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INFLUENCE OF NOZZLE DIAMETER ON TENSILE AND FLEXURAL MECHANICAL PROPERTIES OF FDM 3D PRINTED PET-CF MATERIAL

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Abstract

Fused Deposition Modeling (FDM) is a widely researched and applied technology in the additive manufacturing industry. Extensive research is conducted on FDM due to the numerous factors influencing the material properties of 3D printed products. This study focuses on one such critical parameter: nozzle diameter. Nozzle diameter impacts not only the mechanical properties of FDM printed materials but also surface quality and dimensional stability. Specifically, this research investigates the effect of nozzle diameter on the tensile and flexural mechanical properties of PET-CF material (PET reinforced with chopped carbon fibers), along with its influence on printing time, which directly affects the cost of the final product. The study results demonstrated that nozzle diameter significantly affects the tensile and flexural mechanical properties of FDM printed PET-CF material. Additionally, nozzle diameter was found to influence the total printing time.

Keywords: FDM; 3D Print; PET-CF; Composite; AM Material.

1. Introduction

Fused Deposition Modeling additive manufacturing (AM) technology is one of the most used today due to its versatility, accessibility, cost, ease of use and ability to fabricate complex geometries. In general, additive manufacturing is opposed to traditional subtractive manufacturing methods, it is characterized as a process of creating product from 3D-model data (CAD 3D model), typically layer by layer. This process is also referred to by various synonyms including additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication [1], [2].

FDM 3D printing operates by feeding a thermoplastic filament from a spool through a feeder to an extrusion head, where it is melted and deposited layer by layer on the print bed to form the final product (Figure 1). FDM materials (filaments) include a variety of thermoplastics and composites, with common options being PLA (Polylactic Acid), PC (Polycarbonate), PET (Polyethylene Terephthalate), PP (Polypropylene), ABS (Acrylonitrile Butadiene Styrene), TPU

(Thermoplastic Polyurethane), and Polyamide (Nylon) [3]. FDM technology is widely used in education, research, and various engineering and industrial sectors, including automotive, aerospace, medical and dental applications. It is also popular in maker spaces and start-up hubs, revolutionizing the traditional methods of developing prototypes and products [4].

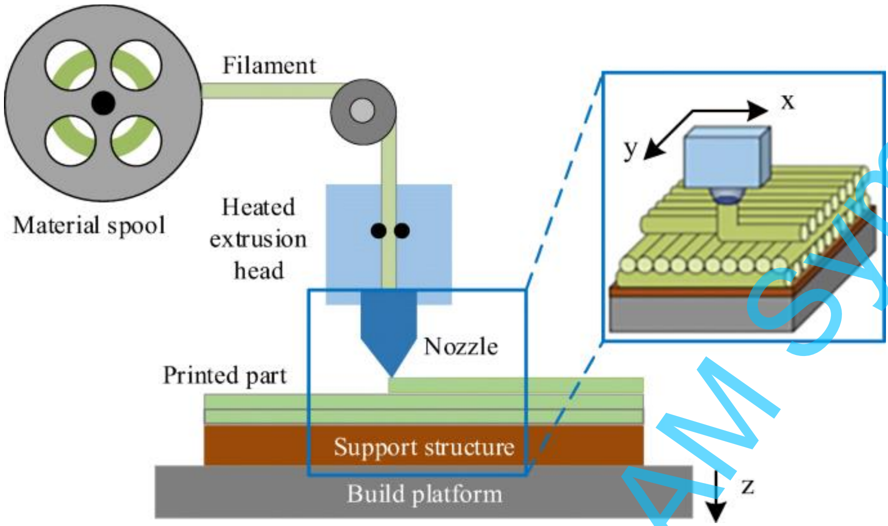

Fig. 1. FDM 3D printing technology process [5]

The advancement of FDM and AM technologies is closely tied to the research and development of the materials used in these processes. Unlike traditional manufacturing methods, AM technologies create materials during the product formation, making the final properties highly dependent on manufacturing parameters and other factors. Key parameters that significantly influence the mechanical properties of FDM 3D printed materials include printing temperature, nozzle diameter, printing speed, layer height, infill density, and printing orientation. These factors are frequently analyzed due to their substantial impact on the final product's performance [6], [7], [8].

