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Optimization of Fiber-Polymer Ratios for Enhanced Mechanical Properties in 3D-Printed Composites

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Abstract: The ratio of fiber to polymer is significant for improving the mechanical properties of fibrous polymers that are used for 3D printers' applications in aerospace, automobile and Biomedical industries. This research on the behavior of fiber reinforced polymer composite material compares the impact of different fiber content on tensile strength, flexural strength, and impact resistance of 3D printed fiber reinforced polymer composites. From a range of fiber contents of 10%, 20%, and 30%, efficiency rises progressively with increasing fiber ratios, with the composite's maximum tensile strength and flexural strength reached 60 and 55 MPa, respectively at the 30% fiber ratio. Nevertheless, if a structure exceeds the maximum of averaged values, one can meet more severe problems that have been described as brittleness and limited versatility in this study, which means that an optimal use of composites should imply a subtle balance between these parameters. Fiber-matrix adhesion is also a significant factor discussed in the study, which is a key parameter that defines the ultimate strength and life of the developed composites.

These results do not only contribute to the knowledge of using 3D-printed composite materials but also provides benefits for proposing specific ideas in industries which attempt to introduce lightweight and high strength parts in their production lines. Some areas for further investigation are the effect of using other fiber orientation and the use of the hybrid fiber-polymer composites to achieve better mechanical properties and overcome problems arising from high fiber content. More specifically, this work helps to enrich the existing knowledge on the nutritional values of fibers and polymers with the aim of achieving optimal fiber-polymer ratios for enhancing the technique of three-dimensional printed composites.

Keywords: Hybrid Composites, Optimization, Mechanical Testing, Impact Resistance, Polymer Matrix, Adhesion, Fiber-Polymer Composites

I. INTRODUCTION

The situations such as Fiber Polymer Composites or the FPCs through 3D filaments are employed in core sectors such as aerospace, automotive and biomedical owing to their properties such as strength, required weight and flexibility. These composites feature an excellent balance of mechanical properties provided by the use of high-performance fibers and polymers, ideal for applications that require high-performance materials in addition to significant design freedom. Fiber-polymer ratio is an important parameter because it influences properties such as tensile strength, impact strength, and flexibility. Greater fiber volume typically leads to increased strength and stiffness and greater polymer volume results in increased flexibility and impact resistance. Much caution is required here; far too much fiber may lead to brittleness and potential print problems, while the other extreme degrades the strength of the composite.

This report explores key research questions: concerning the effects of fiber-polymer ratios on mechanical characteristics, which proportion provides an optimal combination of tensile strength and toughness and the issue of the fiber placement inside the polymer environment. Therefore, based on the understanding of the optimum fiber to polymer ratio in 3D printed composites, this study seeks to increase reliability and efficiency of the composites in enhanced application domains. With this type of optimization, material properties are not only enhanced but the case for 3D printing as an effective tool for the manufacture of high-performance parts is further bolstered.

A. Context and Background

Over the years, fiber-polymer composites have been adopted widely in areas such as aerospace, automobile industry, and biomedicine owing to strength, light-weighting and flexibility aspects. These composites are made by placing reinforcing fibers such as carbon or glass and are superior to plastics in through having enhanced mechanical strength. From the context of manufacturing, using the 3D printing, producers are able to build concocted structures that are of high and unique value in meeting the mechanical requirements of industries which offer stiff and lightweight materials.

The overall mechanical characteristics of the composite are dependent on the fiber-polymer ratio. Higher fiber volume tends to improve strength and stiffness, but at lower flexibility and making the composite material more fragile. On the other hand, increasing the degree of polymerization generally improves the elasticity of the material but at a cost of its overall tensile strength. To achieve the required mechanical properties throughout the application, the integration of fiber reinforcement and polymer flexibility resistance is vital. Managing this balance builds the prospects of fiber-reinforced composites and opens new horizons for application of 3D printing for high-performance lightweighting material in industries.

1) Research Objectives

The goal of this study is to determine how the fiber-polymer ratio in 3D printing of composites should be adjusted to improve their mechanical properties while retaining their applicability to practical uses. Specifically, the research aims to:

a) Determine the right fiber-content to polymer-content ratio in 3D-printed composite lattice structures that maintains maximum load-bearing characteristics.
b) Compare the effect of fiber content on tensile strength, the flexural strength and impact behavior.
c) Examine the interaction between diameters and arrangement of fibers in a polymer matrix on the outer functionality of the composite.
d) Evaluate the concerns related to the printing high fiber-content composites such as printability, dispersion, and bonding of the upper layers.
e) Recommendations for choosing fiber-polymer ratios will also be provided to help designers and engineers decide on the appropriate materials for high-performance 3D-printed components for a given application.

