Bio-Inspired Innovation: Assessing Tensile and Impact Behavior of Fish Scale Hybrid Composites Through Multiscale Analysis

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**Abstract*.*** This study investigates the structural performance of a novel hybrid composite composed of 20% fish scale powder, 20% glass fiber, and 60% epoxy resin. Motivated by the growing demand for sustainable and eco-friendly materials, the research explores the potential of fish scale-reinforced composites in structural applications. Both experimental and computational assessments are conducted to evaluate tensile strength, stiffness, and energy absorption using standard testing equipment and ANSYS simulation tools. Results from experimental testing and numerical simulations confirm the composite’s practical viability. The synergy between fish scale powder and glass fiber enhances the mechanical properties of the hybrid composite, yielding notable improvements in tensile strength and impact resistance. This work highlights the promise of utilizing bio-waste materials as functional reinforcements in advanced composites, paving the way for their integration into lightweight and sustainable structural designs.

# INTRODUCTION

Research on composite materials continues to develop intensively because they combine excellent mechanical capabilities alongside high versatility. Hybrid composites comprised of multiple reinforcement materials embedded in polymers achieve exceptional performance through the combination of various materials benefits. The use of bio-based materials such as fibers and powders from natural sources has arisen as alternative sustainable reinforcements to replace synthetic materials while helping protect both the environment and waste resources. The interest in fish scale-derived materials continues to rise because of their distinctive hybrid composition along with exceptional structural features. The main components in fish scales comprise collagen and hydroxyapatite thus producing a material with strong resistance against damage that shows potential for usage in composites.

The synthetic reinforcement glass fiber stands out for its strength capabilities and lightweight features alongside environmental resistance quality. By uniting epoxy resin and glass fiber elements the composite properties improve substantially to enable structural use and greater impact tolerance to meet multiple design requirements. Epoxy resin, a thermosetting polymer, serves as an effective matrix due to its excellent adhesion, chemical resistance, and mechanical stability. Applied forces undergo distribution throughout the composite materials by the matrix which strengthens the overall performance of the composite.

Standardized testing procedures guide the experimental evaluation of composite materials during mechanical property assessments. The ASTM D638 testing method determines three vital mechanical characteristics including ultimate tensile strength as well as modulus of elasticity and elongation at break during tensile testing. According to ASTM D256 standard procedure impact resistance measures how much energy a material can absorb during unexpected loading actions. Such tests supply fundamental data about composite material reliability properties that enable analysis for real-world usage.

Computer simulation established itself as a vital method alongside experimental testing to forecast material reaction during various loading scenarios. Technical researchers benefit from ANSYS and other FEA software because they can develop virtual models of composite materials that offer crucial numerical outcomes which enhance physical testing results. A composite material’s mechanical capabilities become fully understood through experimental methods combined with computational methods which leads to better engineering application-oriented materials optimization.

K. Ramesh Babu et al. (2019) conducted research to analyse the mechanical properties' response to different fish scale volume fractions. The filler material leads to moderate improvements in the mechanical capabilities of the composite materials according to the investigation results. The previous research indicates that adding 30% fish scale filler to composite volume results in maximum tensile strength enhancement. The material that reaches 30% volume fills the maximum bending strength while reaching 25% volume fills the peak impact strength. The mechanical properties decreased after adding more fish scale filler since the filler presented poor dispersion inside the epoxy matrix. The positive recorded results suggest fish scale natural filler has potential to combine with epoxy resin for composite development [1].

The research conducted by P. Raja Sekaran et al. (2020) analysed bony fishes using ctenoid and ganoids scales. The teeth structure of bony fish scales consists of a mucus-protected shield layer according to scientific recommendation. The research evaluates fish scale fibre performance as epoxy polymer reinforcement material through various volume fraction tests between 5% and 25%. The optimal material properties in fish scale fiber polymer composites required a 20 percent volume addition of practical fiber content. Higher material performance results from fish scale fibres which are well distributed inside the epoxy matrix while also providing improved attachment between fibres and matrix. The mechanical properties of the composite were probably impacted when the fish scale fibre content achieved 25% volume density due to the observed clumping of the fibres [2].

Available long fibre segments underwent size reduction to small pieces (8–10 mm) according to Khatroth Dattatreya et al. (2023) because these shortened fibres produce stable composite properties. The clearing process makes fibers ready for resin attachment to take place [3].

