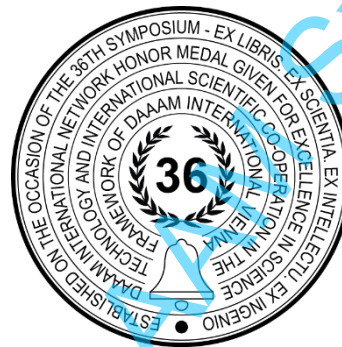


THE INFLUENCE OF ANNEALING ON THE MECHANICAL PROPERTIES OF FDM 3D PRINTED PET REINFORCED WITH CARBON FIBERS

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Abstract

This study investigates the influence of the annealing process on the mechanical properties of FDM 3D-printed PET reinforced with carbon fibers (PET-CF), with a particular focus on tensile strength, flexural strength, and the corresponding elastic moduli. Specimens were thermally treated at three different temperatures (80 °C, 130 °C, and 180 °C) and for three different durations (30 min, 120 min, and 210 min). The obtained results were compared with the material specifications provided by the manufacturer to determine the conditions under which the mechanical properties are maximized. To assess the significance of temperature and annealing time on the material behavior, an analysis of variance (ANOVA) was conducted. This statistical method enabled the identification of key factors and their interactions affecting the tensile and flexural mechanical properties of the PET-CF material. Based on the experimental data, predictive mathematical models were developed to describe the material's behavior as a function of annealing temperature, time, and their interaction.

Keywords: FDM; PET-CF; 3D printing; annealing; ANOVA.

1. Introduction

In modern manufacturing environments, a wide range of technologies are used to produce functional products. Traditional approaches such as subtractive manufacturing, which removes material from a solid block, and formative manufacturing, which reshapes materials using force or heat without adding or removing material, have been foundational for decades. However, additive manufacturing (AM) has recently emerged as a transformative technology based on the principle of adding material layer by layer [1], [2].

Additive Manufacturing, commonly referred to as 3D printing, encompasses a set of technologies that build physical, three-dimensional objects from digital CAD (Computer-Aided Design) models. These models are translated into layers, which are deposited sequentially, offering unique advantages such as design freedom, material efficiency, and fast prototyping. AM supports the use of advanced materials, enables the production of complex geometries, and significantly

reduces lead time and material waste. Consequently, AM has found wide application in aerospace, medical, automotive, architectural, and consumer product industries [3], [4], [5].

Among AM technologies, Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), is the most widely used. First patented in 1989 by Stratasys, FDM belongs to the material extrusion category of AM technologies. In this process, thermoplastic filament is heated in a print head and extruded through a nozzle in a semi-molten state to form layers along a predefined path generated by slicing software (e.g., Ultimaker Cura) [6]. The workflow typically starts with the creation of a 3D CAD model using software like SolidWorks, CATIA, or Autodesk Fusion 360, or through 3D scanning of a physical object (Fig. 1). The model is converted into the STL format and imported into slicer software, which divides it into layers and generates G-code instructions that control the printer's movements [7], [8]. Once the G-code is transferred to the printer, and both the nozzle and build platform reach the desired temperatures, the material is extruded layer by layer until the part is complete. FDM printers are user-friendly and capable of printing multiple parts with varying infill patterns and geometries in a single operation. However, challenges include internal porosity, surface roughness, interlayer adhesion issues, and anisotropy, especially in the Z-direction, which can lead to delamination [9].

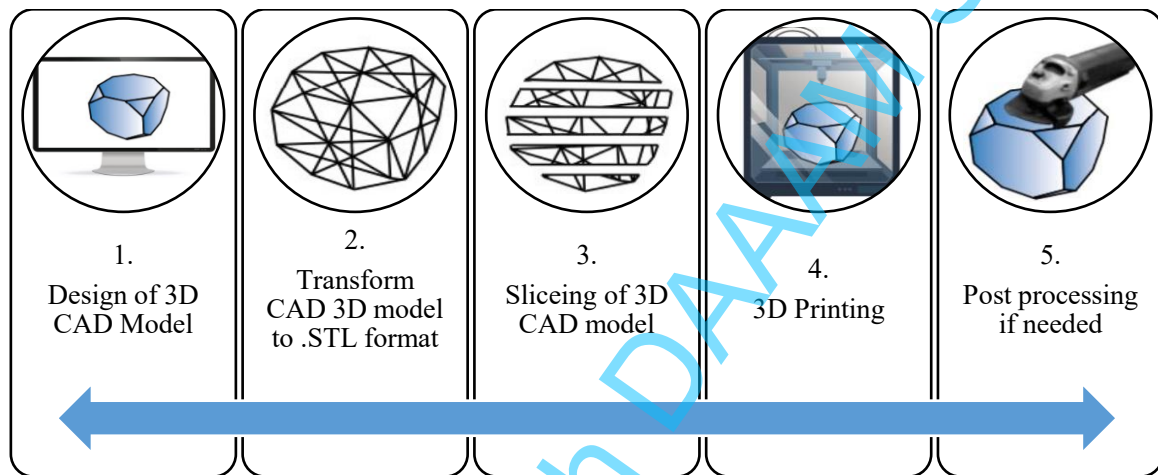


Fig. 1. The principle of product manufacturing using additive technologies [5]

These limitations can be mitigated by optimizing print parameters, but further improvements can be achieved using fiber-reinforced composite filaments. One of the most promising materials is polyethylene terephthalate reinforced with carbon fibers (PET-CF). Carbon fibers significantly enhance the mechanical properties of thermoplastics while maintaining low density. PET-CF filaments are produced by combining PET as the matrix and chopped carbon fibers as reinforcement, through an extrusion process that ensures homogeneous distribution of fibers within the polymer matrix [10].

The resulting composite exhibits high tensile strength, stiffness, and thermal resistance, capable of withstanding temperatures up to 76 °C. These properties make PET-CF suitable for functional prototyping and end-use applications in the automotive, aerospace, and tooling industries. Due to its high wear resistance and rigidity, PET-CF is also used to fabricate replacement parts on demand, reducing downtime in industrial operations. Ultimaker, a leading 3D printer manufacturer, states that PET-CF properties can be further enhanced by thermal post-processing such as annealing [11].

Annealing is a thermal treatment process traditionally used in metallurgy to reduce internal stresses, improve ductility, and increase structural uniformity. When applied to polymer materials, the principle remains similar. In injection molding, for example, controlled cooling improves part strength and thermal resistance. The same technique can be applied to FDM-printed components, which are prone to internal stress and poor interlayer bonding due to rapid cooling between deposited layers [12], [13].

In FDM, layers solidify immediately upon deposition, often resulting in stress accumulation, poor layer adhesion, microcracks, and dimensional distortion. Smaller features cool faster than larger ones, leading to thermal gradients and localized shrinkage. Moreover, the layered structure inherently contains microvoids and imperfections that reduce load-bearing capacity compared to injection-molded counterparts [13], [14].