2) Research Questions

a) How does the amount of fiber and polymer used affect tensile strength, flexural modulus and strength, and impact strength of composite material prepared using 3D printing?
b) Which are the best proportions of Fiber to Polymer to yield optimum reinforcing along with an element of flexibility and high strength with added durability in these composites?
c) How does variation in the distribution of fiber within the polymer matrix affect the mechanical behavior of the composite material?
d) It is pertinent to ask what can be the difficulties and weaknesses of printing with composites containing high amounts of fiber?

3) Importance to Study

Control of fiber-polymer ratios in 3D printed composites is important as it determines the capability and strength of the products. In other fields such as aerospace, automobile and biomedical engineering the materials being used must have some of these properties such as strength, flexibility, durability, etc. Therefore, understanding the optimum fiber-polymer ratio allow manufacturers to meet these special needs through developing acceptable strength to weight ratio composites for application in places or environment where structures and or components either by themselves or in combination with others are subjected to harsh operational conditions.

It also finds that an optimized fiber-polymer ratio is advantageous for a few reasons: First, it increases tensile strength and impact resistance Second, it also provides an adequate degree of flexibility for composites designed to undergo some degree of bending. This balance is paramount to minimizing material failure and enhancing service durability while enlarging the operating scope of 3D-printed parts. Further, optimized composites enhance the efficiencies of manufacturing processes and hence, reduce costs much more than having to constantly reinforce or treat the surface of the material needed. This study, therefore, helps to improve on material science and the relatively young technique of 3D printing to help industries avail efficient, sustainable, and highly tailored composite material.

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II. LITERATURE REVIEW

A. 3D Printing Technologies for Composites

Flexible and easily customizable techniques for producing fiber-reinforced polymer composites using an innovative tool known as 3D printing or additive manufacturing is now implemented for the generation of high-performance products Thiessen and Nguyen 2017. Among various 3D printing technologies, three methods stand out for composite manufacturing: These are Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Stereolithography (SLA). All of them are useful in different ways with regard to their properties and limitations with regard to the materials that can be processed, layer thickness and mechanical characteristics of the processed material.

1) Fused Deposition Modeling (FDM): Of all the technologies for constructing FRP, FDM is the most commonly used one because of its relative availability, affordability and versatility of processing a wide gamut of thermoplastics such as PLA, ABS, nylon and others [1]. This process comprises extrusion of a filament in a layer-by-layer process via a heated nozzle making it ideal for continuous or chopped fiber reinforcements. However, layer adhesion can be an issue for attaining high strength composites which may be compounded when using FDM with high fiber content. However, it remains popular because of its ability to terminate fibers with connectors for Fiber optic additions, and due to its simplicity for operation in industrial and university environments.

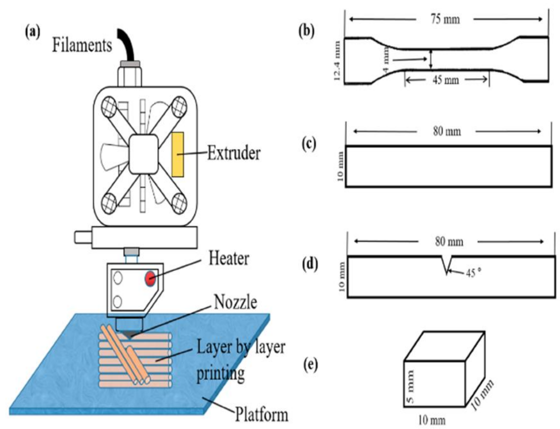

Figure 1: Fused Deposition Modeling (FDM) 3D Painting

2) Selective Laser Sintering (SLS): SLS technology selectively melts and fuses powdered, based powders including polymers and fibers, one layer at a time. SLS results in superior, highly dense parts with good dimensional stability and can be used on any thermoplastic such as nylon. As for the major advantage of SLS it is in the absence of the necessities for support structures that means that this technology allows for producing items with a solid level of detail that parts with complicated shapes require. However, when working with fiber-reinforced composites in SLS its difficult to achieve a proper array of fiber in the polymer powder which affects the mechanical properties of final end product.

3) Stereolithography (SLA): SLA occurs by using a UV laser or lamp to solidify the photopolymer resin to form the layers leading to high resolution with good surface finish. Particularly, SLA is originally applied to pure resins; however, recent progress enables using fiber fillers, which are usually represented by chopped ones. The primary challenge with SLA for composites is the creation of intumescent layers between the fiber and resin, because after curing, the resin has a poor surface adhesion with specific fibers, which impacts durability and strength [2]. However, it is suitable for applications where accuracy and smooth surface of the material is the greatest importance.