The chemical exposure to NaOH in the treatment method eliminates fiber moisture contents to improve its structural strength according to D. Chandramohan et al. (2017). The flexural rigidity of the fibre improves through chemical treatment methods. Last this technique eliminates the entire set of impurities surrounding the fibre material and organizes its molecular structure [4].

The research by Venkatesh Naik (2021) showed plant and animal-based fabrics including jute, sisal, banana and flax, hemp, coir as well as kenaf demonstrate capabilities to replace synthetic fabrications in automotive applications. The organic reinforced composite material provides a combination of strength and stiffness and shows excellent electrical insulation properties and thermal insulation capabilities and ability to absorb sound together with high fracture toughness. Car applications demonstrate potential to decrease product expenses and material loss through the utilization of natural fibre-based composites [5].

# METHODOLOGIES

## Experimental Study – Procurement

The fabrication process of fish scale-based hybrid composite requires LY556 Epoxy Resin as one of its fundamental materials. Epoxy acts as the main matrix in composites that bonds reinforcement agents. It distributes the stress load from the composite while maintaining its integrity. The adhesive strength of this material makes it highly preferable for composite manufacturing since it reinforces structural stability. Applications requiring durability improve through epoxy's combination of high mechanical strength, chemical resistance along with stiffness properties [6-10]. Epoxy resins belong among the most effective bonding materials which makes them one of the most commonly used resins for composites. HY951 Hardener enables epoxy resin to create a thermosetting polymer product suitable for composites because it produces materials with superior mechanical strength alongside high chemical resistance and strong adhesive qualities. The amine-based HY951 hardener together with epoxy resin enables full curing through solidification while it reaches maximum hardness after a time that depends on temperature but generally requires 24 hours at room temperature. Scales of Fish (Labeo Catla, Ctenoid Type): This is a natural reinforcement which is extracted from Labeo Catla. The scales are collected from the local market. The size of the scale structure varies from 1 to 2 µm of thickness and 3 to 4 mm of diameter These scales are layered structured giving resilience and toughness to the composite. Fig.1 and Fig.2 reveals the processing of fish scales from procurement to grinded fish scale fiber [11-15].

A pile of white petals

Description automatically generated

1. Dried fish scales

A close-up of a white ground

Description automatically generated

1. Grinded fish scales

The synthetic reinforcement material glass fiber exhibits exceptional tensile strength together with being rigid. Glass fiber functions as a leading reinforcement material for composite materials because it strengthens their structures against impacts. The reinforcement choice is popular because of its superior strength-to-weight capability which leads to better mechanical performance in the composite material. The tensile resistance of carbon fiber composites exists between 1000 to 3000 MPa and their Young's Modulus remains within 70 and 90 GPa. The two main characteristics of this substance include outstanding material durability and excellent structural support features. Its transparency as well as its lightweight composition at 2.5 g/cm³ proves advantageous at temperatures above 800°C. The essential characteristics of epoxy combined with glass fiber strength enable valuable structural applications in aerospace and automotive industries [16-20].

## Compositions

Table 1 depicts the composition of the composite is based on the Volume fraction Percentage by Weight.

1. Composition of the composite material

|  |  |
| --- | --- |
| **Material** | **Percentage by weight** |
| Epoxy | 60 |
| Fish scale fibre | 20 |
| Glass fibre | 20 |

### Fabrication

The external coverings of Labeo Catla fish are small ctenoid scales which are clean and degreased, dried and then ground into fine powder form. This powder acts have a filler and is mixed with epoxy resin and HY951 hardener. The developed mixture is further incorporated with glass fibre and moulded into a material composite through the hand layup process. Fig.3 shows the composite that is then removed from the mold [21-23]. This material is cut into the dimensions by ASTM standards for specific experimental studies which is revealed in Fig.4.

A square object with a white surface

Description automatically generated with medium confidence

1. Fabricated composite material

A group of rectangular objects with black writing

Description automatically generated with medium confidence

1. Test samples for compression and flexural test with standard dimensions

### Tensile test

Tensile test is used to determine the strength of the material with respect to breaking by tension. In a tensile test, this load is used to determine the failure strength, stiffness or Young’s modulus and elongation of the specimen. Tensile strength offers understanding of load-carrying capacity of a material, free from fracture which is significant in structures. For purposes of this study, tensile test is done according to standards set under ASTM D638. This standard is for the determination of tensile properties of polymer matrix composites. In this testing configuration, a sample specimen of known cross-sectional area is subjected to a uniform rate of strain until fracture occurs [24-26].

