

A Study On Mechanical Properties Of 3d Printed Hybrid Polymer Composites

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Abstract

The use of 3D printing has gained significant popularity for producing functional components, ranging from prototypes and membranes to shields and sports wearables. As this method becomes more prevalent, there is a growing need to address challenges related to the limitations of suitable printing materials compared to traditional materials. Innovative methods for simulating failures in 3D-printed cellular structures have been developed to emphasize the impact of various process variables. The scarcity of appropriate printing materials can be attributed to the constraints of 3D printing techniques in accommodating a diverse range of materials. Over the past decade, 3D printing technologies have found extensive application across industries, including the military, serving as a rapid prototyping, and manufacturing method. However, commercially available printing polymers have exhibited inherently lower mechanical properties, such as strength and stiffness, when compared to traditional manufacturing materials. To overcome these limitations, multi-material additive manufacturing (AM) technology has emerged as a promising alternative. This approach allows for the creation of complex structures with a broad spectrum of mechanical characteristics, presenting a significant advancement over traditional assembly methods. In ongoing efforts to enhance material qualities, there is a current focus on fabricating polymer composites using 3D printing techniques. Various reinforcement materials, including carbon fibers and multi-walled carbon nanotubes (MCNTs), are being incorporated into matrix materials like ABS and PETG. This endeavor aims to exploit the capabilities of 3D printers to innovate and create complex items with improved material properties,

opening the door to further research and development in fast manufacturing processes.

Keywords: ABS, PETG, Carbon Fibers, MCNTs, 3D Printing.

Introduction

Heading 1 Introduction

Today's technology calls for materials with superior qualities to everyday living materials, one such material is referred to as composite. In comparison to monolithic materials, the properties of stiffness, deformation resistance, and indentation resistance capacity are better for composite materials. Therefore, researchers are concentrating on creating newer, better, and more affordable composite materials. Composite materials have been introduced as a new class of materials in the field of materials engineering. The development of materials science and technology has opened numerous opportunities for composite materials to be used more extensively in the automotive, aerospace, and other industries where strength is a key component [1,2].

The sort of composite materials used most frequently in the automobile sector are polymer composites. Natural fiber reinforced polymer composites are particularly employed in the manufacture of door panels, instrument panels, armrests, headrests, seat shells, window frames, molded panel components, bumpers, and underfloor protection for passenger cars. Additionally, nameplates, rear view mirror panels, two-wheeler visors, billion seat coverings, indication covers, and cover L-sides have all been made using sisal, carbon and roselle fibers [3,4].

The method of combining materials to create three-dimensional (3D) objects is known as additive manufacturing (AM), according to the technical committee of the American Society for Testing and Materials. Fused filament fabrication (FFF) is a 3D printing technique based on thermoplastic polymers that makes use of a continuous filament in this context.

One of the most popular materials in 3D printing is poly (ethylene terephthalate)-glycol (PETG), which has a few advantages including chemical alkali resistance, transparency, gloss, low haze, and good printability. Furthermore, great layer

adhesion and very low shrinkage qualities can be attained with the right print parameters. At the same time, it is very sturdy, making it possible to print things with superior impact performance that can operate at high temperatures or in food-safe applications. Due to all these benefits, this material can be used in the food and medical industries [5]. For instance, in the last scenario, its stiff structure enables it to withstand abrasive sterilizing procedures, making it the ideal material for use in medical implants.

However, the properties of the polymers can be enhanced by the addition of carbon fibers, which increases the material's resistance and resilience making it a great option for use in industrial applications and the automobile industry. The addition of carbon fibers expands its range of use to the automotive and aviation industries. Because the material becomes more resilient and resistant, in addition to further lowering the risk of warping, it can be used in this industry and others (such as prosthetics or adjustable wheelchair components) [6,7]. On the other hand, the applications can be expanded to the aerospace and aviation sectors when reinforced with aramid fibers, and MCNT where strong resistance to friction and impact is anticipated [8].

Investigation conducted researchers on PETG and PETG reinforced with carbon fibers and discovered that for both materials, raster orientations of 0 yielded the optimum mechanical performance. In addition, it was found that when raster orientation increased, Young's modulus and ultimate tensile strength decreased. Therefore, it was able to draw the conclusion that the raster orientation and shell presence had a substantial impact on the mechanical properties of PETG with layers printed unidirectionally [9, 10].

The mechanical characteristics of materials are significantly enhanced by the inclusion of carbon fibers. Currently, long carbon fibers, short carbon fibers, and powder are the three basic types of carbon fibers available on the market [11]. The architecture of carbon fibers allows them to endure high-strength mechanical characteristics, but for large-scale composite products, it is challenging to mix the fibers and matrix equally because of the electrostatic attraction of the surface of the fibers [12,13].

Although powdered carbon fibers mechanical characteristics are inferior to those of long and short carbon

fibers, preparing them is simpler. The influence of carbon fibers powder content on the mechanical characteristics of composites is examined through the measurement of the mechanical properties of carbon fibers powder reinforced ABS composites, which serves as a guide for the usage of carbon fibers in manufacturing practice [14,15,16].