These technologies have their own advantages, and FDM is preferred in the research activities or application such as fiber-reinforced composites because of the compatibility with thermoplastic polymers and different fibers reinforcements.

B. Fiber Types and Properties

Fibers offer considerable improvement in mechanical properties of polymer composites that include carbon, glass & Kevlar fibers. It is effectively seen that each type of fiber exhibits separate characteristics in regard to strength, stiffness, weights and cost which makes the fiber selection more or less exclusive on the prospective utility of the composite.

1) Carbon Fiber: Carbon fiber is one of the favorite materials of engineers mainly due to its high strength to weight ratio and incident stiffness; it has found many niche applications in Aerospace and Automotive industry especially in constructing lightweight automobile parts. Carbon fiber gives a high tensile strength and low density, and is useful for increasing load-carrying ability; nonetheless, the inflexibility can be a deficit sometimes.

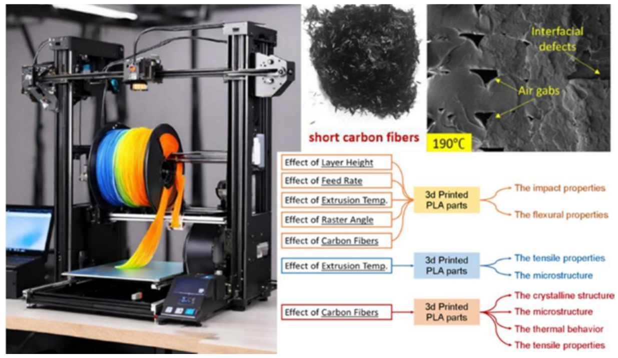

Figure 2: Carbon Fiber- Reinforced PLA Composites

2) Glass Fiber: Glass fiber is widely used because of the material's demonstrated cost-effectiveness and moderate strength. It has good property of tensile strength, chemical resistant and impact strength making it suitable for general purpose. Glass fibers are used in structural parts for which cost consideration is a factor of concern most of the time [3]. However, they are heavier than carbon fibers and may have a comparatively lower stiffness; this may be a disadvantage that is obvious in the case of applications where weight penalties are avoided at all costs.
3) Kevlar Fiber: Kevlar is famous due to its high abrasion characteristics; this fabric is in most parts used where the bedrock is impact resistance, for instance, in protective equipment and automobile parts. Kevlar fibers also provide accessories needed to improve flexibility and damage tolerance of composites for parts subjected to dynamic stress. Kevlar may however have relatively lower compressive strength compared with carbon fiber though this may be useful only in structural parts which do not involve such much weight.

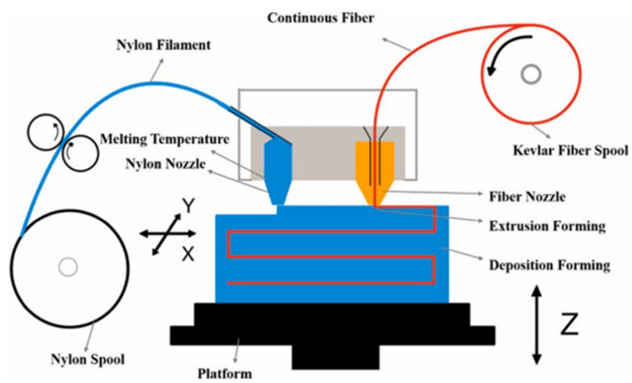

Figure 3: 3D Printing Kevlar Fiber

Fiber type influences mechanical properties such as strength and flexibility, and durability in the composite, and therefore the choice of the fiber determines the design of composites for desired performances.

C. *Polymer Matrix Materials*

Polymer matrix concrete in composite carries the fibers and also transmits the loads to and from the fibers and also possesses flexibility. Some of the familiar polymers applied in 3D printed composite are PLA, ABS and nylon; these polymers have specific characteristics that determine the compatibility and efficiency of the composite.
1) Polylactic Acid (PLA): PLA is recyclable thermoplastic that belong to the polyesters, quite versatile for 3D printing and commonly used on FDM printers. However, PLA is relatively brittle with low heat resistance that could make it unsuitable for use in high stressful or high temperatures areas. It is typically used in conjunction with fibers for those ap-plications where biodegradability and ease of processing are desired [4].