When considering the diameter of the nozzle as an influential factor in FDM 3D printing technology, previous research indicates that it significantly affects the mechanical and physical properties of the FDM printed material. This includes impacts on surface roughness, geometric accuracy of the printed product, and printing time [9], [10].

In the article [11], authors examine the impact of printing nozzle diameter on the tensile strength of samples produced using FDM technology. Tests were conducted with different nozzle diameters and infill types, revealing that tensile strength generally increases with nozzle diameter. Specifically, samples with 50% infill density showed higher strength with larger nozzles, while those with 100% infill density exhibited decreased strength as nozzle diameter increased. Larger nozzles also reduced printing time but compromised visual quality.

In study [12], authors tested nozzle sizes of 0.4 mm, 0.6 mm, and 0.8 mm, and found that larger nozzle sizes generally improved the fatigue life of the ABS specimens. Specifically, specimens printed with a 0.8 mm nozzle diameter demonstrated the longest vibration time before fracture. Larger nozzle sizes contribute to fewer micro voids and defects within the material, enhancing fatigue resistance. However, the printing orientation and environmental temperature had a more significant impact on fatigue performance than nozzle size.

The research [13] aimed to determine the effect of nozzle diameter on the spatial structure (raster width) and selected mechanical properties (tensile strength, Charpy impact strength and impact tensile strength) of PLA samples produced by Fused Filament Fabrication (FFF). Different nozzles with diameters of 0.2 mm, 0.4 mm, 0.8 mm, and 1.2 mm were tested, with a constant layer height of 0.2 mm and 100% infill. The study found that nozzle diameters greater than 0.4 mm resulted in increased air voids between print paths, which influenced impact strength by absorbing energy during tests. Samples produced with 0.4 mm and 0.8 mm nozzles showed higher tensile strength, while those with 0.2 mm nozzles showed the lowest mechanical properties. This suggests that larger nozzle diameters enhance layer interconnection and mechanical strength, particularly when the layer height is appropriately matched to the nozzle diameter.

The authors in [14] analyzed the influence of nozzle diameter on the flexural strength of sintered alumina (Al_2O_3) disks created using FDM printing of a ceramic–polymer filament. Statistical analysis revealed that a nozzle diameter of 0.6 mm provided the smallest variation in mass and geometric dimensions of the ceramic samples. The best mechanical properties were achieved with a layer height of 0.4 mm, as this minimized voids between horizontal layers, enhancing strength. The authors found a non-linear relationship between the weight of sintered samples and nozzle diameter. Using a 0.6 mm nozzle diameter offers a balance between maintaining accurate geometric dimensions and maximizing flexural strength, making it a preferred choice for producing high-strength sintered alumina components.

The authors in [15] conducted a thorough examination of the impact of nozzle diameter on the tensile strength of 3D-printed polylactic acid (PLA) parts, focusing on six nozzle sizes ranging from 0.3 to 0.8 mm. The study, performed using an open-source FFF 3D printer, revealed a significant correlation between nozzle size and tensile strength. Smaller nozzles resulted in parts with higher tensile strength due to finer layers and improved interlayer adhesion. However, the study also highlighted the trade-off between tensile strength and printing time associated with smaller nozzle sizes, underscoring the importance of balancing these factors when optimizing 3D printing processes for specific applications.

The authors in study [16] examined the influence of nozzle diameter on the tensile and flexural properties of 3D printed PLA material specimens using a range of diameters (0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm, and 0.8 mm). Tensile and flexural tests were conducted, revealing that both strengths generally increase with nozzle diameter, up to a certain point. The maximum tensile strength of 33.32 MPa was achieved with a 0.6 mm nozzle, while the maximum flexural strength of 76.76 MPa occurred with a 0.5 mm nozzle.

In research [17] authors investigated the impact of different printing parameters, including nozzle diameter, on the fatigue behavior of polylactic acid (PLA) in FDM 3D printing. Standard samples were produced with varying print speeds, temperatures, and nozzle diameters, and subjected to rotary bending fatigue tests. The study revealed that nozzle diameter significantly influenced the fatigue resistance of the specimens, with larger diameters decreasing resistance due to inappropriate layer thickness ratios. However, lower print temperatures increased fatigue lifetime. A cubic model was developed to predict fatigue lifetime based on stress level, print speed, temperature, and nozzle diameter, with significant interactions observed among parameters.

