OPTIMIZING HEATED CHAMBER TEMPERATURE FOR TENSILE PERFORMANCE IN FDM-PRINTED PLA

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ABSTRACT: Thermal conditions during fused deposition modeling (FDM) play a critical role in determining the mechanical performance of polylactic acid (PLA), particularly due to rapid cooling and weak interlayer bonding. This study investigates the influence of a controlled heated chamber environment on the tensile behaviour of PLA printed using a desktop FDM system. Tensile specimens were fabricated under four chamber conditions: ambient (non-heated), 40°C, 50°C, and 60°C, and tested in accordance with ASTM D638 Type IV. The results indicate that moderate chamber temperatures of 40°C and 50°C produce a consistent improvement in tensile strength compared to ambient conditions, with the highest performance observed at 40°C. In contrast, specimens printed at 60°C exhibit reduced tensile strength, indicating the onset of thermal softening. Although the improvement is modest, it reflects enhanced process stability and interlayer consolidation. Overall, the findings establish a practical thermal window of 40–50°C for improving tensile performance in desktop FDM systems, providing a useful baseline for future studies on virgin, recycled, and modified thermoplastic materials.

KEYWORDS: *Additive Manufacturing; Fused Deposition Modeling; Heated Chamber;*

Polylactic Acid; Tensile Properties

1.0 INTRODUCTION

Fused deposition modeling (FDM) is one of the most widely adopted additive manufacturing techniques due to its affordability, simplicity, and suitability for desktop fabrication systems. Polylactic acid (PLA) is among the most used thermoplastic materials in FDM because of its biodegradability, low processing temperature, minimal warpage, and good dimensional stability [1]. Despite these advantages, the mechanical response of polymer materials is highly sensitive to temperature-dependent behaviour, which directly influences tensile performance and fractured mechanisms under different environmental conditions [2].

The reduction in mechanical performance is largely attributed to rapid cooling of the extruded filament during the deposition process, which limits polymer chain diffusion across adjacent layers and results in incomplete interfacial bonding [3]. Several thermal management strategies, including auxiliary heating, infrared pre-heating, enclosed chambers and actively heated chambers, have therefore been proposed to improve the thermal history of deposited materials and enhance mechanical performance [4].

Previous studies generally agree that increasing the ambient printing temperature improves interlayer consolidation by reducing cooling rates and extending the diffusion time between deposited filaments [5]. However, the reported optimum chamber temperatures vary considerably among studies because they depend on material type, printer configuration and processing conditions. Furthermore, excessive thermal exposure has been reported to induce thermo-viscoelastic softening and stiffness degradation as PLA approaches its glass transition temperature ($T_g \approx 65^\circ$ C), thereby reducing mechanical performance [6]. These findings suggest that while chamber heating can be beneficial, the thermal window that maximises tensile strength remains uncertain.

A critical review of the existing literature reveals that most studies have focused on industrial-scale FDM systems, high-temperature enclosed printers, or specialised thermal management techniques [7]. Comparatively, fewer studies have investigated moderate chamber temperatures suitable for commercially available desktop FDM printers. In addition, many published works emphasise the optimisation of multiple process parameters simultaneously, making it difficult to isolate the individual influence of chamber temperature on tensile behaviour. Consequently, a clear understanding of the optimum moderate-temperature conditions remains lacking. To address this research gap, this study investigates the tensile performance of virgin PLA fabricated using a custom-built heated chamber integrated with a desktop FDM printer. Chamber temperatures ranging from ambient conditions to 60°C were evaluated to determine an effective thermal processing window that enhances tensile strength without inducing thermal softening.

Unlike previous studies that primarily focus on industrial systems or broad process optimisation, this work specifically evaluates the influence of moderate chamber temperatures under practical desktop printing conditions. The novelty of this study lies in establishing an experimentally validated thermal operating window of 40–50°C for desktop FDM printing while simultaneously validating the performance of the developed heated chamber. The findings provide baseline mechanical data and practical thermal design guidance for future investigations involving virgin, recycled and modified PLA materials, as well as the development of cost-effective heated chamber systems for desktop additive manufacturing.

2.0 METHODOLOGY

The experimental procedure adopted in this study is summarised in Figure 1, which illustrates the overall workflow from material selection to statistical analysis. The methodology consists of six main stages: material preparation, printer and chamber configuration, specimen fabrication, specimen conditioning, tensile testing and data analysis.