### Impact test

The Izod impact test measures the ability of the material to withstand impact forces which are normally uncontrolled and dynamic. The test determines the toughness of the material when it is subjected to shocking impacts like those caused by a fall. In this study, impact strength testing can define the composite’s toughness which is an important factor for applications which requires high energy absorbing capacity [24-27]. This is done in accordance with ASTM D256 standard test methods which provide methods for determining the impact resistance of materials. In the test to measure surface hardness the weighted pendulum slams down, this strikes the notched specimen. The energy absorbed by the specimen to fracture is expressed as the impact strength, which gives an indication of the energy capacity of the composite material [28-32].

## Computational study

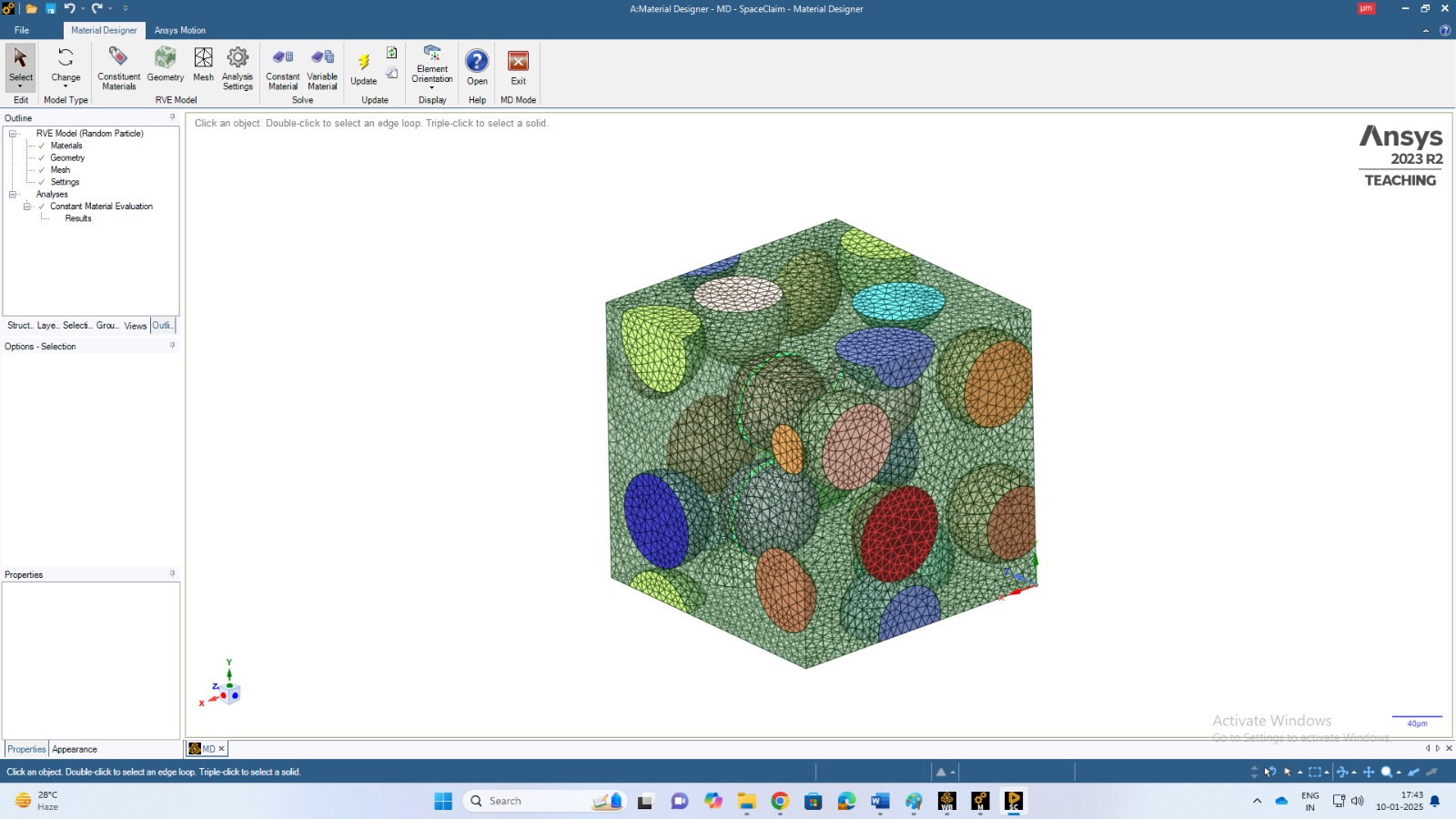
The computational analysis for the mechanical properties of the composite material is studied through the below section.