Annealing improves mechanical and thermal properties by relieving internal stresses, enhancing interlayer diffusion, and promoting the formation of stable crystalline regions. The key parameters in the annealing process are temperature, exposure time, and the cooling method. The annealing temperature must lie between the material's glass transition

temperature (T_g) and melting temperature (T_m) to enable molecular mobility without melting the polymer. Prolonged exposure at optimal temperature facilitates molecular reorganization and interlayer fusion [13].

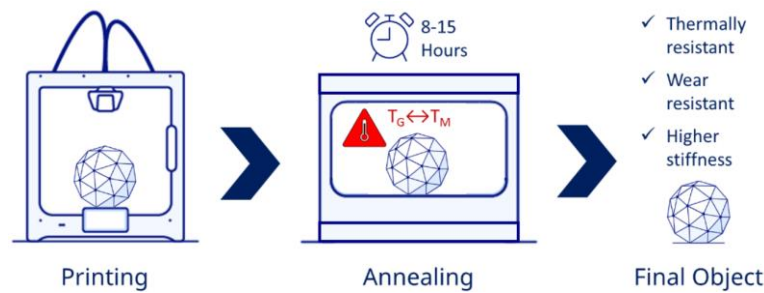


Fig. 2. Schematic representation of the annealing process applied to FDM 3D printed PET-CF material [14]

Controlled cooling, whether inside the oven or in ambient air, is essential for minimizing warping and dimensional inaccuracies. Gradual temperature decline promotes molecular alignment into energetically favorable crystalline patterns, enhancing density and structural integrity. However, excessive crystallization may reduce material toughness, and uneven heating can lead to internal stress buildup, deformation, or degradation of the polymer chains [13], [15].

While annealing offers notable advantages, such as increased stiffness, thermal resistance, and dimensional stability, it must be carefully controlled to avoid brittleness and geometric distortion.

In this study, a detailed experimental investigation was carried out to evaluate the influence of annealing temperature and time on the mechanical properties of FDM-printed PET-CF composite material. Samples were thermally treated at three different temperatures (80 °C, 130 °C, and 180 °C) and for three different durations (30, 120, and 210 minutes). The focus was placed on analyzing the resulting changes in tensile and flexural strength, as well as in the corresponding modulus of elasticity. Based on the experimental data, predictive mathematical models were developed to describe the relationship between annealing conditions and mechanical properties, contributing to optimized post-processing strategies for FDM 3D printed PET-CF materials.

2. Literature review

Several studies have investigated how annealing affects the mechanical behavior of FDM-printed materials. Annealing has been shown to improve tensile and flexural strength, hardness, and dimensional stability, although outcomes depend on the material type, annealing temperature, and exposure time.

Rengiseti et al. [13] studied the mechanical behavior of PLA, ABS, PETG, and their carbon-fiber-reinforced variants (PLA-CF, CF-ABS, and PETG-CF). All samples were annealed at a temperature 5 °C above their glass transition temperature (T_g) for 60 minutes. The samples were heated in a cold oven to the target temperature, then allowed to cool inside the oven after heating. PETG and PETG-CF showed significant improvements in tensile strength and Young's modulus, while flexural strength slightly decreased. This suggests a complex balance between improved stiffness and reduced flexibility due to heat treatment [16].

Bart DE Wijk [12] evaluated the effects of annealing on PLA and PET-CF materials printed under controlled conditions. PLA samples were annealed at 80 °C and 110 °C, and PET-CF samples at 120 °C, 170 °C, and 220 °C, each for a duration of 2 hours. PET-CF specimens annealed at lower temperatures showed up to an 18.5% increase in flexural strength, while higher temperatures led to increased stiffness and thermal resistance. However, interlayer adhesion decreased at higher temperatures, indicating a potential trade-off between thermal performance and structural integrity [13].

Valvez et al. [14] examined PETG and its reinforced versions (PETG-CF and PETG-KF), using a B2X300 printer and a 0.6 mm nozzle. Samples were annealed at 90 °C, 110 °C, and 130 °C for 30, 240, and 480 minutes. Increased temperature and duration generally enhanced flexural strength and elastic modulus, but dimensional deformation was also observed. For parts where dimensional precision is critical, careful selection of annealing parameters is necessary [17].

Stojković et al. [15] investigated the effects of annealing temperature, exposure time, and print layer height (0.1 mm, 0.2 mm, 0.3 mm) on PLA, PETG, and PETG-CF. Samples were annealed at temperatures ranging from 60 °C to 100 °C for 30, 60, and 90 minutes. The results showed that increasing layer height reduced tensile strength, while longer annealing times improved mechanical properties, especially for PETG-CF. This material also showed the smallest dimensional change and highest modulus of elasticity, indicating its robustness under thermal treatment [18].

Sathish Kumar et al. [16] studied the influence of infill density and annealing on PETG and PETG-CF samples. Infill densities of 25%, 50%, 75%, and 100% were analyzed. Samples were annealed at temperatures 5 °C above their T_g for 60 minutes. Increasing the infill density resulted in higher hardness, tensile and flexural strength, and toughness. For PETG-CF with 100% infill, flexural strength increased by 18% and tensile strength by 25%, compared to annealed PETG, confirming the benefit of carbon fiber reinforcement and thermal treatment [19].

Across these studies, researchers have explored how annealing improves mechanical properties in various thermoplastic composites, including PLA, PETG, ABS, and their carbon and Kevlar-reinforced variants. A common approach involves combining annealing with optimization of print parameters such as infill density and layer height. While improvements in tensile and flexural properties are well documented, outcomes can vary significantly depending on the specific material formulation and annealing protocol.

Building upon this background, the current study focuses on Ultimaker's PET-CF composite filament and aims to determine the optimal annealing parameters—temperature and time—for improving tensile and flexural mechanical properties. Experimental tests were conducted using nine different annealing conditions to evaluate mechanical behavior and develop mathematical models that correlate treatment conditions with performance outcomes. This approach enables a more systematic understanding of post-processing effects on high-performance 3D printed composites.

3. Methodology

The experimental part of this research was conducted to investigate the influence of annealing temperature and time on the mechanical properties of FDM 3D printed PET-CF material. The experiments were fully carried out in the Laboratory for Testing of Polymeric Materials of the Kingdom of Norway (IPMLab), located at the Faculty of Mechanical Engineering, University of Sarajevo. Samples were subjected to thermal treatment at three different temperatures and three different time intervals, followed by tensile and flexural mechanical testing. The complete procedure is illustrated in Figure 3.