Heading 1 Experimental Work

In this section, we provide a concise overview of the experimental work, encompassing the selection of base materials, reinforcements, their respective weight percentages, the employed processing techniques, and the key testing parameters.

Heading 2 Base Material

Heading 3 PETG: Polyethylene terephthalate glycol, commonly referred to as PETG or PET-G, represents a thermoplastic polyester renowned for its notable attributes such as substantial chemical resistance, durability, and formability, making it a preferred material in manufacturing. The physical properties of PETG are outlined in Table 1.

Table 1 Physical Properties of PETG [17]

Parameters	Value
Density	1.23g/cm ³
Shore Hardness	78
Yong's Modulus	2950MPa
Melting Temperature	260 ⁰ C

Heading 3 ABS: Acrylonitrile butadiene styrene, abbreviated as ABS, is a widely used thermoplastic polymer, particularly favored for injection molding applications. This engineering plastic is valued for its cost-effectiveness and the ease with which it can be machined by plastic manufacturers. Table 2 provides an overview of the physical properties of ABS.

Figure 1(a) illustrates the raw material presented in the form of a spool, exhibiting a white color, and possessing a diameter of 1.75mm. In contrast, Figure 1(b) depicts the raw material in spool form, characterized by a crystal-clear appearance and a diameter of 1.75mm.

Table 2 Physical Properties of ABS [18]

Parameters	Value
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Density	1.04g/cm ³
Shore Hardness	100
Yong's Modulus	3200Mpa
Melting Temperature	200°C



(a)

(b)

Figure 1 (a) PETG Spool (b) ABS Spool

Heading 2 Reinforcement Materials

Heading 3 Carbon Fiber: Carbon Fiber, occasionally referred to as graphite fiber, is a polymer renowned for its exceptional strength and lightweight characteristics. This material is remarkably robust, being five times stronger than steel and twice as stiff. Table 3 provides an overview of the physical properties of Carbon Fiber, while Figure 2 showcases the presentation of carbon fiber in powder form.

Table 3 Physical Properties of Carbon Fiber [19]

Parameters	Value
Density	1.75g/cm ³
Hardness	50.5 HRC
Yong's Modulus	183Gpa
Melting Temperature	1500°C



Figure 2 Carbon Fiber (Powder Form) Figure 3 MCNT Fiber (Powder Form)

Heading 3 Multi Walled Carbon Nano Tubes: Walled Nanotubes (WNTs) can be conceptualized as a series of single-wall tubes nested concentrically. This structure may include as few as 6 or as many as 25 concentric walls, leading to Multi-Walled Nanotubes (MWNTs). Consequently, the diameters of MWNTs can reach up to 30nm, in contrast to the 0.7 – 2.0 nm range typical for Single-Walled Nanotubes (SWNTs). Table 4 presents the physical properties of Multi-Walled Carbon Nanotubes (MCNT), while Figure 3 displays the powdered form of MCNT fibers.

Table 4 Physical Properties of MCNT [20]

Parameters	Value
Density	1.72g/cm ³
Shore Hardness	70 HRC
Yong's Modulus	270Gpa
Melting Temperature	3550 ⁰ C

Heading 1 Processing Technique

The polymer material is processed using a 3D printing technique, as depicted in Figure 4, showcasing the 3D printing apparatus employed in this study. Figure 5 illustrates the build orientation in terms of X, Y, and Z axes. For further insights into the composite composition, Table 5 provides information on the percentage of matrix and reinforcement utilized during the processing of polymer composites.