The objective of this study was to assess the impact of two different nozzle diameters (0.4 mm and 0.6 mm) on the tensile and flexural mechanical properties of FDM 3D printed PET-CF material. The analysis focused on key mechanical characteristics including maximum strength, modulus of elasticity, and total deformation prior to specimen failure in both tensile and flexural tests. Furthermore, the study investigated the influence of nozzle diameter on printing time, with detailed findings presented in subsequent sections.

2. Materials and Methods

This research focuses on the experimental analysis of the influence of nozzle diameter on the tensile and flexural mechanical properties of FDM 3D-printed PET-CF material. The experimental procedure is illustrated in the flow diagram shown in the figure below.

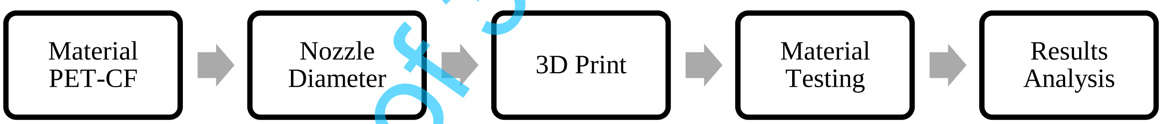

Fig. 2. Experimental procedure flow diagram

The material analyzed in this study was PET-CF from Ultimaker, a carbon fiber-reinforced variant of Polyethylene Terephthalate containing chopped carbon fibers. PET-CF is a composite material that retains the excellent printability of PETG while offering enhanced stiffness, as well as improved temperature and chemical resistance, which can be further improved through annealing. This material is suitable for applications such as tooling, functional prototyping, manufacturing aids, and more. The mechanical properties of PET-CF material by the manufacturer are presented in the table below [18].

Mechanical properties	Test method	Typical value (XY, flat)
Tensile modulus	ASTM D3039 (1 mm / min)	4342 ± 89 MPa
Tensile strength	ASTM D3039 (5 mm / min)	50,6 ± 0,6 MPa
Elongation at break	ASTM D3039 (5 mm / min)	5,5 ± 0.6%
Flexural modulus	ISO 178 (1 mm / min)	5743 ± 150 MPa
Flexural strength	ISO 178 (5 mm / min)	102,8 ± 2,6 MPa
Flexural strain at brake	ISO 178 (5 mm / min)	No break (>10%)
All properties are for specimens printed in flat position and with 0,6 mm CC Core nozzle diameter.		

Table 1. Ultimaker PET-CF FDM 3D Printed material properties by manufacturer

The 3D CAD models of the testing specimens were designed in Solidworks 2023 in accordance with ISO 527-2 for tensile testing and ISO 178 for flexural testing, as illustrated in Fig. 3. These CAD models were then converted into STL format using Solidworks, enabling their use in slicer software for 3D printing preparation.

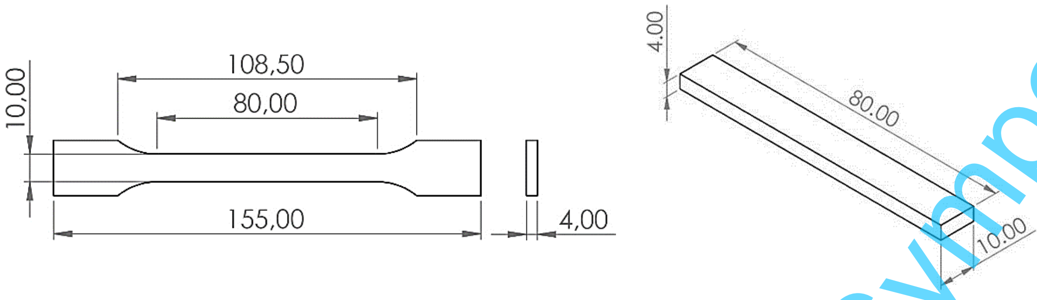

Fig. 3. Tensile (left) and flexural testing specimen (right)

Specimens and printing parameters were prepared and defined using CURA 5.6.0 slicer software. All specimens were oriented flat for printing. Due to the composite nature of the material, which includes carbon fibers, a CC Core nozzle was used for printing, with nozzle sizes of 0.4 mm and 0.6 mm. All specimens are 3D printed on Ultimaker S5 Pro with printing parameters presented in Table 2.