Virgin PLA filament (PolyLite PLA, white, 1.75 mm diameter) was selected as the printing material because it provides a consistent baseline for evaluating the influence of chamber temperature without the effects of previous thermal or mechanical degradation. All specimens were fabricated using a Creality Ender 3 V3 SE FDM printer equipped with a 0.4 mm nozzle. Slicing was performed using Creality Print software.

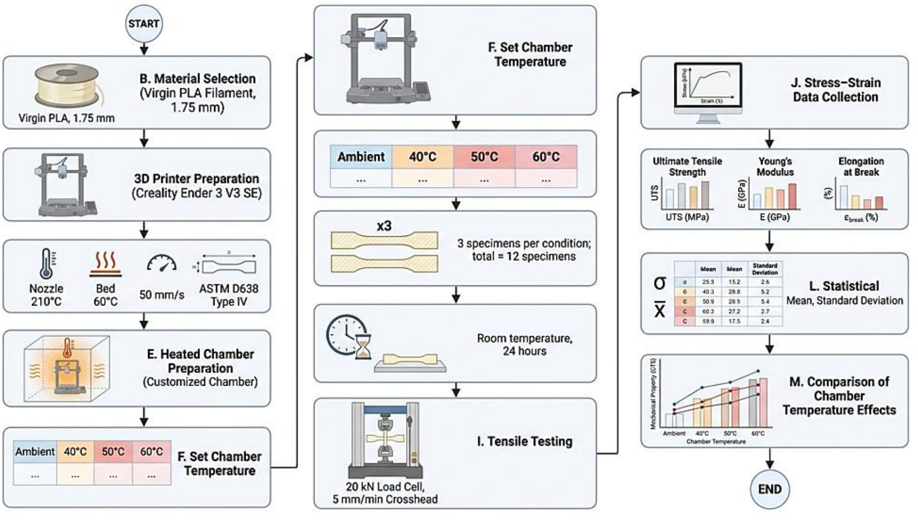

Figure 1: The experimental procedure

To minimise the influence of process parameters other than chamber temperature, all printing parameters were kept constant throughout the study. The nozzle temperature was maintained at 210°C, the heated bed temperature at 60°C, and the printing speed at 50 mm/s. These parameters were selected based on the filament manufacturer's recommendations and previous literature to ensure stable extrusion, adequate interlayer bonding and good dimensional accuracy.

The influence of chamber temperature was investigated using a custom-built heated chamber (Figure 2) designed to provide a controlled thermal environment during printing. The system operated with a 240 V power supply, a 300 W heater, and a maximum temperature of 100°C, and included a circulation fan (up to 5.5 m/s) to ensure uniform temperature distribution. Four chamber conditions were examined: ambient, 40°C, 50°C, and 60°C, selected to represent moderate temperatures below the glass transition of PLA.

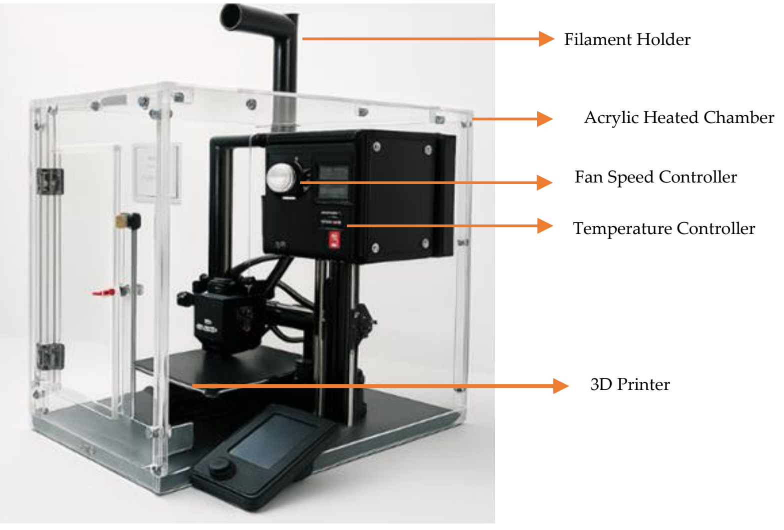

Figure 2: The customized resilient additive heating chamber

Tensile specimens were fabricated according to ASTM D638 Type IV with a thickness of 3 mm and gauge length of 25 mm. Three specimens were produced per condition (total of 12). All samples were conditioned at room temperature for 24 hours prior to testing to minimise residual thermal stresses. Mechanical testing was conducted using a Universal Testing Machine (20 kN load cell) at a crosshead speed of 5 mm/min. Stress–strain data were recorded to determine tensile strength, Young's modulus, and elongation at break. The results were analysed by calculating mean values and standard deviations for each condition to evaluate repeatability and the effect of chamber temperature on tensile behaviour.

