.

Successful fabrication of glass fibre with optimal fibre orientation of 90˚ and fibre reinforcement of 25 wt% was achieved and cost effective using simple hand lay-up technique. The resulting composite is found suitable for the manufacture of local headgears with comparable strength and cost performance with standards.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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