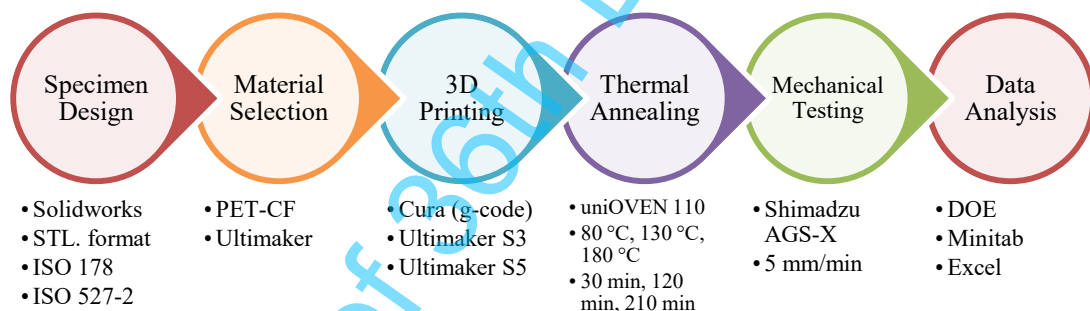


Fig. 3. Overview of the experimental procedure

Test samples for evaluating tensile and flexural mechanical properties were designed using SolidWorks 2025 software. The geometry for tensile testing followed the ISO 527-2 standard [20], while the geometry for flexural testing was based on ISO 178 [21]. The dimensional characteristics of both types of specimens are shown in Figure 4.



Fig. 4. Geometric characteristics of tensile and flexural test specimens

The CAD models were exported to STL format for slicing and G-code generation. Model preparation for 3D printing was performed using UltiMaker Cura 5.6.0. For the Ultimaker PET-CF (black) filament, predefined parameters within Cura (Normal Profile 0.15 mm, Shell Thickness 1.8 mm, Infill Density 100%) were used to ensure minimal influence of slicing settings on the final mechanical results. The printing parameters used are listed in Table 1.

3D Printing Parameters	Value
Nozzle diameter, [mm]	0,6
Layer height, [mm]	0,15
Infill density, [%]	100%
Printing temperature, [°C]	270
Build plate temperature, [°C]	80
Printing speed, [mm/s]	25
Fan speedora, [%]	10

Table 1. 3D printing parameters for PET-CF specimens

After slicing, all samples were printed in a flat orientation on desktop FDM 3D printers: Ultimaker S3 and Ultimaker S5. A total of 100 samples were printed—50 for flexural testing and 50 for tensile testing. After 3D printing, the specimens were annealed using a uniOVEN 110 laboratory oven, shown in Figure 5.



Fig. 5. Laboratory oven uniOVEN 110 used for thermal annealing and test specimens inside

For both tensile and flexural tests, 45 samples were thermally treated under nine different combinations of temperature (80 °C, 130 °C, and 180 °C) and time (30 min, 120 min, and 210 min). For each combination, five specimens were used. Additionally, five untreated samples for each test type were preserved as a control group to evaluate the influence of annealing by comparison.

After the annealing, the samples were removed from the oven and left to cool at room temperature. Mechanical testing of the annealed and non-annealed samples was performed using a Shimadzu AGS-X universal testing machine, with a maximum force capacity of 10 kN. Tensile testing was conducted in accordance with ISO 527-2, while flexural testing followed ISO 178. The crosshead speed for both types of testing was set to 5 mm/min, as shown in Figure 6.

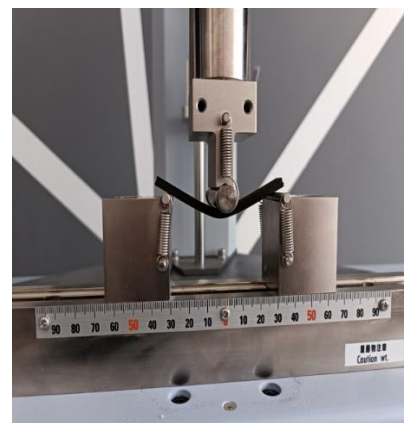
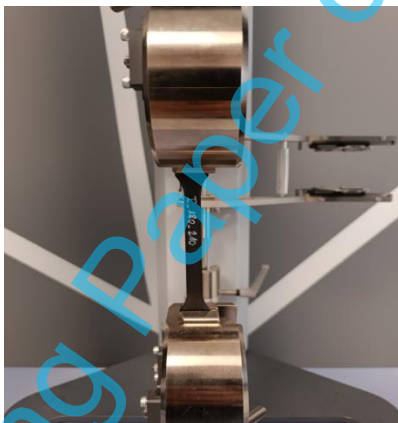


Fig. 6. Tensile (left) and flexural (right) testing setup

Test data acquisition and logging were performed using the TrapeziumX software, developed by Shimadzu. Initially, the mechanical results of the untreated specimens were compared to the values provided in the material's Technical Data Sheet (TDS) to verify the consistency of the printed specimens with the manufacturer's specifications. Subsequently, the results of the annealed samples were compared to the untreated control group to evaluate the effect of annealing on the mechanical properties.

Collected data were analyzed statistically using Python programming language along with Microsoft Excel and Minitab software. The results and discussion derived from this analysis are presented in the following chapters.

3.1. Material

The material used in this study is UltiMaker PET CF — a carbon fiber-reinforced version of polyethylene terephthalate (PET), designed for high-performance FDM 3D printing. It is supplied as 2.85 mm filament spools (750 g) and is optimized for use with UltiMaker S series printers. UltiMaker PET CF combines the easy printability of PETG with significantly improved stiffness, dimensional stability, and chemical and thermal resistance. After annealing, it can withstand temperatures up to 180 °C, making it suitable for functional prototypes, tools, replacement parts, and manufacturing aids. Compared to other composites like PA CF, PET CF offers better ease of use, lower warpage, excellent surface finish, and reliable print quality.

In this work, all specimens were printed using predefined settings in UltiMaker Cura 5.3 (layer height 0.15 mm, infill 100%, nozzle 0.6 mm) and conditioned at room temperature for 24 hours before testing. All samples were printed individually using new filament spools on UltiMaker S7 with the UltiMaker Material Station to ensure dry storage and optimal results. Table below present the mechanical properties of UltiMaker PET CF before and after annealing, as specified by the manufacturer.