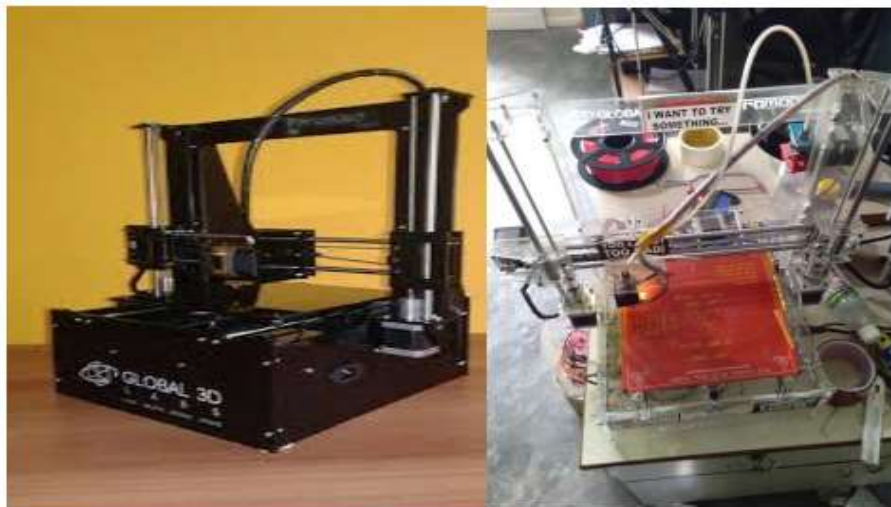


Figure 4 FDM Apparatus Used

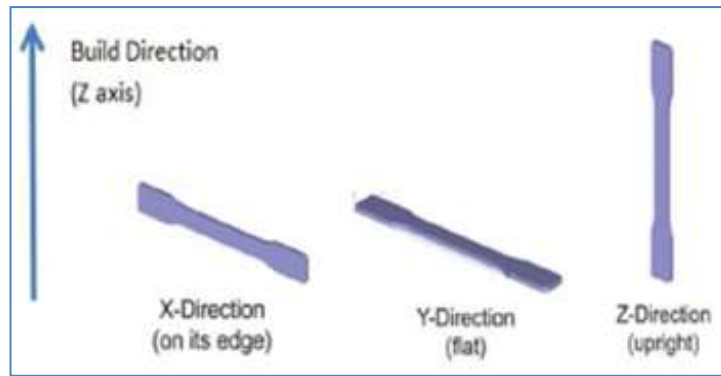


Figure 5 Build Orientation [21]

PETG and ABS composites undergo direct processing in the form of fibers. However, in the case of composite materials like carbon fiber and Multi-Walled Carbon Nanotube (MCNT) fibers, the reinforcements are initially in powder form. The processing involves blending these powders, and the resultant mixture is extruded to obtain it in the form of fibers. These fibers are then built in the desired direction, with adjustments made to the weight percentages as needed.

Table 5 Matrix and Reinforcement Details

Sl.N o	Matrix Material	Weight Percentage	Reinforcement Material	Weight Percentage
1	PETG	100	-	-
2	ABS	100	-	-
3	PETG	98	Carbon Fiber	2
4	ABS	98	Carbon Fiber	2
5	PETG	96	Carbon Fiber	2
			MCNT	2
6	ABS	96	Carbon Fiber	2
			MCNT	2

Heading 1 Results & Discussions

Heading 2 Evaluation of Mechanical Properties

Heading 3 Shore Hardness Test

Hardness is a key parameter in evaluating the mechanical properties of polymeric materials, and it is often assessed through a widely adopted test. This test involves measuring a material's resistance to penetration by a harder substance. Materials are categorized as rigid, hard, or tough based on their ability to withstand such penetration. The assessment of hardness typically employs a specialized indenter, which can

have various shapes, that is pressed into the material's surface with a predetermined force. This penetration method provides valuable insights into the material's mechanical characteristics.

The Durometer, a device employed for measuring Shore hardness, utilizes a calibrated spring to exert force on an indenter. The measured hardness is determined by the depth of penetration of the indenter under this applied load. This indentation hardness is influenced by several factors, including the material's penetration characteristics, modulus of elasticity, and viscoelastic properties, all of which are inversely related to hardness. The results of the hardness test are affected by multiple parameters such as the shape of the indenter, the applied force, the duration of application, and other relevant aspects. In Table 6, the hardness of diverse materials is presented alongside the percentage increase in strength. Figures 6 to 8 visually depict the hardness of different materials at varying build orientations. These representations offer a comprehensive view of how hardness varies across materials and orientations, providing valuable insights into their mechanical properties.

Table 6 Hardness of Various Materials With % of Increase

Sample	PETG	ABS	% of Increase in Hardness
A1 (X 80)	85	89	4
A2 (Y90)	87	91	4
A3 (Z100)	89	90	1
Sample	PETG+CF2	ABS+CF2	
A4 (X 100)	84	89	6
A5 (Y80)	85	90	6
A6 (Z90)	79	91	13
Sample	PETG+CF2+MCNT2	ABS+CF2+MCNT2	
A7 (X 90)	59	87	32
A8 (Y100)	56	74	24
A9 (Z80)	69	88	22