### Engineering data

The engineering data concerning fish scales and epoxy is supplied through the ANSYS Material Designer for micro-level analysis [33-39]. Given that the fibers from fish scales serve as fillers within the composite matrix, it is vital to effectively integrate their mechanical properties. This integration guarantees that the resultant material characteristics can be accurately incorporated and subsequently employed in ANSYS ACP (Ansys Composite PrepPost) for sophisticated analysis and simulation of the composite structure. The particle size of the fish scale filler utilized in the composite is specified as 80 micrometres, which promotes uniform dispersion and enhances reinforcement within the epoxy matrix. The engineering data relevant to this micro-analysis is detailed in Table 2. This refined composition and particle size information are essential for precise material modelling and performance forecasting during simulation and analysis [40-55]. Fig.5 illustrates the simulation analysis of the microstructure, while the mechanical properties obtained for the composite material are presented in Table 3.

1. Engineering data provided for micro analysis of fish scale-epoxy

|  |  |  |  |
| --- | --- | --- | --- |
| **Material** | **Density (g.cm^-3)** | **Young’s modulus (MPa)** | **Poisson ratio** |
| Fish scale fiber | 0.9 | 12 | 0.48 |
| Epoxy resin | 1.19 | 3800 | 0.35 |

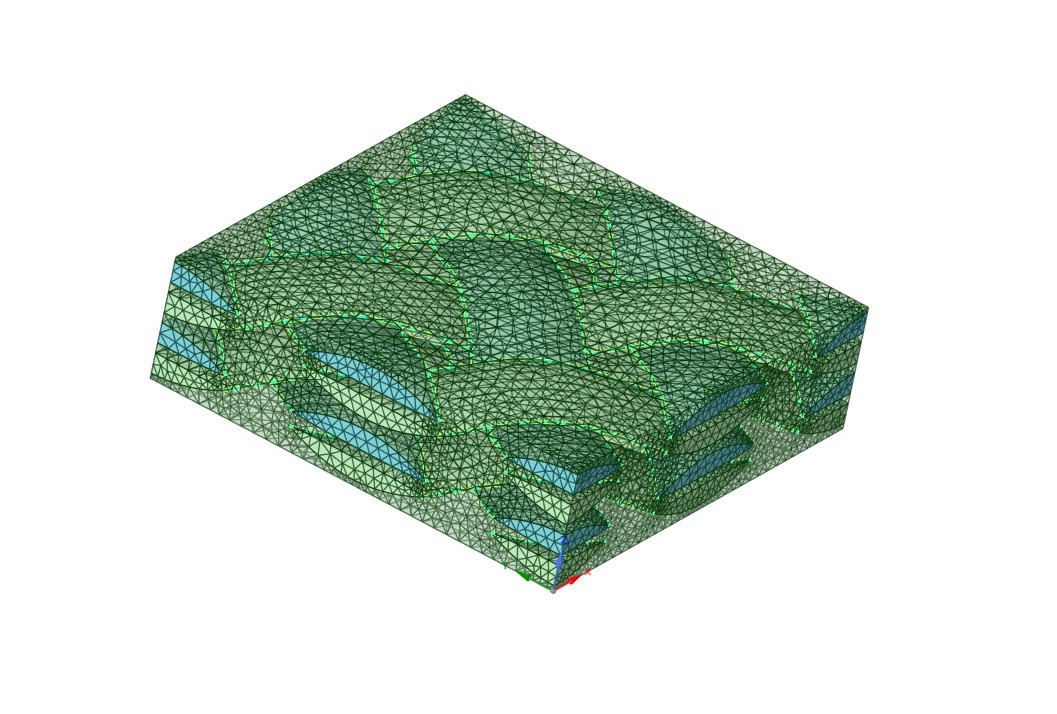


1. Micro analysis of Epoxy- Fish scale fiber material
2. Obtained mechanical properties for composite material

|  |  |  |
| --- | --- | --- |
| **Engineering constants name** | **Value** | **Unit** |
| E1 | 5052.4 | MPa |
| E2 | 5084.2 | MPa |
| E3 | 5086.1 | MPa |
| G12 | 1833.7 | MPa |
| G21 | 1849.9 | MPa |
| G23 | 1855.9 | MPa |
| nu12 | 0.35931 | - |
| nu13 | 0.36359 | - |
| nu23 | 0.36257 | - |
| rho | 1.1169 | g/cm3 |