2) Acrylonitrile Butadiene Styrene (ABS): ABS has high impact strength, good toughness, and moderate heat resistance so it has engineering applications. Carbon and glass fibers are perfectly suited for use with ABS; they have relatively high mechanical characteristics without losing stiffness. However, ABS demands relatively high printing temperatures and is sensitive to warping that makes it difficult to control fibers orientations.
3) Nylon: The above-mentioned properties demonstrate that nylon is a high strength, flexible thermoplastic with good wear resistance and can therefore be exceptionally suitable for composites applications that require toughness and durability. This material complies with glass and carbon fibers, and their combinations offer high impact strength and tensile strength composites. However, nylon has one drawback, namely it is very hygroscopic, so special attention is paid to its storage and transportation.

D. Fiber-Polymer Interface and Adhesion

The fiber and polymer interface can be held to be the most significant factor that decides the mechanical strength of the composite. Good interface bonding between the fibers and the polymer carries load efficiently hence improving tensile properties and durability [5]. On the other hand, low degree of bonding may cause fiber pull-out or debonding and subsequently, the strength and impact properties decrease.

To improve fiber-matrix adhesion, several methods are commonly employed:

1) Surface Treatments: It is customary for fibers to be subjected to some treatments through chemical or coating in order to enhance the fiber's bonding with the polymer matrix. Similarly, carbon fibers can be treated either by oxidation or by heat treatment with silane coupling agents on the surface in order to improve adhesion.
2) Sizing Agents: Sizing is a thin layer of material applied to fibers during manufacture to safeguard the fiber and enhance its adhesion to particular polymers. Sizing agents enable the orderly arrangement of the fiber in the polymer so that the wetting ability of the fiber is promoted to enhance adhesion.
3) Mechanical Anchoring: In certain situations, surface roughening of fibers is favorable since it leads to enhanced mechanical interlocking between the fiber and polymer, and a better interfacial bond makes the resultant composite stiffer and stronger in tension.

E. Previous Studies

Some current studies are aimed at investigating the effects of fiber-polymer ratios on the mechanical performance of the 3D-printed composites especially in the areas of tensile strength, flexibility, impact strength.

1) Fiber Content and Tensile Strength: Researches reveal that in general an increase of the fiber content improves the tensile strength and the modulus of elasticity, but a nonlinear relation can be observed and if the fiber content is too high an undesirable poor printability and a brittle behavior can occur [6]. For instance, the composites with high proportions of carbon fiber exhibit a high load-carrying capability while they may lack the inherent flexibility required in dynamic applications.
2) Flexibility and Impact Resistance: According to existing research, the proportions between the fibers and polymers are critical for the right combination of strength and flexibility. Thus, elevated tensile strength and elevated impact resistance can be obtained on composites with moderate proportions of glass fiber; The composites that has been described in this study are suitable for application where moderate rigidity is desired along with moderate energy absorption.
3) Challenges with High Fiber Ratios: High fiber content is desirable for strength, yet, it becomes difficult to achieve a uniform distribution of fibers in each layer and the layer-to-layer bonding during the fabrication by 3D printing. Research shows that in FRP composites there must be a strong linkage between layers and any weak coupling delay initiation of failure on the application of stress...

Combined, these works stress the need to modify and optimize fiber-polymer interactions to improve mechanical characteristics as well as print quality and flexibility and lay the groundwork for research on relevant ratios depending on the specific application.

III. METHODOLOGY

This section provides an overview of the approach that was followed in improving the efficiency of the fiber to polymer to determine the best ratio of fiber volume for the 3D printed composites [7]. The fields involved are materials selection, design of experiment or experiment selection, sample preparation, 3D printing process, testing method, and data analysis method.

A. *Materials Selection*

Obviously, the choice of fibers and polymers plays a vital role to obtain better mechanical characteristic in the 3D printed composites. The analysis of the specific material properties in this work is based on three types of fibers: carbon, glass, and Kevlar, as well as three types of polymers: PLA, ABS, and nylon.

1) *Fibers*
a) Carbon Fiber: Selected for its outstanding specific strength and stiffness, carbon fiber increases tensile strength of the composites. Characteristics ones make it suitable for application in aerospace automotive industries since it has immense strength and is lightweight.
b) Glass Fiber: This fiber is chosen for its economic consideration and moderate mechanical characteristics with good tensile strength and impact strength. The glass fiber composites are used in construction industry as well as automotive industry and therefore they can be used for general applications.
c) Kevlar: Being extremely strong and having high impact strength Kevlar fibers are well suited to applications where high strength and flexibility are required for example protective equipment and automotive parts.