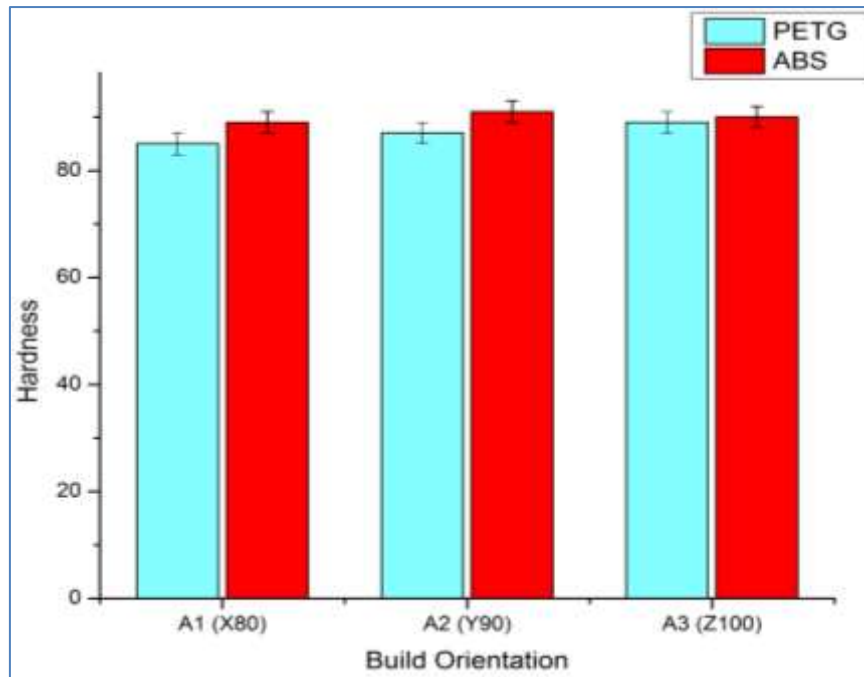


Figure 6 Hardness v/s Various Materials (Build Orientation)

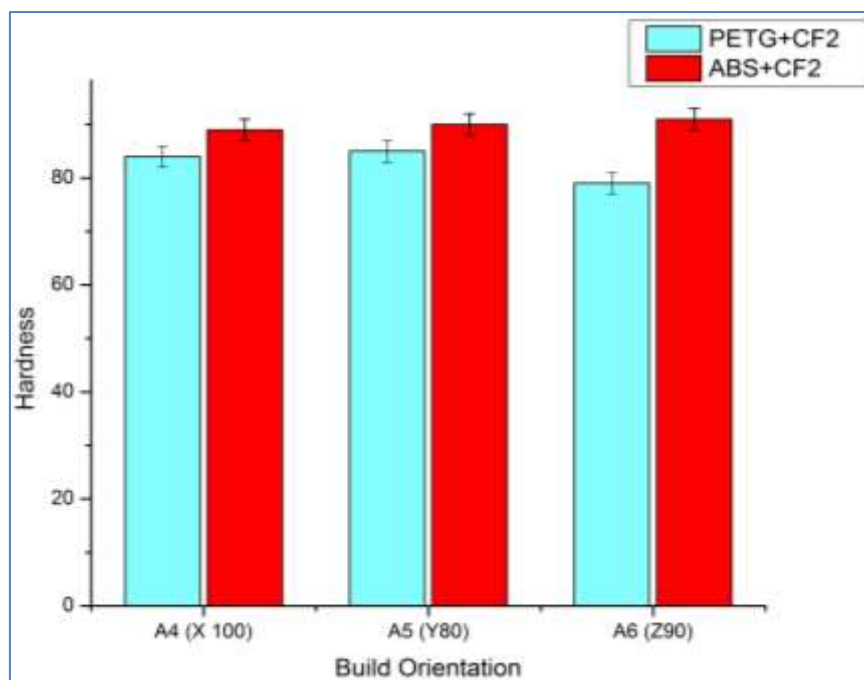


Figure 7 Hardness v/s Various Materials (Build Orientation)

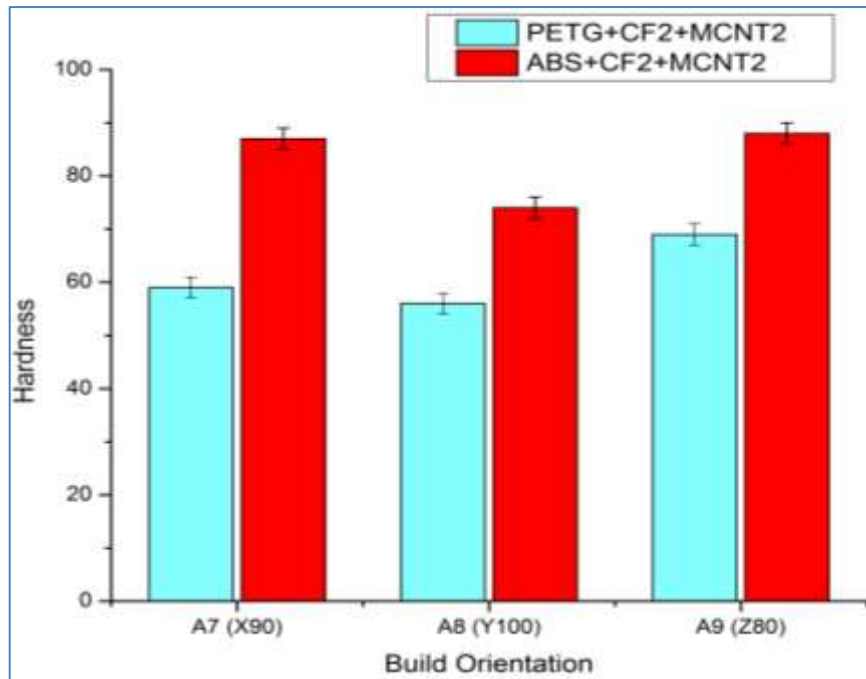


Figure 8 Hardness v/s Various Materials (Build Orientation)