### General properties

In the ANSYS Material Designer, the woven composite feature is employed to model various composite configurations. The matrix is adjusted to comprise 80% fish scale-epoxy composite, based on previous microanalysis findings. The overall mechanical properties of both the glass fiber and the fish scale-epoxy composite, as determined from the microanalysis, were incorporated into the material model. Additionally, analyses were conducted for all compositions, facilitating an accurate depiction of the two distinct matrix materials, each paired with its corresponding reinforcement configurations. The use of woven fabric allowed for a more effective simulation of fiber orientation and distribution within the matrix, leading to improved predictions of the composite's mechanical properties. Fig.6 illustrates the simulation analysis of the woven fabric composite material [56-66]



1. Micro analysis of Epoxy with glass fiber as woven material, material-1

### Computational procedure

The computational methodology for conducting mechanical tests encompasses multiple stages, commencing with the creation of the composite material in ANSYS ACP, followed by evaluation within the static structural module. Initially, the engineering data, obtained from microanalysis, is established for the matrix material, which consists of epoxy resin combined with fish scale fiber, alongside E-glass fiber utilized for reinforcement. The computational model is constructed in accordance with ASTM standards relevant to the mechanical tests, adhering to the specified dimensions. Subsequently, the model is discretized and arranged into fabric layers, with the details of the discretization process outlined in Table 4. The composite structure is composed of five layers, alternating between three matrix layers and two E-glass fiber layers. After the composite is produced in ACP, it is transferred to the static structural module for testing. Fig.7 to Fig.10 provides a visual representation of the aforementioned methodology [67-72].