Mechanical properties	Method	No annealing	After annealing
Tensile (Young's) modulus	ASTM D3039 (1mm / min)	4342 ± 89 MPa	5530 ± 124
Tensile stress at yield	ASTM D3039 (5 mm / min)	50.6 ± 0.6 MPa	-
Tensile stress at break	ASTM D3039 (5 mm / min)	75.2 ± 0.8 MPa	72,8 ± 2,0
Elongation at yield	ASTM D3039 (5 mm / min)	3.9 ± 0.1%	-
Elongation at break	ASTM D3039 (5 mm / min)	5.5 ± 0.6%	3,4 ± 0,2
Flexural modulus	ISO 178 (1 mm / min)	5743 ± 150 MPa	6280 ± 114
Flexural strength	ISO 178 (5 mm / min)	102.8 ± 2.6 MPa at 4.4%	136,6 ± 2,8
Flexural strain at break	ISO 178 (5 mm / min)	No break (>10%)	3,0 ± 0,1

Table 2. Mechanical properties of UltiMaker PET CF before and after annealing, as specified by the manufacturer [14]

According to UltiMaker's technical documentation, annealing at 120 °C for 2 hours can improve strength by up to 30%, stiffness by 10%, and increase heat resistance from 76 °C to 181 °C [14].

4. Results and discussion

Following the mechanical testing of FDM 3D printed PET-CF material, the obtained results were analyzed and are presented in this chapter. A total of 100 specimens were tested, consisting of 50 samples for tensile testing and 50 samples for flexural testing. The average values for all tested groups are summarized in tabular format. Table 3. summarizes the results from the tensile and flexural tests, showing average values of tensile strength (R_m , MPa) and Young's modulus (E , GPa) for each condition.

Temperature (°C)	Time (min)	Tensile properties		Flexural properties	
		R_m [MPa]	E [GPa]	R_m [MPa]	E [GPa]
Nontreated (non-annealed)		47.5	4.0	84.6	4.8
80	30	46.8	4.0	85.0	4.9
80	120	45.6	4.0	84.3	4.8
80	210	45.4	3.9	83.2	4.7
130	30	51.8	4.5	109.8	5.5
130	120	50.0	4.5	108.1	5.5
130	210	56.3	4.6	109.5	5.5
180	30	43.8	4.6	110.7	5.5
180	120	47.1	4.6	105.9	5.5
180	210	47.8	4.7	100.6	5.5

Table 3. Average tensile and flexural properties for PET-CF samples under different annealing conditions

The variation in tensile strength of PET-CF samples after annealing is presented in Figure 7, where all annealing conditions are shown in a single comparative chart. The results indicate that annealing at 80 °C leads to a decreasing trend

in tensile strength. Longer exposure times result in more pronounced degradation, with the most significant reduction observed after 210 minutes—showing a 4.42% decrease compared to the untreated reference.

In contrast, samples annealed at 130 °C exhibited an overall improvement in tensile strength at all time intervals. The most notable increase was recorded after 210 minutes, with an improvement of 18.34% over untreated specimens. This represents the highest tensile strength achieved in the entire experiment and highlights the 130 °C / 210 min combination as the most favorable condition for enhancing tensile performance.

Annealing at 180 °C showed a variable influence. At 30 minutes, tensile strength dropped significantly by 7.95%. However, with increased exposure time, the strength gradually recovered. Still, no substantial improvement was recorded compared to untreated samples, indicating that excessive temperature may initially weaken the material before structural stabilization occurs.

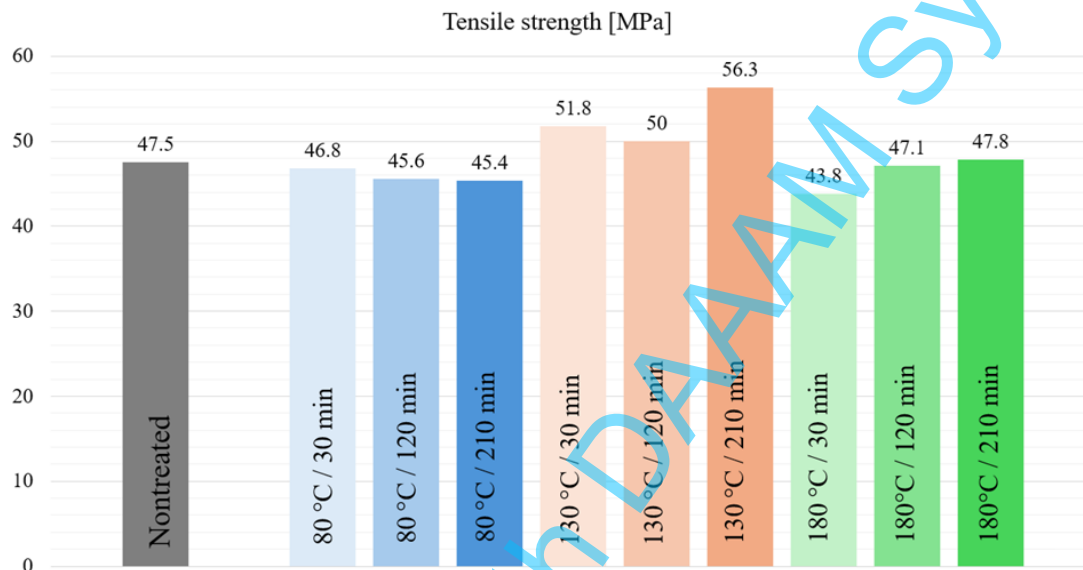


Fig. 7. Influence of annealing in different conditions on tensile strength of PET-CF samples

The results for tensile modulus are presented in Figure 8, which combines all data points across the three annealing temperatures into a single chart. At 80 °C, a slight initial improvement of 1.51% was observed after 30 minutes of treatment. However, prolonged annealing times (120 min and 210 min) led to a decrease in tensile modulus, with a 1.5% drop recorded after 210 minutes.

At 130 °C, a continuous increase in tensile modulus was observed with longer annealing times. The improvement was most evident at 210 minutes, suggesting that the exposure duration positively correlates with material stiffness at this temperature.

Annealing at 180 °C produced the most significant increase in tensile modulus. Even the shortest exposure time (30 min) resulted in a 15.67% enhancement. The trend continued with increasing time, reaching a maximum improvement of 18.7% after 210 minutes. This clearly indicates that higher annealing temperatures, when combined with longer durations, can considerably enhance the stiffness of PET-CF under tensile loading.