In Figure 8, the hardness results for various build orientation specimens reveal that the ABS+CF2 reinforced composite exhibits the highest hardness rating when compared to PETG+CF2. This disparity in hardness can be attributed to the ABS material's rigidity, causing an increase in hardness as it resists the penetration of the indenter (test needle), unlike the more flexible PETG. The lower observed hardness in PETG+CF2 is a consequence of the indenter penetrating the PETG surface more readily. The presence of carbon fiber in the PETG composite initially resists deformation, but under increased load, the indenter shears through the surface of the fiber, resulting in a reduced hardness. This is due to PETG having inherently lower hardness compared to carbon fiber, making it more susceptible to shearing. Remarkably, this trend holds consistent across various build directions. The incorporation of Multi-Walled Carbon Nanotubes (MCNT) in the composite further enhances its strength due to the superior hardness of MCNT compared to other elements, contributing to increased overall material hardness and resistance.

Heading 3 Impact Test

The primary objective of an impact test is to offer a comprehensive evaluation of a material's toughness or "fracture resistance" by quantifying the energy required for complete fracture. In the IZOD test, a type of bending-type

impact test, key metrics include the energy necessary for the complete fracture of a sample in relation to its thickness (indicating impact resistance) and the energy required relative to the shattered cross-sectional area (indicating impact energy). Essentially, the measured energy encompasses the total amount needed to initiate a crack in the sample and allow it to propagate until it matches the length of the sample (indicating fracture resistance). Alternatively, it can measure the energy needed to initiate a crack and let it progress until it covers the same surface area as the cross-sectional area of the sample (indicating fracture resistance). The impact test serves as a crucial method for examining the properties of diverse materials. It provides insights into significant aspects such as the formation of substantial and deep scars on the component, the extent of stretching, and the occurrence of layer pullout, contributing to a comprehensive understanding of the material's behavior under impact conditions.

Table 7 shows the impact test details of various materials with % of increase in the strength. Figures 9 to 11 show the impact of energy of various materials at different build orientations.

Table 7 Impact Test of Various Materials With % of Increase

Sample	PETG	ABS	% of Increase in Impact Strength
A1 (X 80)	12	14	14
A2 (Y90)	10	12	17
A3 (Z100)	13	16	19
Sample	PETG+CF2	ABS+CF2	
A4 (X 100)	16	20	20
A5 (Y80)	19	21	10
A6 (Z90)	14	23	39
Sample	PETG+CF2+MCNT2	ABS+CF2+MCNT2	
A7 (X 90)	18	22	18
A8 (Y100)	19	23	17
A9 (Z80)	21	24	13

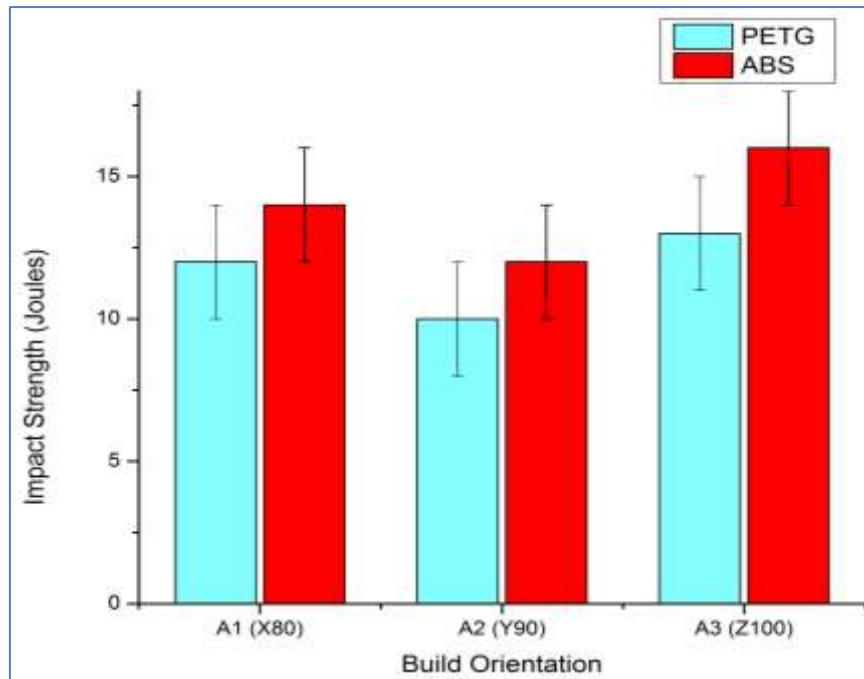


Figure 9 Impact Strength v/s Various Materials (Build Orientation)