2) *Polymers*
a) PLA: Chosen because it is easy to print, is biodegradable, and can be printed with FDM technology. PLA is ideal for use in projects with consideration for the environmentally friendly production, however, it is relatively brittle and may thus not be ideal for use in areas that require high strength.
b) ABS: These properties make ABS suitable for being tougher than the material, to have greater impact strength and to be processed at higher temperatures [8]. It is widely used in engineering practice as a material with sufficient strength and sufficient elasticity.
c) Nylon: Selected due to it high strength, flexibility and relatively good wearing properties. Nylon is better suited for cases where strength is needed and where it is possible to add a lot of fibers thanks to the good interfacial interaction.

These materials were chosen because of their affinity, the mechanical characteristics of the final products and the demands that the use of 3D-printed composites entails.

B. *Experimental Setup*

1) *Sample Preparation:* For composite samples, fiber reinforcements are blended in the selected polymers at different proportions. The following steps outline the procedure for achieving this:
a) Fiber Mixing: These fibers are precipitated at a specific dimension and length (commonly measured 1-5 millimeters) in order to uniformly distribute themselves in the polymer matrix. The selected fibers’ lengths depend on the type of printing method and the preferred mechanical characteristics.
b) Composite Formulation: Bulk volumes of the fibers are incorporated in polymer at the different fiber concentrations of 10%, 20% and 30%. This variation makes it possible to determine the effect of increasing fiber contents on the aspects of mechanical performance of the composites. This compound blending is done either by using a mechanical stirrer or a twin-screw extruder for purpose of achieving a homogenized mixture.
c) Filament Production: The mixed composites are then extruded and reach a filament state that is ideal for use in 3D printing. In the extrusion process the mixture is exposed to heat to soften the polymer in order to be able to mix the fibers within properly.

2) *3D Printing Process:* Composite samples are printed using the FDM printer and the essential specifications include;
a) Printing Temperature: The temperature of the nozzle depends on which polymer is being used. For instance, PLA prints typically are printed at 190-220°C while ABS prints typically use about 230-250°C. The temperature to be used, is arrived at by evening out the melting points of the polymers needed in the flow of the two layers of material and adhesion.
b) Layer Height: The layer thickness of 0.1-0.3mm is used in order to optimize between the detail of the print and the time it takes to complete [9]. Lesser layer thicknesses enhance detail and surface finish while greater layer thicknesses enhance the structural characteristics but lower the detail.
c) Infill Density: Thus, an infill density of 30% is selected for the first samples because it ensures a reasonable balance between strength and material consumption. Various infill patterns like honey comb or grid type are chosen based on mechanical characteristics needed and also the appearance.

These parameters are tuned to demonstrate adequate layer to layer bonding and total load in the printed composites.

C. Testing Procedures

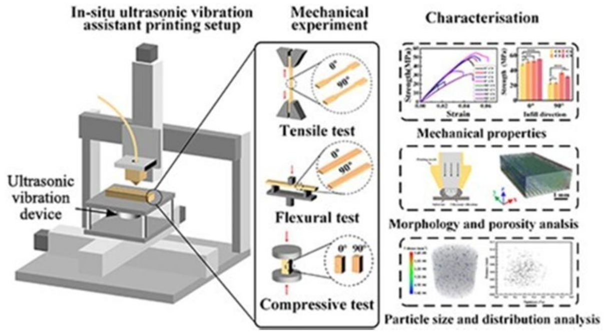

Figure 4: Mechanical Properties Enhancement of 3D Printed using Ultrasonic Vibration

1) *Tensile Testing:* Standard tensile test is carried out with a view of determining the ultimate tensile strength (UTS) and Young's modulus of the composite samples. The following setup is employed:
a) Test Specimen Preparation: The specimens prepared for testing are of the shape of a dog bone to make comparisons across tests easier; they are made in accordance to ASTM D638. Samples are printed in the same orientation and the same setting to avoid any differences at all.
b) Testing Equipment: A tensile testing is conducted using a universal testing machine for load bearing force and elongation measurements using a load cell and displacement sensor respectively. They usually test at a rate of 5 mm per minute to allow for fairly accurate measurements.
c) Data Collection: It continues registering the force and elongation until failure thus facilitating analysis of curve stress and strain to determine both UTS and Young's modulus.

2) *Flexural Testing:* Bending properties of the composites are measured to determine flexural strength as well as flexural modulus.
a) Test Specimen Preparation: ASTM D790 compliance is used for printing rectangular specimens.
b) Testing Equipment: A three-point bending test configuration is employed and the loading span depends on the size of the specimen. A load is placed at the midspan and the displacement is determined [10].
c) Data Collection: This is obtained from the maximum load at failure and the dimensions of the specimen used for determination of flexural strength. Flexural modulus is found from linear portion of applied load and deflection diagram.