3.0 RESULTS AND DISCUSSION

3.1 Tensile Strength Results

This section presents the tensile strength results of FDM-printed PLA. Under ambient (non-heated) conditions, the specimens exhibited an average tensile strength of 54.28 MPa, with moderate scatter attributed to variations in interlayer bonding caused by rapid and uncontrolled cooling during deposition.

Specimens printed at a chamber temperature of 40°C exhibited the highest average tensile strength of 55.11 MPa, representing an improvement of approximately 1.5% over the ambient condition. Although the increase is relatively modest, it is consistent across all three specimens, indicating that moderate chamber heating contributes to more stable printing conditions and improved interlayer bonding. This behaviour agrees with previous studies reporting that controlled thermal environments reduce cooling rates, enhance polymer chain diffusion, and improve mechanical performance of FDM-printed PLA [1, 9, 10]. The relatively small improvement also suggests that chamber temperature is only one of several factors governing tensile performance, while parameters such as raster orientation, layer thickness, and printing speed continue to influence the final mechanical properties [5].

Figures 3 and 4 compare the tensile strength distributions of specimens printed under ambient and 40°C conditions, respectively. Besides the higher average tensile strength, the specimens printed at 40°C also exhibit reduced scatter, indicating improved process repeatability and more uniform interlayer consolidation under controlled thermal conditions.

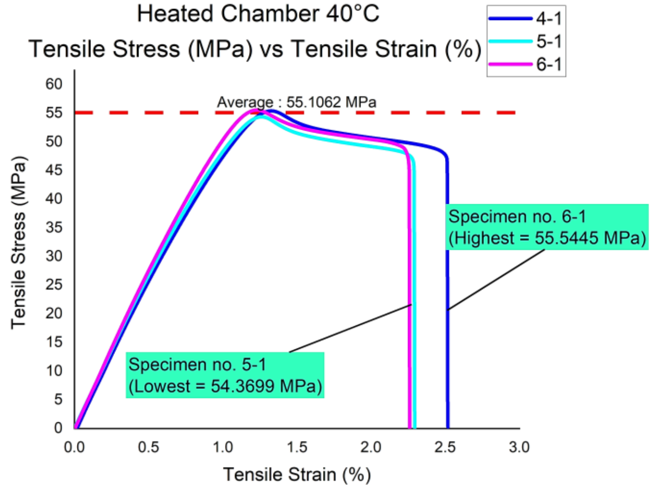

Figure **3**: Tensile strength of the non-heated chamber specimens

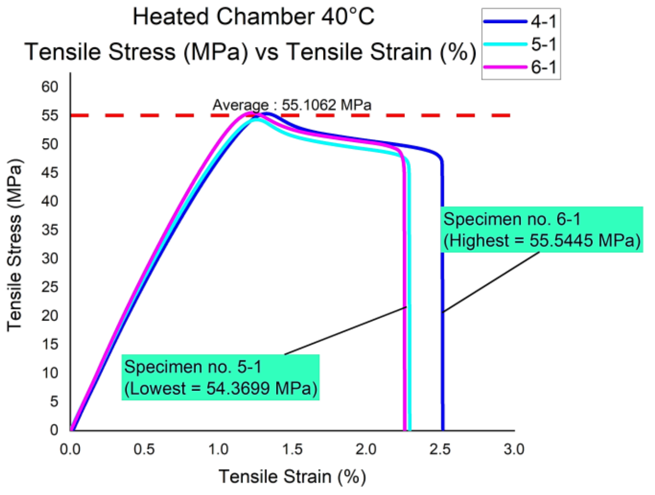

Figure **4**: Tensile strength of the 40°C heated chamber specimens

At 50°C, the average tensile strength (55.04 MPa) remained comparable to that observed at 40°C, indicating a plateau in mechanical performance. This suggests that the material continues to benefit from improved interlayer interaction within this temperature range; however, further increases in temperature do not result in significant additional gains.

In contrast, specimens printed at 60°C exhibited a slight reduction in tensile strength (54.34 MPa), approaching the value obtained under ambient conditions. This reduction suggests that excessive chamber heating begins to offset the benefits of improved interlayer bonding through thermal softening and reduced material stiffness. Similar reductions in tensile properties at elevated temperatures have been reported in thermo-mechanical investigations of PLA, where increasing temperature promotes molecular relaxation and lowers load-bearing capability [6, 11, 14]. This indicates that the beneficial effect of interlayer diffusion is eventually outweighed by thermo-viscoelastic softening as the temperature approaches the glass transition region. Therefore, the present results indicate that excessive thermal exposure is not advantageous for tensile performance, despite providing additional heat during deposition.