Printing parameters	
Layer height	0,15 mm
Infill density	100 %
Printing temperature	270 °C
Build plate temperature	80 °C
Print speed	30 mm/s
Fan speed	10 %
CC Core nozzle diameter	0,4 mm and 0,6 mm
Printing parameters are defined using CURA "Normal profile" 0,15 mm	

Table 2. Printing parameters used for 3D printing testing specimens with 0,4 mm and 0,6 mm nozzle diameter

For each type of testing, ten replicas of each test sample were printed and subsequently tested for tensile and flexural properties using a Shimadzu AGS-X universal testing machine with a capacity of 10 kN (Fig. 4).

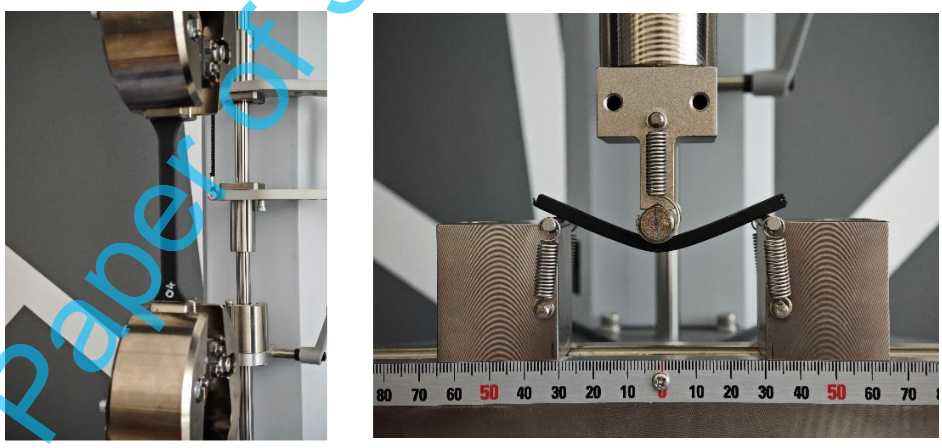

Fig. 4. Tensile (left) and flexural (right) testing on AGS-X universal testing machine

Data collection and monitoring were conducted using Shimadzu's Trapezium-X software, which facilitated the plotting of stress-strain diagrams. The printing time for each sample was determined based on calculations provided by the CURA software. Subsequently, all data were statistically analyzed using Excel.

3. Results and Analysis

Tensile and flexural tests were performed with a constant testing speed of 5 mm/min, according to ISO 527-2 and ISO 178 standards. Stress-strain diagrams were plotted and presented on Fig. 5.