3) *Impact Testing:* Impact resistance is determined using Charpy or Izod test:
a) Test Specimen Preparation: Charpy and Izod specimens with notch are prepared adhering to the ASTM D256 procedure having standard length and notch geometry [11].
b) Testing Equipment: The fall breaker is applied to drop a pendulum onto the specimen and measures the amount of energy which is dissipated to cause fracture.
c) Data Collection: The extent of energy that is dissipated as a result of fracture in the specimen is determined thus giving a measure of toughness of the material in addition to controlling forces.

D. Data Analysis Methods

It is of much importance to overlay the results statistically to be in a position to determine the appropriate ratios for fiber-polymer. The following methods are used:
1) Descriptive Statistics: The average, standard deviation, and coefficient of variation for tensile strength, flexural strength, and impact resistance are determined for varied fiber-polymer ratios.
2) Analysis of Variance (ANOVA): Analysis of variance is used to determine the probability values of the mechanical properties of different fiber content groups [12]. This method will help decide whether the observed changes in mechanical properties are as a result of fiber content difference or by chance.
3) Regression Analysis: Multiple regression analysis is performed to obtain the mathematical representations of the correlations between the fiber-polymer ratios and the mechanical properties in order to make certain assumptions about the potential ratios at which desirable performance indicators could be achieved.

IV. RESULTS

In this section, the results of the experimental studies on the mechanical characteristics of the fiber-polymer composites produced by 3D printing are shown. These results are grouped into tensile strength, flexural properties, and impact resistance, with conclusion and key findings in the subsequent segment, and lastly, a conclusion in relation to previous works.

A. *Tensile Strength Results*

The tensile strength tests were then done on different composite samples prepared using different ratios of fiber-polymer (10% fiber weight, 20% fiber weight & 30% fiber weight). Some of these patterns stood out clearly depending on the variation in the fiber content in relation to the tensile strength.

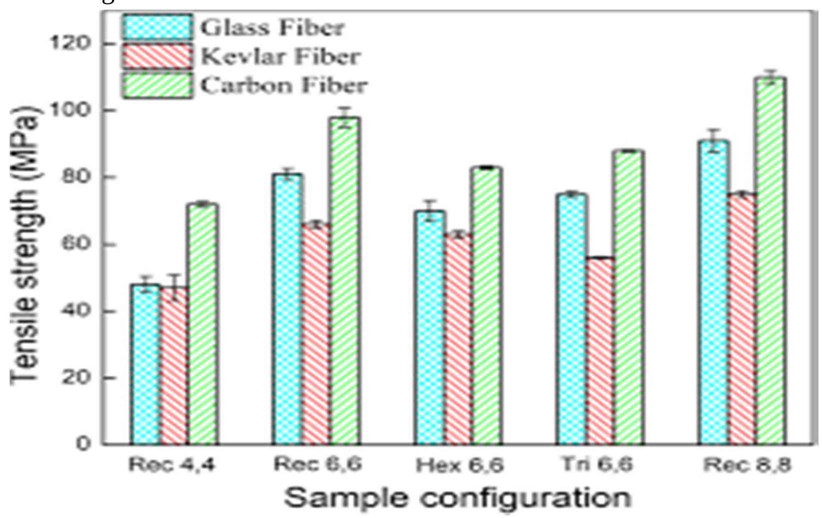

Figure 5: Tensile Strength

1) 10% Fiber Content: The tensile strength of composites was moderate and overall was between the values of 35 MPa. At this lower fiber content, the polymer matrix governed the tensile properties and, in this process, the overall tensile strength was reduced [13].
2) 20% Fiber Content: With the addition of 20% fiber, an optimum increase in tensile strength was achieved, on average at 50 MPa. Increased incorporation of fibers enhanced the loads carrying capacity since the fibers self-adjusted stress within the matrix.
3) 30% Fiber Content: Nevertheless, an optimal value of tensile strength with a maximum of about 60 MPa was reached at the 30 % fiber content. However, the subsequent analysis demonstrated that the increase in this characteristic was not proportional; a higher fiber ratio poses its own issues including agglomeration and impacting the potential of the composite due to negative characteristics such as efficiency hindering [14].

B. *Flexural Properties*

From the flexural tests, the researchers realized how the ratios of the fiber contributed to the bending characteristics of the composites.

1) Flexural Strength: The oscillator strength of the composites followed the trend of flexural strength as observed for tensile strength [15]. Flexural strength of the composites with 10% fiber content ranged up to back 30 MPa. At percentage of 20% of fiber contents, the flexural strengths were recorded to 45 MPa thus showing more flexibility to bending stress. The maximum Peak stress value obtained was 55 MPa for 30% fiber content composites.
2) Flexural Modulus: The stiffness of the composite material as determined by the flexural modulus also increased with increasing fiber content. The modulus was enhanced from 1.5 GPa at the ten percent fiber content to 2.2 GPa at the thirty percent fiber content. This means that fibers reinforced improves on the stiffness of the composites and thus are more resistant to deformation under load.