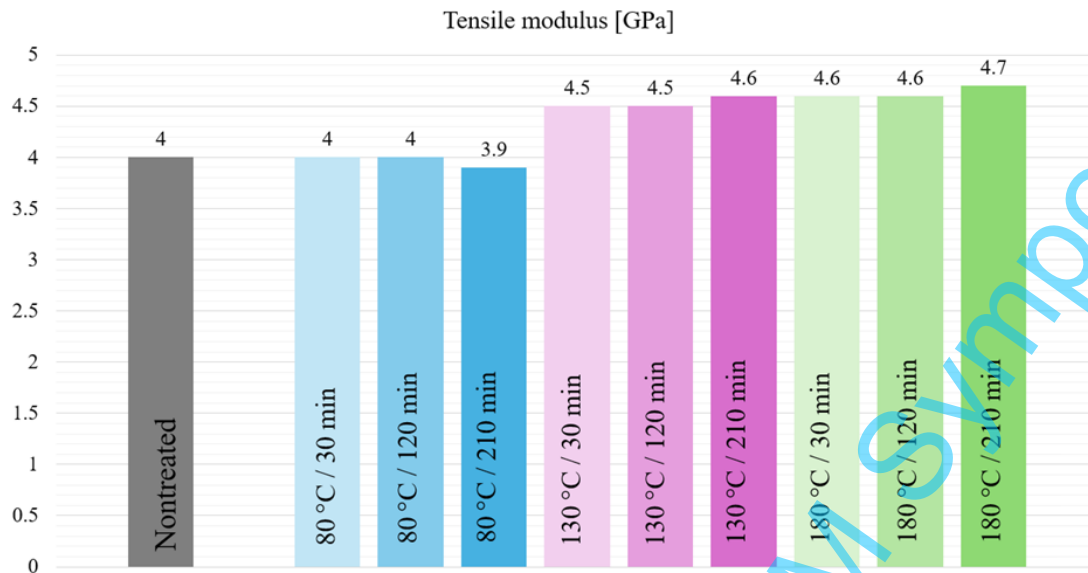


Fig. 8. Influence of annealing in different conditions on tensile modulus of PET-CF samples

The analysis of flexural strength results indicates that annealing has an even more pronounced impact on the flexural mechanical properties of PET-CF compared to tensile properties. All variations across different temperatures and durations are consolidated in Figure 9.

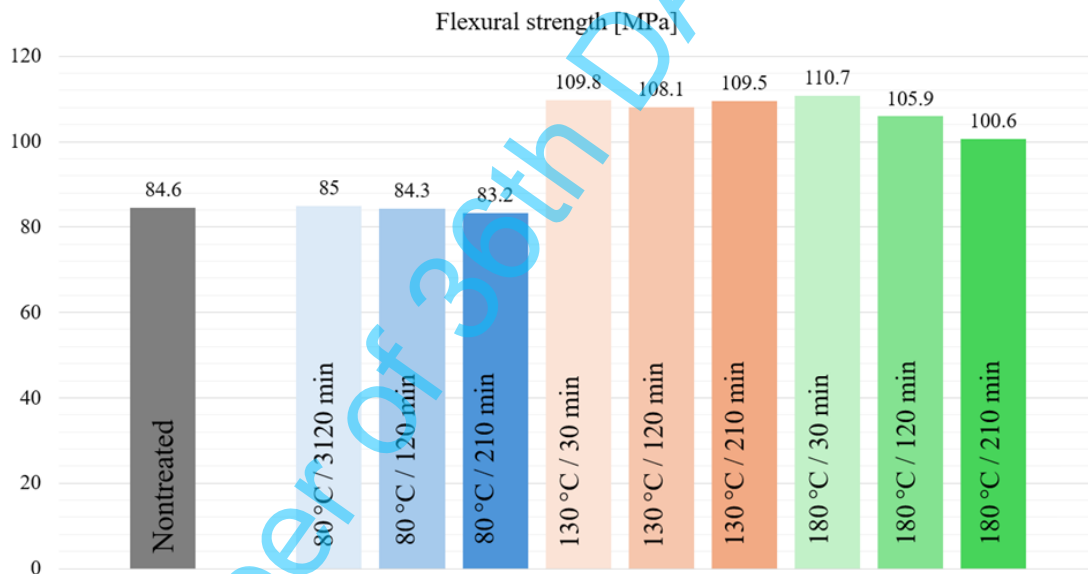


Fig. 9. Influence of annealing in different conditions on Flexural strength of PET-CF samples

At 80 °C, a slight improvement of 0.4% was observed after 30 minutes of treatment. However, with longer exposure times, the flexural strength began to decrease. A reduction of 0.35% was recorded after 120 minutes, and a more noticeable decrease of 1.7% occurred after 210 minutes, compared to the untreated reference samples.

Annealing at 130 °C produced significant improvements in flexural strength. After just 30 minutes, strength increased by 29.8%. Although a slight decline to 27.7% was noted at 120 minutes, the strength rose again to 29.4% after 210 minutes. These results suggest that annealing at 130 °C consistently enhances flexural performance, though the effect is somewhat influenced by treatment duration.

At 180 °C, the initial 30-minute treatment resulted in the highest increase in flexural strength recorded in this study—30.85%. With longer exposure times, the improvement gradually declined: 25.12% after 120 minutes and 18.22% after 210 minutes. This trend indicates that while high temperatures promote strong initial gains, prolonged treatment may lead to diminishing returns.

The evolution of flexural modulus under different annealing parameters is shown in Figure 10. At 80 °C, flexural modulus increased by 2.4% after 30 minutes, but longer treatments reduced this benefit. After 210 minutes, the modulus dropped by 1.05% compared to the non-annealed samples, suggesting that prolonged low-temperature annealing may not be beneficial for flexural stiffness.

At 130 °C, a consistent improvement was observed with increasing treatment time. The flexural modulus rose by 13.13% after 30 minutes, reached 13.64% after 120 minutes, and peaked at 15.2% after 210 minutes, indicating strong positive effects from moderate-temperature annealing.

At 180 °C, flexural modulus exhibited the highest recorded increases. The value improved by 15.14% after 30 minutes, peaked at 16.47% after 120 minutes, and slightly decreased to 15.87% after 210 minutes. Despite the small drop at longer durations, the results clearly demonstrate the beneficial effect of high-temperature annealing on flexural stiffness.

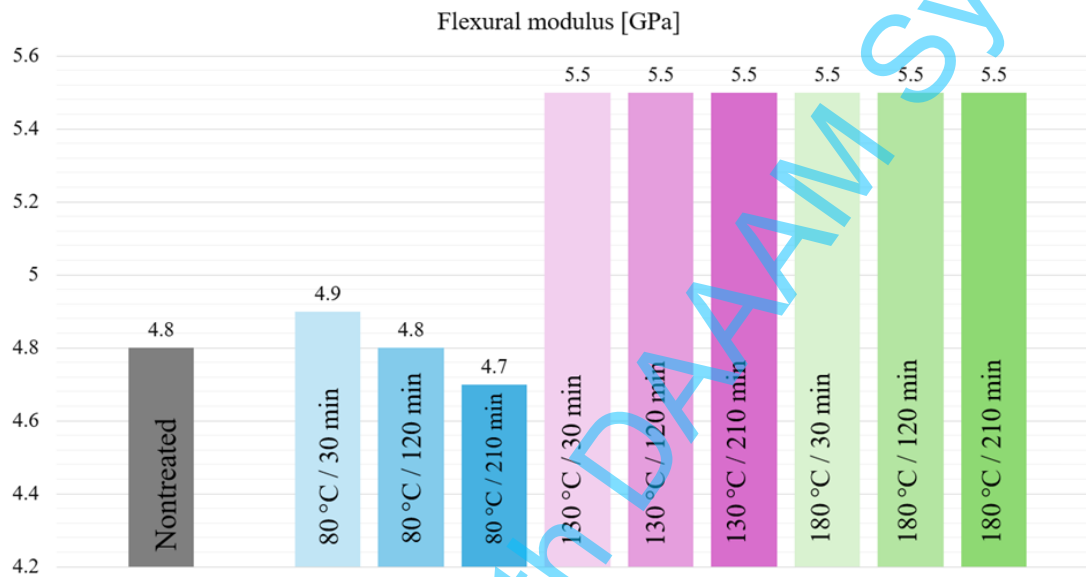


Fig. 10. Influence of annealing in different conditions on Flexural modulus of PET-CF samples