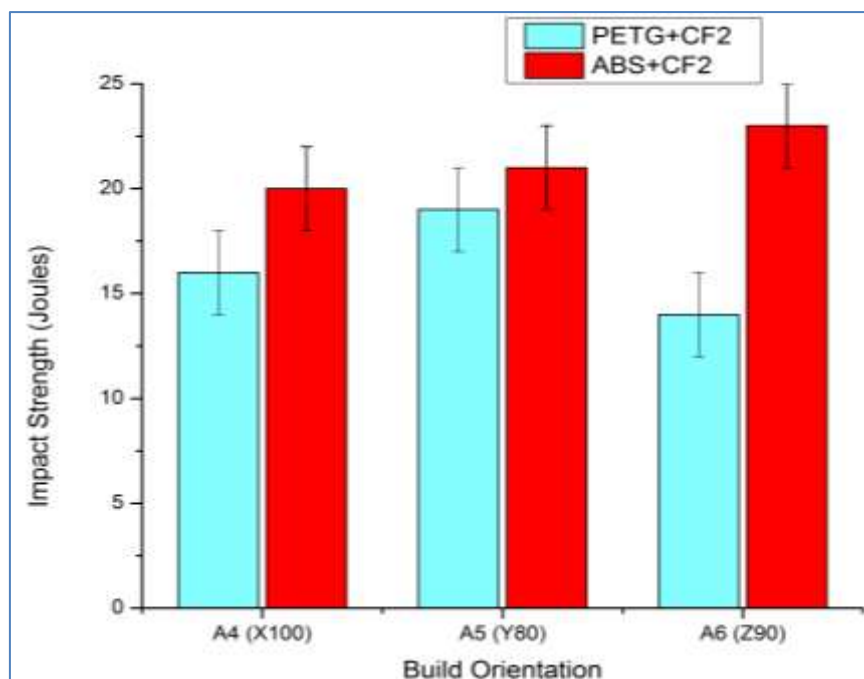


Figure 10 Impact Strength v/s Various Materials (Build Orientation)

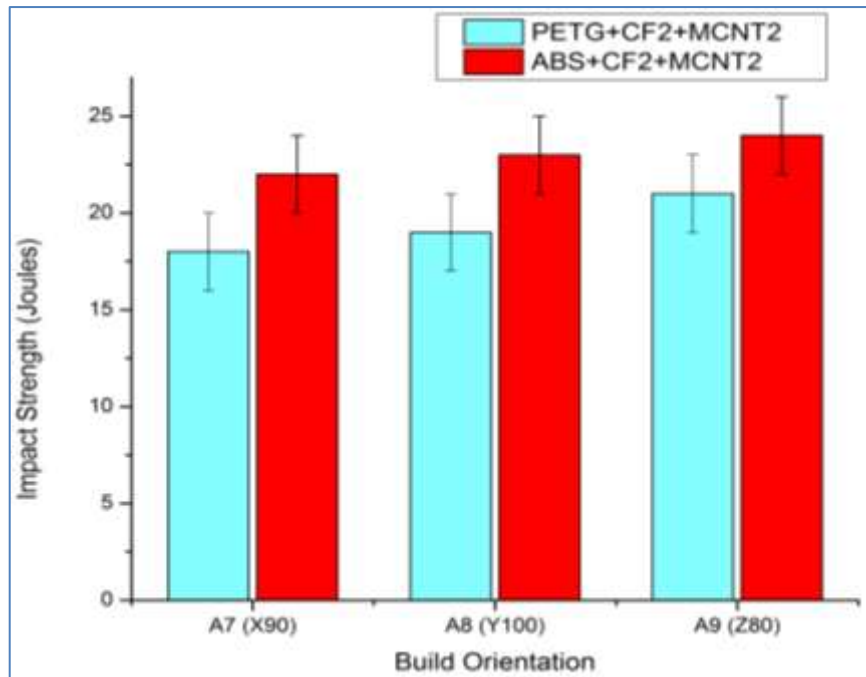


Figure 11 Impact Strength v/s Various Materials (Build Orientation)

Impact testing serves as a method for determining the material's toughness by quantifying the energy absorption during instantaneous cracking of the test sample. The impact energy results, presented in Figures 9 to 11, indicate that the addition of PETG and Carbon fiber led to a decrease in impact resistance compared to ABS and carbon fiber. This reduction in strength can be attributed to the formation of stress-failure zones at the contact area between ABS and Carbon fiber. In ABS composites, the Carbon fiber phase bears most of the load during the impact test, contributing to the observed decrease in impact resistance. The effectiveness of the fiber in enhancing impact strength is particularly notable when the fiber possesses a high tensile strain to failure characteristic. From a material standpoint, the incorporation of Carbon fiber has notably increased the impact strength of ABS in comparison to PETG. Furthermore, the addition of Multi-Walled Carbon Nanotube (MCNT) reinforcements follows a similar trend of enhancing impact strength, indicating a positive impact on the material's overall toughness.

Heading 3 Tensile Test

Table 8 provides an overview of the tensile characteristics for each parameter under investigation. The primary objective of this test is to examine the correlation between stress and strain in tensile specimens for each specific print condition. However,

for a comprehensive understanding of the overall material behavior, average values for the ultimate tensile strength (UTS) are computed for each set of samples. This approach ensures a consolidated view of the material's tensile properties across various print conditions, offering valuable insights into its performance under different parameters.