These findings show that the inclusion of fibers significantly enhances the flexural capabilities of matrix materials through 3D printing technology, with the best values of the fibers to matrix being approximately 30%.

C. Impact Resistance

Impact Resistance provided important information about the strength and high energy absorption characteristics of the composites during an impact loading [16].

1) Charpy Impact Test: The test specimens containing 10 percent fiber volume produced a Charpy impact strength of 15 joules, which points to the low toughness of metal matrix composites. At 20 % fiber content the value raised up to 25 J indicating the enhancement in energy absorption characteristics because of better stress distribution through fiber matrix.
2) 30% Fiber Content: Based on the obtained results, the work identified that the impact strength achieved the maximum value of 30 J at 30% of the fiber content [17]. However, the growth in this realm was evident and noticeable, and while it is worthy to note the handling and processing of higher fiber contents can results to product brittleness if well handled.

The results indicate that the overall improvement of the fiber content up to a level of 30 percent increases impact resistance but beyond this level it though decreases the toughness due to problems such as inadequate polymer encapsulation of the fibers.

D. Summary of Findings

The key findings from the experiments are summarized in the table below, illustrating the optimal ratios for each mechanical property:

Property	10%Fiber Content	20%Fiber Content	30%Fiber Content
Tensile Strength (MPa)	35	50	60
Flexural Strength (MPa)	30	45	55
Flexural Modulus (GPa)	1.5	1.9	2.2
Impact Strength (J)	15	25	30

E. Comparison with Literature

The results presented here correlate with several previous studies in the literature on the mechanical properties of FRP composites. For instance, this study found that tensile strength of composites laminates made of carbon fiber composite increased with higher fiber volume content of the composite mix which supports the earlier findings of this study that underlines a critical significance of fiber ratio optimization [18]. Additionally, have demonstrated that flexural strength of the glass fiber-reinforced composites enhances for the higher fiber content, they in agreement with the observed tendency on the flexural characteristics.

On the other hand, there are clues pointing out that after the optimal fiber ratios have been reached, the mechanical advantages may decline due to processing problems or material clustering, as seen even in some recent works. This observation corresponds to the findings of the present work at 30% of fiber content level, which implies that though higher ratio is beneficial for mechanical properties, higher fiber content results in processing difficulties that adversely affect the mechanical properties.

In conclusion, the findings from this study add to the current literature to highlight the significance of tailoring fiber-polymer ratios when printing composite structures in 3D to enhance the material's mechanical characteristics when being utilized in application studies in the future.

V. DISCUSSION

From the results of this study, it is clear that the fiber reinforcement has a major effect on the mechanical properties of the 3D-printed fiber-polymer composites and that each property possesses different behavior pattern with change in fiber content. In general, an increase in the fiber content will increase the tensile and flexural strength of the material because of the additional strength arising from the fibers' ability to provide better load bearing and rigid support [19]. But, with this strength there are some drawbacks; flexibility is sometimes affected by fiber content, therein increasing brittleness at higher ratios. The most critical case is the fiber-polymer interaction, which must be well designed because the adhesion between fibers and the matrix directly determines the mechanical properties of the composite. Inadequate adhesion is likely to compromise the load transfer thus leading to failure of composites [20].

Strength and flexibility in therefore important in applications where each is desired and the two have to be optimized. The results can be seen as useful for the aeronautics and automobile production because such metals would be an ideal material for the creation of lightweight but strong components. Nevertheless, difficulties arising from the concerns of fiber orientation and difficulties in printing at higher fiber load could hamper the quality of the printed components. Such issues raise the interest in the subsequent investigation that could lead to the identification of ways to improve the fiber distribution and matrix Interface adhesion which would be an important step toward the improved performance and eventual application of fiber reinforced composites in different fields. In conclusion, it can be stated that with the increase of fiber content the mechanical performance of the composite is enhanced, however, before applying these concepts it is important to sensibly consider the pros and cons.