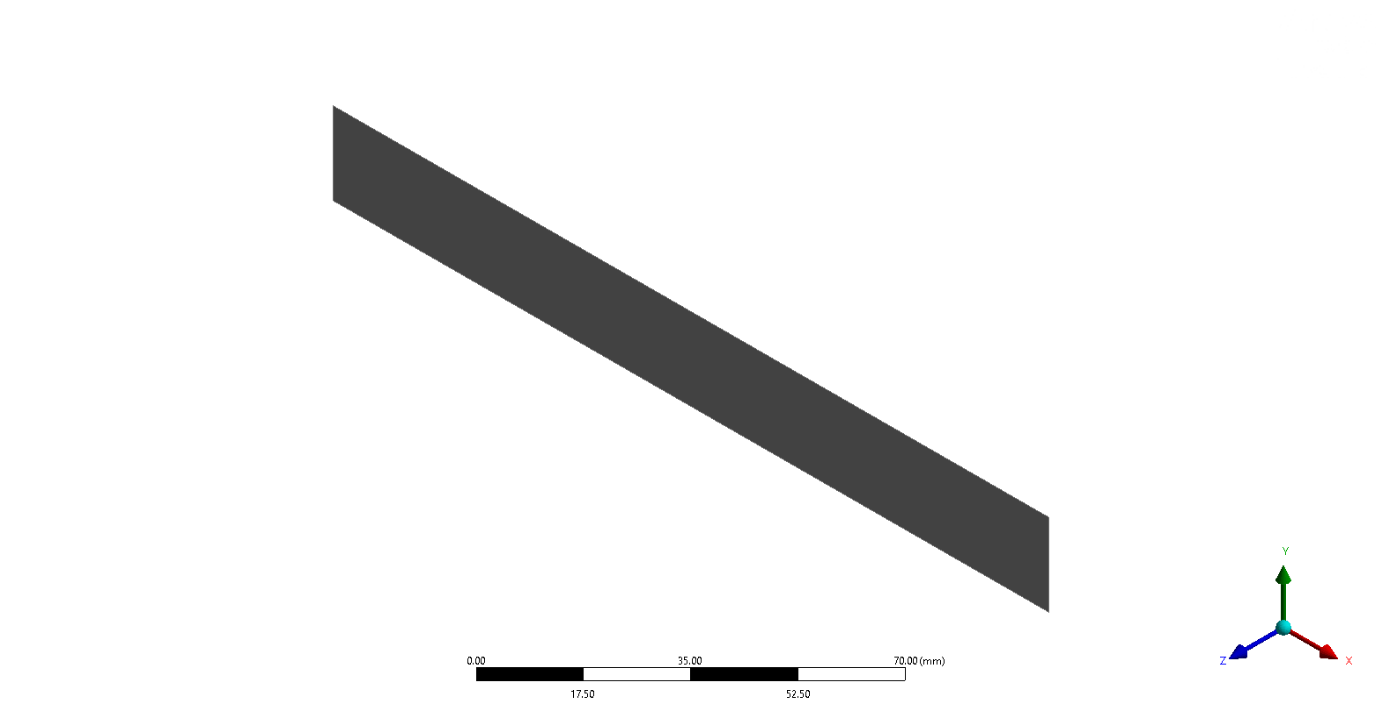
1. Details of discretization

|  |  |
| --- | --- |
| Physical preference | Mechanical |
| Element size | 1.0 mm |
| Use adaptive sizing | No |
| Smoothing | High |

A black and white image of a long thin line

Description automatically generated

1. Simulated model of the composite material with ASTM D638 dimensions for tensile testing



1. Simulated model of the composite material with ASTM D695 dimensions for compression testing

A black and white image of a long thin line

Description automatically generated

1. Simulated geometry of the composite material with ASTM D790 dimensions for flexural testing

A long grey rectangular object

Description automatically generated

1. Discretization of the computational model of the composite material

### Tensile test

Boundary conditions are applied, with one end fixed as a support and a tensile force of 3210 N applied to the other end, reflecting the experimental results that showed the specimen could withstand this load. The simulation is then executed for conventional glass fiber-epoxy matrix composite and glass fiber-fish scale epoxy matrix. The results are analysed to evaluate the material's tensile performance. The following Figures 11 and 12 visually represent the applied boundary conditions for mentioned procedures.

A long rectangular object with black lines

Description automatically generated

1. Fixed support given at one end as boundary condition for tensile test

A long rectangular object with black lines

Description automatically generated

1. Tensile load of 3210 N is given at the other end as boundary condition

# RESULTS AND DISCUSSIONS

## Experimental test result

The hybrid composite materials, illustrated in Figure 4, were prepared in accordance with ASTM standards D 638 and D 256. This section presents a discussion of the experimental results and their analysis. The performance assessment of the fish scale-reinforced hybrid composites, featuring different compositions, is carried out using tensile and impact testing methods. Fig.13 displays the samples of the composite materials that were tested.



1. Tested composite material samples

### Tensile test

The test specimen is clamped between two clamps and fixed firmly in a tensile testing apparatus. Under management, the force exerted to the specimen is gradually increased. In Figure 14 the tensile testing of the specimen can be observed. During the progressive test, the force and material deformation are measured as the test is carried out until the test specimen breaks. It offers very helpful information on the material's mechanical behaviour and tensile resilience. The load versus displacement graph of tensile test sample 1 and 2 can be observed in Fig.15 and Fig.16 respectively.



1. Tensile testing of the composite material

A graph of a line graph

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1. Force vs displacement graph of tensile test sample 1 with a cross-sectional area of 60.162 mm²

A graph with a line going up

Description automatically generated

1. Force vs displacement graph of tensile test sample 2 with a cross-sectional area of 47.385 mm²

### Impact test

In the Izod impact test, a pendulum hammer is used to strike one side of a specimen that has been notched. The notch is quite important because, when an impact is delivered, it causes the stress concentration at a specific place to fracture. A quantitative evaluation of the material's toughness is provided by noting the energy used by the test specimen during its fracture. In Fig.17 the Izod impact testing of the specimen can be observed. The material's appropriateness for applications where durability under abrupt loads is essential can be ascertained by using these absorption energy statistics to forecast the material's capacity to absorb impact forces during service. The results of the impact test revealed that the specimen can withstand an impact load of 2 joules in both the samples.