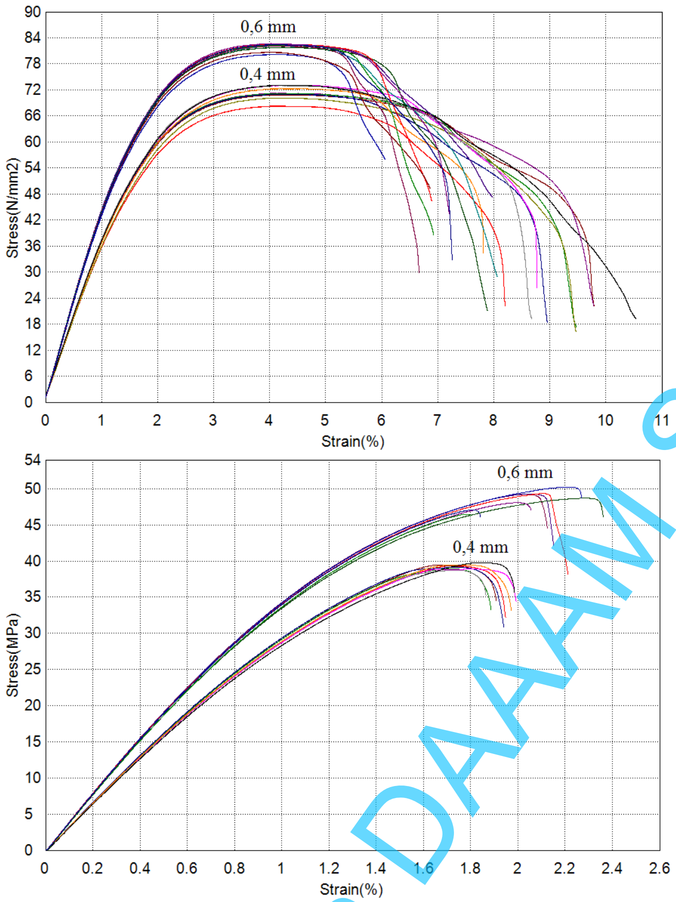

Fig. 5. Stress-strain diagrams for tensile (upper) and flexural (lower) mechanical properties for different nozzle diameter

The analysis of the study results focused on evaluating the impact of nozzle diameter on tensile and flexural strength, the modulus of elasticity in both tension and flexural, the maximum deformation before brake during tensile and flexural testing, and the total printing time.

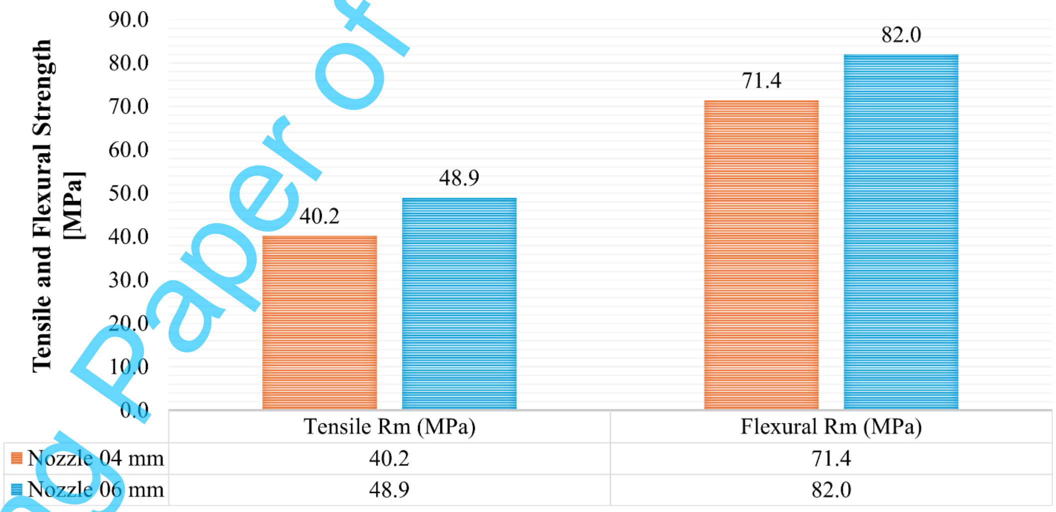

Fig. 6. Tensile and flexural strength of PET-CF FDM 3D printed material with different nozzle diameter

From the Fig. 6., it can be concluded that nozzle diameter affects the tensile and flexural strength of FDM 3D-printed PET-CF material. The diagram indicates that using a 0.6 mm diameter nozzle increases tensile strength up to 21.6% and flexural strength up to 14.8%.