To better understand how annealing parameters influence the mechanical behavior of PET-CF samples, a statistical analysis was performed using Minitab software. The Design of Experiments (DOE) methodology was applied, specifically a full factorial design with two input factors: annealing temperature (80 °C, 130 °C, 180 °C) and annealing time (30, 120, 210 minutes). Table 4. summarizes the factors and their corresponding levels used in the experimental design. For each combination of input parameters, five test specimens were produced and measured. To minimize the impact of outliers, the maximum and minimum values were excluded, and the ANOVA analysis was conducted using the remaining three data points.

Factor	Levels	Values
Temperature (°C)	3	80, 130, 180
Time (min)	3	30, 120, 210

Table 4. Factors and levels used in the experimental design

Analysis of variance (ANOVA) was used to determine the statistical significance of each factor and their interactions on the mechanical properties. A significance level of 95% was used, and results with a p-value less than 0.05 were considered statistically significant. In addition, regression models were developed to predict mechanical responses based on input parameters. The model accuracy and reliability were assessed using R^2 (R-sq, coefficient of determination), adjusted R^2 , and predicted R^2 . A model was considered acceptable if the adjusted R^2 exceeded 75% and the difference between adjusted and predicted R^2 was less than 20%.

The final mathematical model, developed to predict the tensile strength of the FDM-printed PET-CF composite material, is provided in Table 5. This model enables the estimation of tensile performance based on specific annealing parameters.

R_m (MPa)	=	$47.019 - 1.10 T_{80} + 4.11 T_{130} - 3.02 T_{180} - 0.24 t_{30} - 1.62 t_{120} + 1.86 t_{210} + 1.35 T_{80} * t_{30} + 1.23 T_{80} * t_{120} - 2.58 T_{80} * t_{210} - 1.73 T_{130} * t_{30} - 1.68 T_{130} * t_{120} + 3.41 T_{130} * t_{210} + 0.37 T_{180} * t_{30} + 0.45 T_{180} * t_{120} - 0.83 T_{180} * t_{210}$
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Table 5. Equation for predicting tensile strength

The analysis of variance (ANOVA) and corresponding results for tensile strength are presented in Table 6.3. Based on the data, the contribution of each individual input factor, as well as their interactions, to the variation in tensile strength within the developed model can be clearly observed. This analysis provides valuable insight into the most influential parameters in the annealing process and confirms the statistical validity and reliability of the tensile strength prediction model.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F	P
Model	8	385.75	56.73%	385.75	48.22	2.95	0.027
Temperature (°C)	2	245.21	36.06%	245.21	122.6	7.5	0.004
Time (min)	2	55.21	8.12%	55.21	27.6	1.69	0.213
Temperature * Time	4	85.34	12.55%	85.34	21.33	1.31	0.306
Error	18	294.21	43.27%	294.21	16.34		
Total	26	679.96	100.00%				

Table 6. ANOVA results for tensile strength

The ANOVA results presented in Table 6. indicate that only the temperature is a statistically significant factor ($p = 0.004$), contributing 36.06% to the model. The other factors—time and the temperature–time interaction—are not statistically significant (p -values greater than 0.05). Time contributes 8.12%, while the two-way interaction between temperature and time contributes 12.55% to the model. These results show that the model explains only 56.73% of the total variation (R -sq), leading to the conclusion that the model is not satisfactory. Additionally, the results shown in Table 7. indicate that the majority of the variation in tensile strength (R_m) cannot be reliably predicted using the developed mathematical model.

S	R-sq	R-sq (adj)	R-sq (pred)
4.04287	56.73%	37.50%	2.65%

Table 7. Coefficient of determination (R -sq) for the model – Tensile strength

The final mathematical model developed to predict the tensile modulus of FDM-printed PET-CF material is presented in Table 8.

E (GPa)	=	$4.36667 - 0.3889 T_{80} + 0.1333 T_{130} + 0.2556 T_{180} + 0.0111 t_{30} - 0.0111 t_{120} - 0.0000 t_{210} + 0.0444 T_{80} * t_{30} + 0.0333 T_{80} * t_{120} - 0.0778 T_{130} * t_{210} - 0.0111 T_{130} * t_{30} - 0.0222 T_{130} * t_{120} + 0.0333 T_{130} * t_{210} - 0.0333 T_{180} * t_{30} - 0.0111 T_{180} * t_{120} + 0.0444 T_{180} * t_{210}$
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Table 8. Equation for predicting tensile modulus

The ANOVA results for the tensile modulus model, shown in Table 9., indicate a strong model fit with 97.88% of the total variation explained. Temperature is the most influential factor, with a significant p -value (0.000) and a contribution of 95.86%. The interaction between temperature and time is also statistically significant ($p = 0.016$), contributing 1.92%, while time alone is not significant ($p = 0.658$) and has a minimal effect. With only 2.12% of unexplained variation, the model is considered highly accurate, emphasizing the importance of temperature and its interaction with time.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F	P
Model	8	2.15333	97.88%	2.15333	0.26917	103.82	0
Temperature (°C)	2	2.10889	95.86%	2.10889	1.05444	406.71	0
Time (min)	2	0.00222	0.10%	0.00222	0.00111	0.43	0.658

Temperature * Time	4	0,04222	1.92%	0.04222	0.01056	4.07	0.016
Error	18	0.04667	2.12%	0.04667	0.00259		
Total	26	2.2	100.00%				

Table 9. ANOVA results for tensile modulus

The ANOVA results presented in Table 10. indicate that the majority of variation in the tensile modulus (E) can be accurately predicted by the developed mathematical model. The coefficient of determination (R-sq) shows that the model explains 97.88% of the total variation, while the adjusted R-sq value of 96.94% confirms the model's robustness without overfitting. Additionally, the predicted R-sq of 95.23% demonstrates the model's strong ability to forecast outcomes reliably. Together, these indicators suggest that the model is highly reliable, with minimal error and excellent predictive performance.