1. Impact testing of the composite material
2. Experimental results obtained from the tests

|  |  |  |
| --- | --- | --- |
| **Testing** | **Sample 1** | **Sample 2** |
| Tensile test (kN) | 3.210 | 1.710 |
| Impact test (J) | 2 | 2 |

The mechanical properties of the composite material under various tests are listed in Table 5.

## Computational Results

A computational analysis is performed to assess the physical and mechanical characteristics of the hybrid composite derived from fish scales. This section presents the results concerning the material's density, total deformation, and equivalent stresses experienced under applied loads [6-8]. Density plays a vital role in determining the composite's weight and structural efficiency, especially in applications that require lightweight materials [9-11]. Evaluating the density facilitates an understanding of the composite's appropriateness for the aerospace and transportation industries [12-14]. Furthermore, finite element analysis (FEA) is carried out using ANSYS to simulate the composite's response to various loading conditions [15-17]. The findings on total deformation offer valuable insights into the material's flexibility and displacement under stress, while the equivalent stress analysis indicates how the material handles and distributes applied forces [18-20]. These findings are crucial for assessing the composite's mechanical performance and its potential uses in practical applications [21-23].

### General properties

The mechanical properties, obtained through the procedure involving the microanalysis of the fish scale-epoxy matrix with the incorporation of fiber material as woven fabric reinforcement is listed in Tables 6 [24].

1. Obtained mechanical properties of composite material

|  |  |  |
| --- | --- | --- |
| **Engineering constants name** | **Value** | **Unit** |
| E1 | 14284 | MPa |
| E2 | 14250 | MPa |
| E3 | 9730.8 | MPa |
| G12 | 7287.3 | MPa |
| G21 | 3004.4 | MPa |
| G23 | 3004.4 | MPa |
| nu12 | 0.36336 | - |
| nu13 | 0.32462 | - |
| nu23 | 0.32453 | - |
| rho | 1.5717 | g/cm3 |

### Mechanical properties

This section presents the computational results of the mechanical tests, which includes the equivalent stress experienced by the composite materials. These results provide the material's mechanical behaviour under various types of loading, validating its performance and structural integrity based on the applied boundary conditions and load. The total deformation and equivalent stress experienced by the Glass fiber reinforced Fish scale-epoxy matrix composite material under tensile load can be observed from Fig.18 and Fig.19 respectively.

A colorful chart with black lines

Description automatically generated with medium confidence

1. Total deformation on material-1 under the tensile load of 3210 N

A line of lines with different colors

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1. Equivalent stress experienced by material-1 under the tensile load of 3210 N

# DISCUSSIONS

## Experimental interpretation

Tests of tensile behaviour and impacts evaluated the mechanical properties in fish scale-based hybrid composites. The experimental analysis indicates different mechanical properties between the two evaluated samples. Sample 1 demonstrated superior tensile strength than Sample 2 since it bore a higher test load of 3.210 kN compared to 1.710 kN. The tensile strength measurement showed that Sample 1 yielded 53.38 MPa yet Sample 2 reached 36.12 MPa thus demonstrating a stronger tensile performance by 47.8% in Sample 1. The impact test results produced consistent outcomes for both tests because the samples absorbed 2 J of impact energy without showing any variations. Tensile strength showed significant variation because material distribution and fiber alignment and minor fabrication irregularities could be responsible factors.

## Computational interpretation

From the computational analysis, FISH scale-based hybrid composite demonstrated compelling structural characteristics from both experimental and computational evaluation. The material showed elasticity by stretching 0.29 mm when subjected to a 3.210 kN force as it generated 82.137 MPa tensile force without losing its bending capabilities. The values generated through computation accurately match experimental tensile test findings thus proving the composite is dependable for bearing loads. The composite exhibits an optimal weight-to-strength relationship because of its density rate of 1.5717 g/cm³ which enables it to replace heavier synthetic materials. This advantageous characteristic makes the material suitable for vital weight-reduction applications in aerospace and transportation fields.

# CONCLUSIONS

Fish scale-based hybrid materials show great potential for mechanical performance according to the research findings. The practical use of fish scale-based hybrid composites for engineering projects will improve with studies that optimize the fabrication techniques and material consistency together with durability testing. The implementation of fish scale powder boosts mechanical properties yet sustainable features, yet the manufacturing of fish scale fibers remains complex and time-consuming. Large-scale industrial production may suffer from this time-consuming preparation method which lowers the factory-scale ability of fish scale powder compared to synthetic alternatives.

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