When a material is subjected to stress, an initial linear zone is observed where the material undergoes elastic deformation, returning to its original length upon the removal of stress. This elastic behavior persists until the yield point is reached, marking the transition to plastic deformation. Beyond the yield point, the material no longer returns to its initial length when the load is removed. It's worth noting that the length of the linear region varies among substances, signifying that some materials have more extended elastic regimes than others. This variability underscores the diverse mechanical responses of materials to stress and their distinctive elastic properties.

The tensile test results, as depicted in Figures 12-14, reveal that the combination of PETG and Carbon fiber exhibits lower strength compared to the combination of ABS and Carbon fiber. This decrease in strength can be attributed to the fact that the carbon fiber bears a significant portion of the stress, potentially indicating poor adhesion between PETG and the fibers, leading to limited load transfer at these interfaces. Several contributing factors contribute to the observed reduction in strength in the PETG and carbon fiber combination. These include the presence of air gaps between adjacent printed layers, elevated shear forces at the layer interface, and challenges in achieving effective fiber-matrix contact. These combined factors contribute to a weakened overall strength in the PETG and carbon fiber composite, emphasizing the importance of proper adhesion and load transfer for optimal material performance in such combinations.

In composites, the presence of voids and local imperfections, particularly at the matrix/fiber interface or between layers, can result in brittle failure of the material. However, in the composite with the combination of ABS and Carbon fiber, neither the microstructure nor the fracture surface reveals any discernible defects. This absence of defects suggests that the incorporation of numerous carbon fibers contributes to increased stiffness and strength in the

composites, ultimately leading to a brittle failure mode for the material. A similar reinforcing effect is observed with the addition of Multi-Walled Carbon Nanotube (MCNT) reinforcements. In both cases, the reinforcement agents, whether carbon fibers or MCNT, play a crucial role in enhancing the stiffness and strength of the composite, which, in turn, influences the material's fracture behavior towards a more brittle failure mode.

Table 8 Impact Test of Various Materials With % of Increase

Sample	PETG	ABS	% of Increase in Tensile Strength
A1 (X 80)	5.24	7.68	32
A2 (Y90)	16.33	18.27	11
A3 (Z100)	18.66	19.1	2
Sample	PETG+CF2	ABS+CF2	
A4 (X 100)	22.16	29.33	24
A5 (Y80)	29.4	34.805	16
A6 (Z90)	27.58	30.31	9
Sample	PETG+CF2+MCNT2	ABS+CF2+MCNT2	
A7 (X 90)	28	34.5	19
A8 (Y100)	39	40	3
A9 (Z80)	40.76	45.13	10

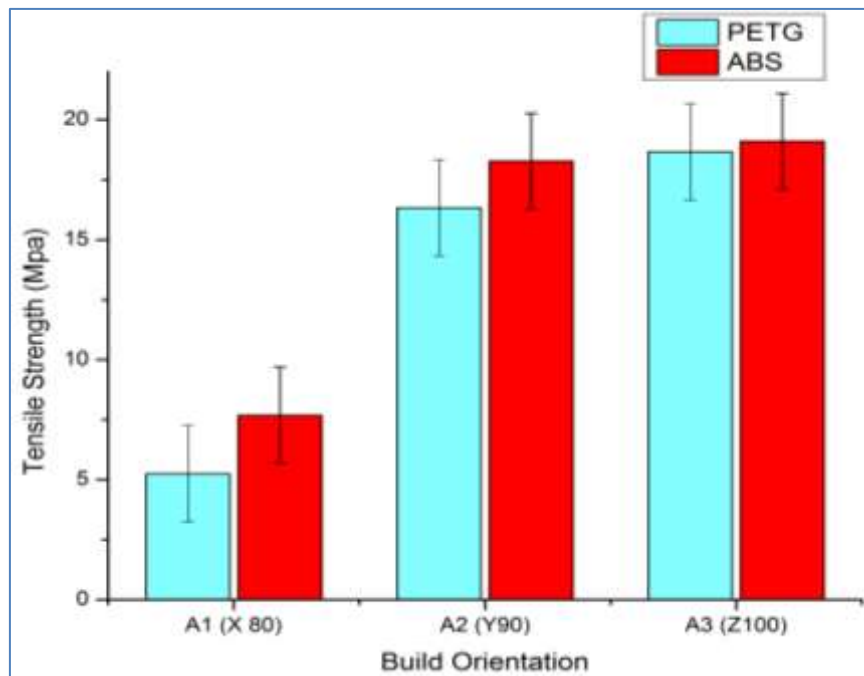


Figure 12 Tensile Strength v/s Various Materials (Build Orientation)