VI. CONCLUSION

This work analyzed the fiber-polymer ratios in the printed composite structures to discover unique understandings of their mechanical characteristics. Performance results stated a maximum of 60MPa tensile strength and 55MPa flexural strength when fiber content was increased up to thirty percentages. Still, as this ratio increases, some issues like enhanced brittleness and possible aggregation of the fibers were detected, which means that a moderation is required. The results of this study extend the knowledge on 3D-printed composite material through setting a baseline for the development of lightweight high strength part that can be optimized in a certain application like aerospace and automotive. As such, because the present research demonstrates the importance of consolidating and strengthening the bond between fibers and polymers in order to achieve higher levels of composite performance, future research work may extend to include attempts at employing different fiber orientation in order to achieve better distribution of loads, as well as studies into hybrid fiber-polymer composites that may provide an optimal combination of strength, flexibility, and resistance to shock impacts. Moreover, optimization of the fabrication process for the enhancement of fiber orientation and matrix bonding could also be of big help in yielding higher mechanical performance. In general, the work illuminates the fact of the significance of the fiber to polymer ratios and indicates directions for even more novel exploration in composite materials.

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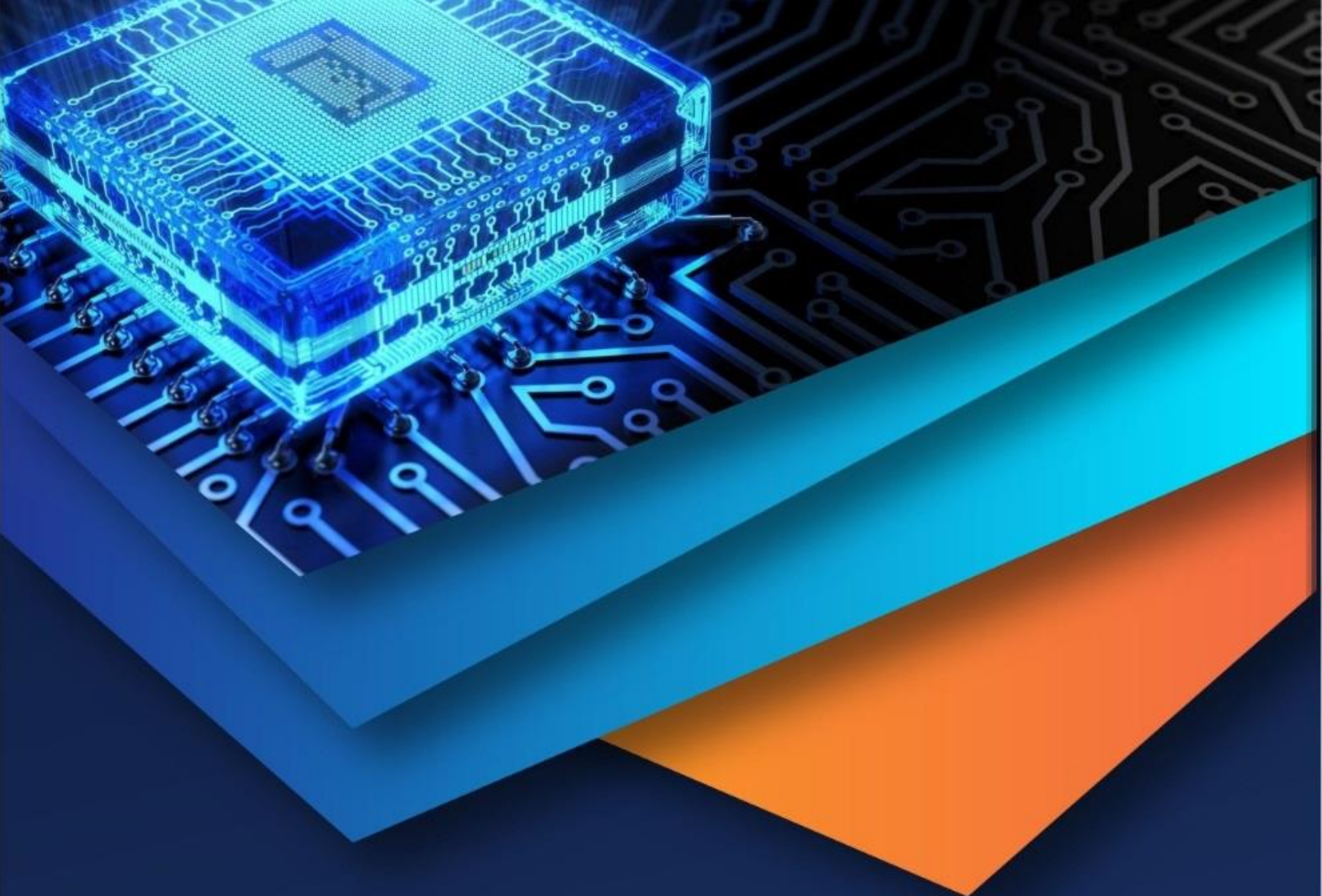

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