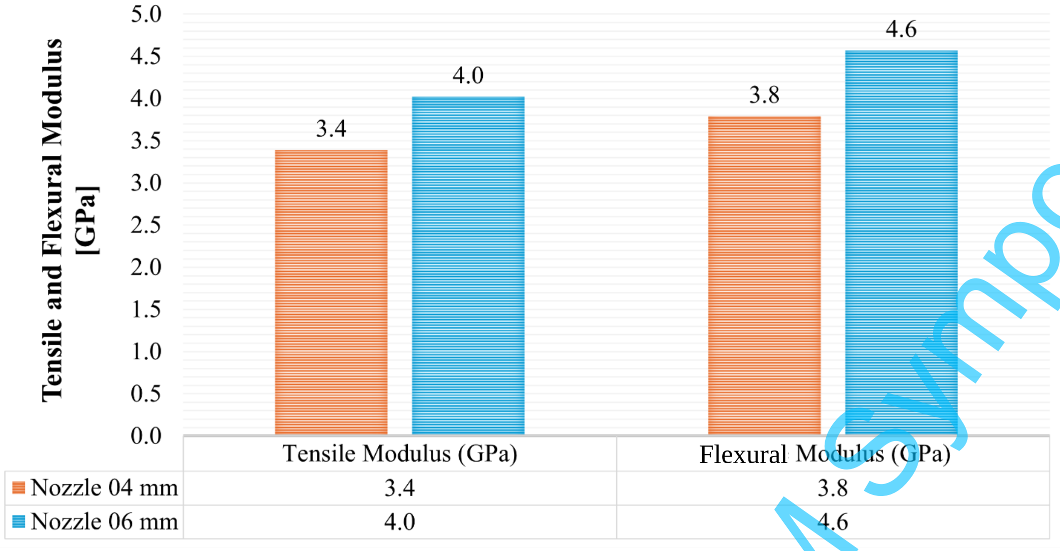

Fig. 7. Tensile and flexural modulus of PET-CF FDM 3D printed material with different nozzle diameter

Analyzing the modulus of elasticity during tensile and flexural tests, it was concluded that FDM 3D printing of PET-CF material with a larger nozzle diameter increases the modulus of elasticity (Fig. 7). The analysis shows that using a nozzle diameter of 0.6 mm compared to 0.4 mm increases the modulus of elasticity in tension up to 17.6%, and in flexural up to 21%.

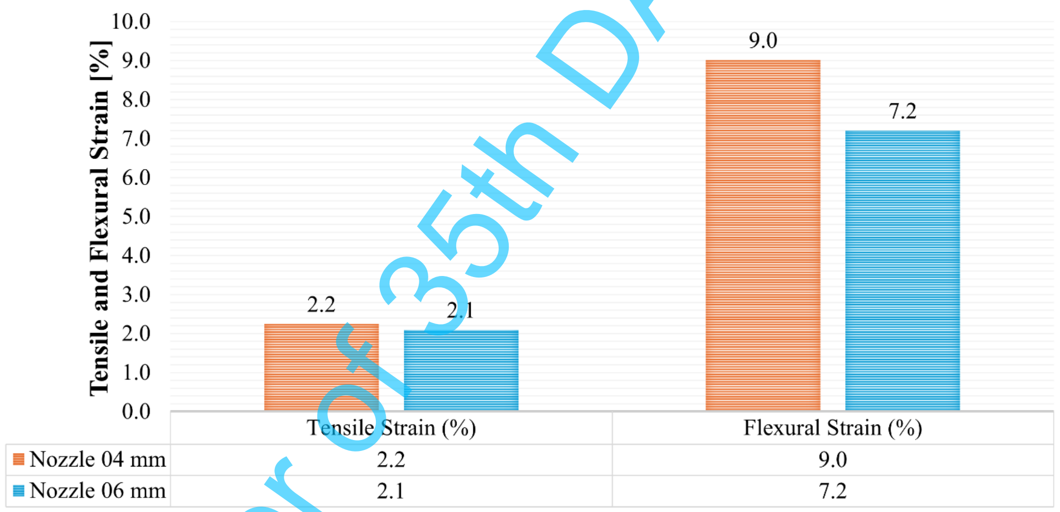

Fig. 8. Tensile and flexural strain before brake of PET-CF FDM 3D printed material with different nozzle diameter

In contrast to the effects on strength and modulus of elasticity, the influence of nozzle diameter on the strain before brake during tensile and flexural tests shows that using a larger nozzle diameter reduces the strain. Fig. 8. illustrates that the strain before brake in the tensile test was reduced by 4.5%, and in the flexural test, it decreased by up to 20% when the PET-CF material is FDM 3D printed with a 0.6 mm nozzle diameter.

In addition to the mechanical properties, the influence of the nozzle diameter on the printing time was also analyzed, where the printing time was expressed as the time to 3D print one test sample for testing the tensile and flexural mechanical properties. As expected, using a 0.6 mm diameter nozzle for 3D printing testing samples reduces the printing time by up to 31% (Fig. 9).