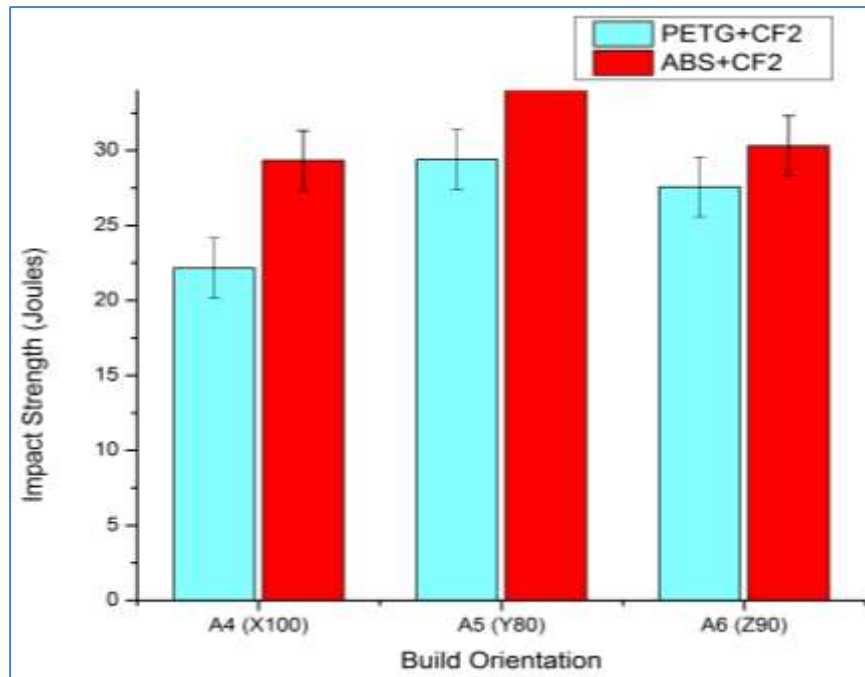


Figure 13 Tensile Strength v/s Various Materials (Build Orientation)

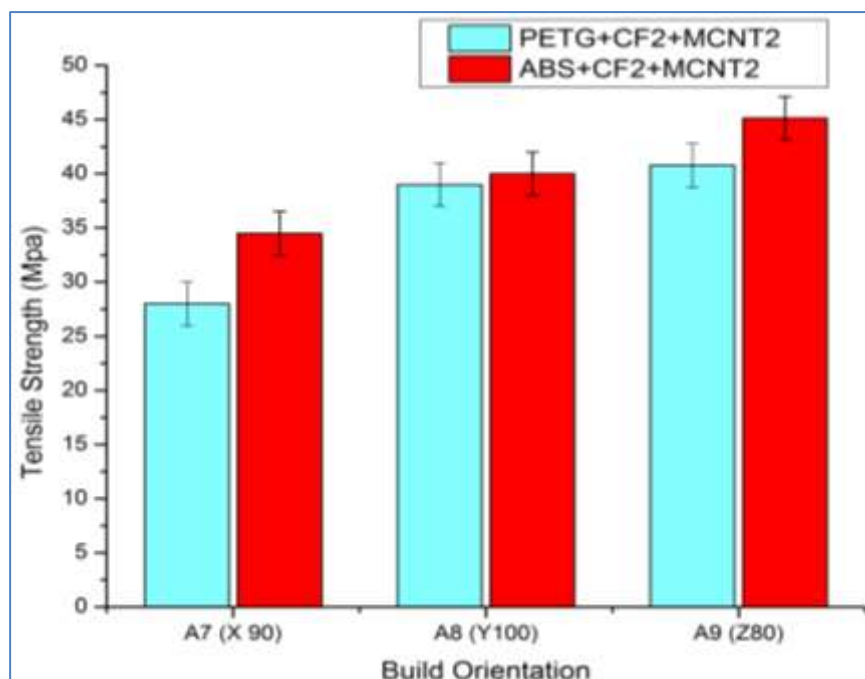


Figure 14 Tensile Strength v/s Various Materials (Build Orientation)

Heading 1 Conclusions

The conclusions derived from the current investigations are as follows:

1. The study focused on the development of composites using carbon fiber reinforcement with PET and ABS through the fused deposition modeling process. The

research aimed to investigate a range of mechanical properties associated with these composites.

2. The research involved a comparative analysis of the properties of PETG combined with carbon fiber and ABS combined with carbon fiber. The study observed that the addition of carbon fibers to the matrix materials resulted in enhanced flexural strength and impact strength.
3. The inclusion of ABS led to a 4% improvement in hardness, while combining ABS with carbon fiber resulted in a 13% increase. Notably, the incorporation of both carbon fiber and carbon nanotubes (MCNT) with ABS showed a significant enhancement, achieving a remarkable 32% improvement in hardness.
4. By incorporating ABS, there was a notable 19% increase in impact strength. Additionally, the combination of ABS with carbon fiber demonstrated a more substantial improvement, reaching 39%. Interestingly, the introduction of both carbon fiber and multiwalled carbon nanotubes with ABS still contributed to an 18% enhancement in impact strength.
5. The introduction of ABS resulted in a significant 32% enhancement in tensile strength. Further improvements were observed when combining ABS with carbon fiber, showing a 24% increase. Moreover, the incorporation of both carbon fiber and MWCNTs with ABS contributed to a notable 19% improvement in tensile strength.
6. The inclusion of carbon elements has markedly enhanced the flexural and impact properties of the matrix, opening avenues for exploring different reinforcement levels.

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