S	R-sq	R-sq (adj)	R-sq (pred)
0.0509175	97.88%	96.94%	95.23%

Table 10. Coefficient of determination (R-sq) for the model – Tensile modulus

The significance of the input factors is also illustrated in the Pareto chart shown in Figure 11., clearly identifying which factors are statistically significant. Temperature stands out as the dominant factor with the greatest influence, while time has no significant effect. The interaction between temperature and time shows statistical significance but with a smaller impact compared to temperature. This trend is further confirmed in the 3D surface plot in Figure 11., which demonstrates how the tensile modulus (E) is affected by annealing temperature and time. The diagram shows that increasing the temperature (up to 180 °C) significantly raises the tensile modulus, while longer annealing durations (210 minutes) lead to only minor improvements. The highest values are observed at the combination of high temperature and extended time, confirming that temperature is the key factor in maximizing tensile modulus.

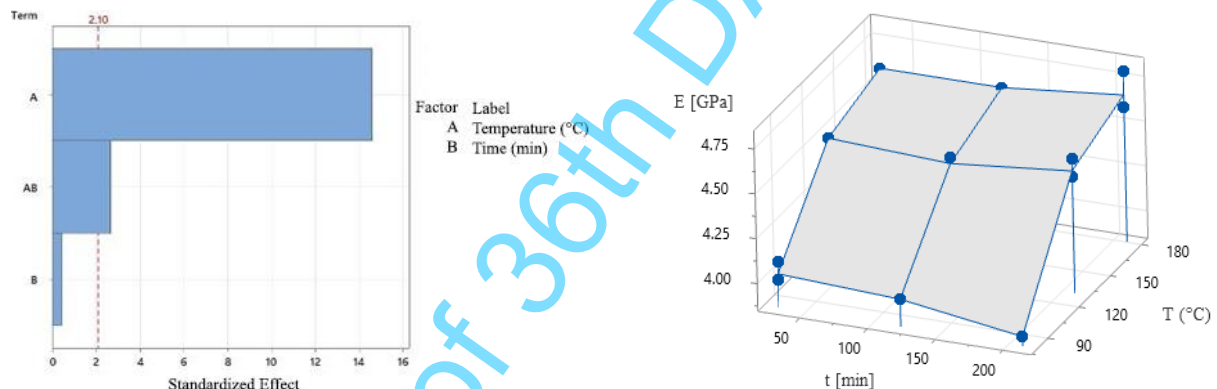


Fig. 11. Significance analysis of factors for tensile modulus – Pareto chart (left) and 3D plot showing the influence of temperature and annealing time on tensile modulus (right)

Based on the experimentally obtained values of flexural strength and flexural modulus for FDM-printed PET-CF material subjected to various annealing temperatures and exposure times, a statistical evaluation was performed to identify the key influencing factors. The final mathematical model developed to predict the flexural strength of the material is presented in Table 11.

R (MPa)	=	99.567 - 15.484 T_80 + 9.158 T_130 + 6.326 T_210 + 1.689 t_30 - 0.156 t_120 - 1.533 t_210 - 1.013 T_30 * t_30 + 0.307 T_80 * t_120 + 0.706 T_130 * t_210 - 1.966 T_130 * t_30 - 0.526 T_130 * t_120 + 2.492 T_130 * t_210 + 2.979 T_180 * t_30 + 0.220 T_180 * t_120 - 3.198 T_180 * t_210
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Table 11. Equation for predicting flexural strength

ANOVA results presented in Table 12. show that the model explains 96.68% of the total variation, indicating a high level of fit. Temperature is the dominant factor, with a significant p-value ($p = 0.000$) and a contribution of 92.71%. Time is also statistically significant ($p = 0.048$), but with a low contribution of 1.33%, making it less influential. The interaction between temperature and time is significant ($p = 0.025$) with a contribution of 2.64%. The remaining unexplained variation is only 3.32%, confirming the model's reliability. Optimization should focus primarily on temperature, while time and interaction effects are relevant but less impactful.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F	P
Model	8	3413.31	96.68%	3413.31	426.66	65.59	0.000
Temperature (°C)	2	3272.88	92.71%	3272.88	1636.44	251.58	0.000
Time (min)	2	47.05	1.33%	47.05	23.53	3.62	0.048
Temperature * Time	4	93.37	2.64%	93.37	23.34	3.59	0.025
Error	18	117.09	3.32%	117.09	6.5		
Total	26	3530.4	100.00%				

Table 12. ANOVA results for flexural strength

The ANOVA results presented in Table 13 indicate that the majority of variation in flexural strength can be predicted using the developed mathematical models. The coefficient of determination (R-sq) shows that the model explains 96.68% of the total variation. The adjusted R-sq is 95.21%, confirming a good model fit without overfitting, while the predicted R-sq of 92.54% demonstrates strong predictive capability. Together, these values suggest that the model is reliable, accurately represents the data relationships, and maintains minimal error with high predictive performance.

S	R-sq	R-sq (adj)	R-sq (pred)
2.55044	96.68%	95.21%	92.54%

Table 13. Coefficient of determination (R-sq) for the model – Flexural strength

The significance of individual factors is also illustrated in the Pareto chart (Figure 12.), where temperature clearly emerges as the dominant factor with the highest statistical influence. While time and the interaction between temperature and time also exhibit statistical significance, their effects are notably less pronounced compared to temperature. The 3D plot shown in Figure 12. further illustrates how flexural strength (Rm) is influenced by both annealing temperature and time. Based on the diagram, the highest flexural strength is achieved at an annealing temperature of 130 °C and a duration of 120 minutes.

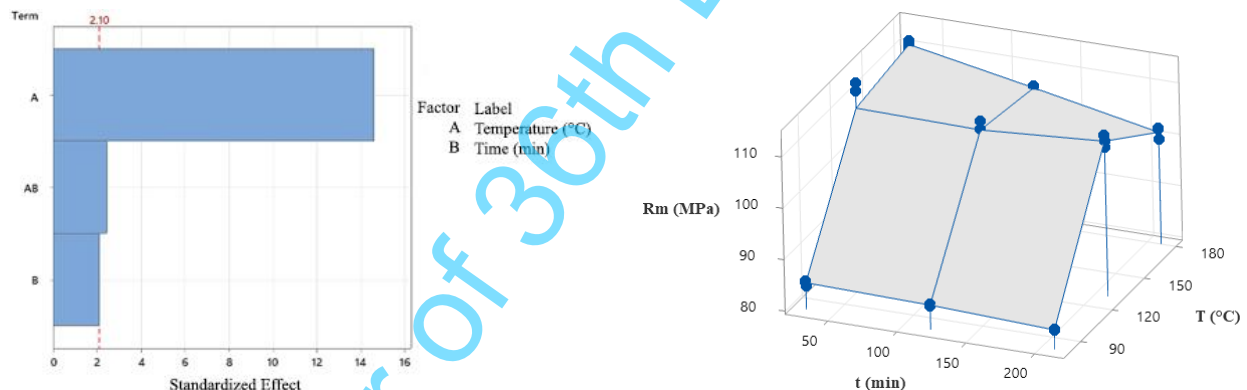


Fig. 12. Significance analysis of factors for flexural strength – Pareto chart (left) and 3D plot showing the influence of temperature and annealing time on flexural strength (right)

The mathematical model developed to predict the flexural modulus of FDM-printed PET-CF material, based on experimental results obtained under different annealing temperatures and exposure times, is presented in Table 14.