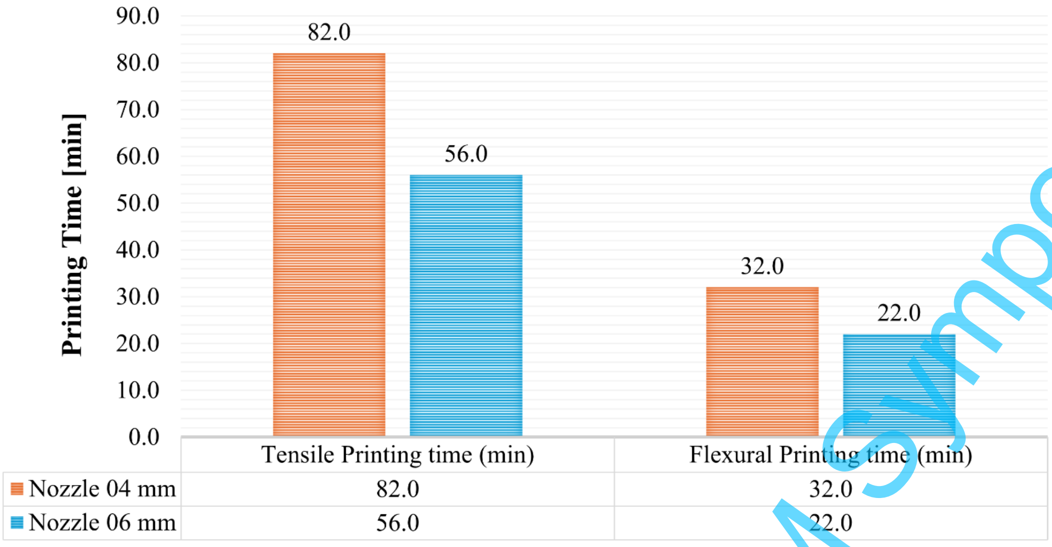

Fig. 9. Influence of nozzle diameter on printing time of tensile and flexural testing specimens

4. Conclusion

The study systematically evaluated the impact of nozzle diameter on the mechanical properties and printing efficiency of FDM 3D-printed PET-CF material. The findings can be summarized as follows:

- Strength: Nozzle diameter significantly influences the tensile and flexural strength of FDM 3D printed PET-CF material. Specifically, using a 0.6 mm nozzle diameter resulted in an increase in tensile strength by up to 21.6% and flexural strength by up to 14.8%.
- Modulus of Elasticity: The modulus of elasticity in both tension and flexural tests also showed improvement with a larger nozzle diameter. A 0.6 mm nozzle increased the modulus of elasticity by up to 17.6% in tension and up to 21% in flexural testing compared to a 0.4 mm nozzle.
- Strain Before Failure: Contrary to the observed enhancements in strength and modulus of elasticity, the strain before failure during tensile and flexural tests decreased with an increase in nozzle diameter. The strain before failure in tensile tests was reduced by 4.5%, and in flexural tests, it decreased by up to 20% when using a 0.6 mm nozzle diameter.
- Printing time: Using a nozzle with 0,6 mm diameter for 3D printing of PET-CF material reduces printing time by up to 31%, which finally affects the reduction of the price of the FDM 3D printed product itself.

These results indicate that while a larger nozzle diameter can enhance the strength and stiffness of FDM 3D-printed PET-CF materials, it may also lead to a reduction in ductility and speed up the process of 3D printing. Therefore, the selection of nozzle diameter should be carefully considered based on the specific requirements of the application, balancing the need for strength and stiffness against the desired level of material deformability.

For future research, it is recommended to analyze how the nozzle diameter affects other mechanical properties such as compressive strength, hardness, and impact toughness. Additionally, extending the analysis beyond mechanical properties to investigate its effects on surface quality, dimensional accuracy, and other pertinent aspects in FDM 3D printed PET-CF materials is essential. This comprehensive approach will deepen our understanding of nozzle size's multifaceted influence and contribute to refining additive manufacturing processes for enhanced product performance and quality. Also, analyze other dimensions of the nozzle diameter to make optimizations.

5. Acknowledgments

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