E (GPa)	=	5.26327 - 0.4826 T_80 + 0.2688 T_130 + 0.2139 T_180 - 0.0015 t_30 + 0.0083 t_120 - 0.0068 t_210 + 0.0546 T_80 * t_80_30 + 0.0238 T_80 * t_120 - 0.0784 T_80 * t_210 - 0.0332 T_130 * t_30 - 0.0091 T_130 * t_120 + 0.0423 T_130 * t_210 - 0.0213 T_180 * t_30 - 0.0147 T_180 * t_120 + 0.0360 T_180 * t_210
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Table 14. Equation for predicting flexural modulus

The ANOVA analysis and results presented in Table 15. show the contribution of input factors to the model. The analysis indicates that the model explains 98.27% of the total variation, demonstrating a high level of fit to the data. Temperature stands out as the primary influencing factor ($p = 0.000$), contributing 97.34% to the output (flexural modulus). Time is not statistically significant ($p = 0.798$) and contributes only 0.03%. In contrast, the interaction between temperature and time is statistically significant ($p = 0.008$), contributing 1.35%, suggesting a relevant but much smaller effect compared to temperature alone. The model's unexplained variation is 1.28%, further confirming its adequacy.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F	P
Model	8	3.20322	98.72%	3.20322	0.4004	174.06	0.000
Temperature (°C)	2	3.15827	97.34%	3.15827	1.57914	686.49	0.000
Time (min)	2	0.00105	0.03%	0.00105	0.00052	0.23	0.798
Temperature * Time	4	0.0439	1.35%	0.0439	0.01097	4.77	0.008
Error	18	0.04141	1.28%	0.04141	0.0023		
Total	26	3.24462	100.00%				

Table 15. ANOVA results for flexural modulus

The ANOVA results presented in Table 16. indicate that the model explains 98.27% of the total variation. The adjusted coefficient of determination (R-sq adj) is 98.16%, while the predicted coefficient of determination (R-sq pred) is 97.13%. Together, these values suggest that the model is reliable and accurately describes the relationships within the data, with minimal error and strong predictive capability.

S	R-sq	R-sq (adj)	R-sq (pred)
0.0479616	98.72%	98.16%	97.13%

Table 16. Coefficient of determination (R-sq) for the model – Flexural modulus

The significance of the input factors is also illustrated in the Pareto chart (Figure 13), clearly showing which variables have a statistically significant influence. Temperature demonstrates a dominant effect, while the interaction between temperature and time is also statistically significant, though with a much smaller contribution. Time alone does not show statistical significance and has no meaningful impact. The 3D surface plot in Figure 13 reveals that temperature is the primary factor influencing the increase in flexural modulus. At elevated temperatures (130 °C and 180 °C), the modulus significantly improves, while variations in annealing time do not notably affect the outcome. The highest recorded flexural modulus was 5.6 GPa, achieved at 130 °C after 120 minutes of annealing.

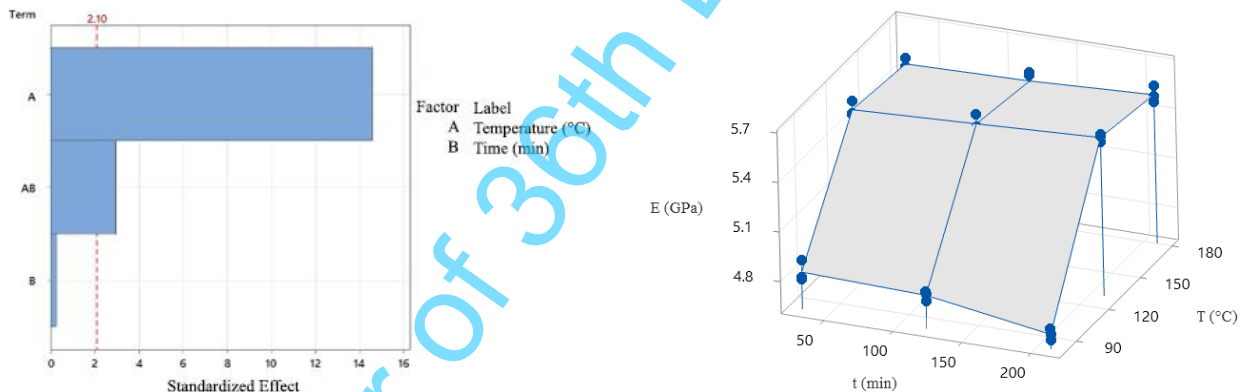


Fig. 13. Significance analysis of factors for flexural modulus – Pareto chart (left) and 3D plot showing the influence of temperature and annealing time on flexural modulus (right)

5. Conclusion

This study investigated the effect of annealing on the mechanical properties of FDM-printed PET-CF material, with a focus on tensile and flexural strength, as well as tensile and flexural modulus. Specimens were annealed at three temperatures (80 °C, 130 °C, and 180 °C) and three durations (30, 120, and 210 minutes), and the results were analyzed using ANOVA and linear regression models.

The findings confirmed that annealing can significantly improve the mechanical performance of PET-CF. The most notable improvements were achieved at higher temperatures and longer durations. The maximum observed increases were 30.85% in flexural strength, 18.34% in tensile strength, 18.7% in tensile modulus, and 15.87% in flexural modulus. These results support the claim that thermal post-processing enhances mechanical performance but also highlight differences compared to manufacturer specifications—primarily due to differences in printer models, filament storage conditions, and moisture sensitivity of the PET-CF material.

ANOVA results showed that temperature is the dominant factor affecting all mechanical properties, while time and the interaction between temperature and time had limited or no statistical significance. The model for predicting tensile strength was found to be inadequate, likely due to outliers and inconsistent cooling conditions. Improving the model's accuracy could be achieved by increasing the number of replicates and introducing controlled post-annealing cooling.

Future work should focus on studying the influence of moisture, the impact of controlled cooling on mechanical properties, exploring annealing effects on different FDM filaments, and developing software tools for optimizing annealing conditions.

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