Figures 5 and 6 illustrate this trend, where tensile strength remains relatively stable between 40°C and 50°C before decreasing at 60°C. Table 1 summarises the tensile force and tensile strength obtained under all chamber conditions. Overall, the experimental results support the existence of an optimum chamber temperature range between 40°C and 50°C, where sufficient thermal energy enhances interlayer bonding without inducing significant thermal softening. Although the improvement in tensile strength is relatively small, the consistency of the results suggests that controlled chamber heating enhances process stability and provides a practical means of improving the mechanical reliability of desktop FDM-printed PLA components.

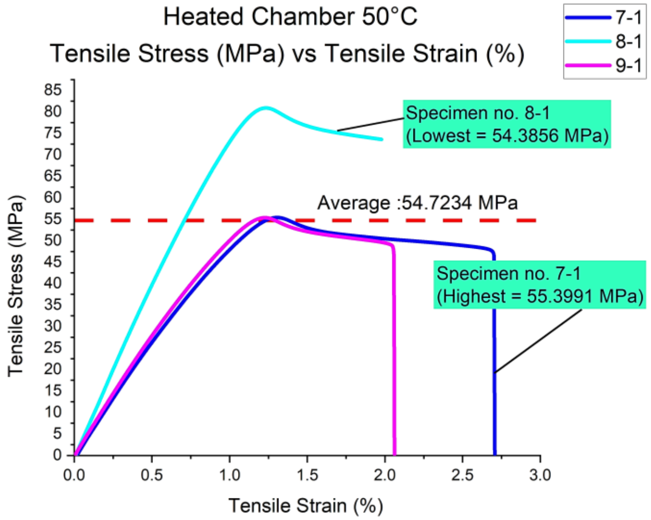

Figure **5**: Tensile strength of the 50°C heated chamber specimens

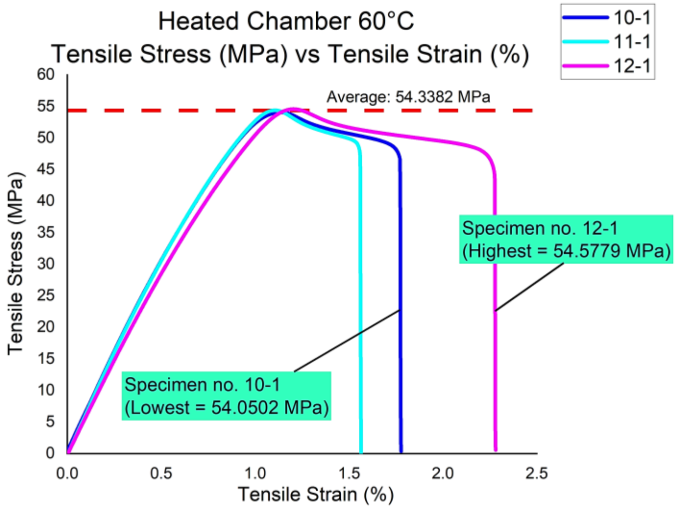

Figure **6**: Tensile strength of the 60°C heated chamber specimens

Table 1: vPLA tensile test results

Set	Parameter vPLA	Specimen No.	Tensile Force (N)	Tensile Strength (MPa)
A	Non-heated chamber	1-1	975.421	54.1901
		2-1	988.929	54.9405
		3-1	966.969	53.7205
		Average	977.106	54.2837
B	Heated Chamber 40°C	4-1	997.273	55.4041
		5-1	978.657	54.3699
		6-1	999.800	55.5445
		Average	991.910	55.1062
C	Heated Chamber 50°C	7-1	997.184	55.3991
		8-1	978.940	54.3856
		9-1	996.297	55.3498
		Average	990.807	55.0448
D	Heated Chamber 60°C	10-1	972.904	54.0502
		11-1	978.956	54.3865
		12-1	982.402	54.5779
		Average	978.087	54.3382

3.2 Statistical Analysis of Tensile Strength

A statistical analysis was performed to evaluate the influence of chamber temperature on the tensile strength of FDM-printed PLA. Figure 7 presents the individual tensile strength values for all specimens, where samples fabricated at 40°C and 50°C show a consistent upward shift relative to the non-heated condition. In contrast, specimens printed at 60°C exhibit a noticeable downward shift in tensile strength. Although the absolute differences among the conditions are relatively small, the clustering of data points indicates repeatable behaviour under moderate chamber heating.

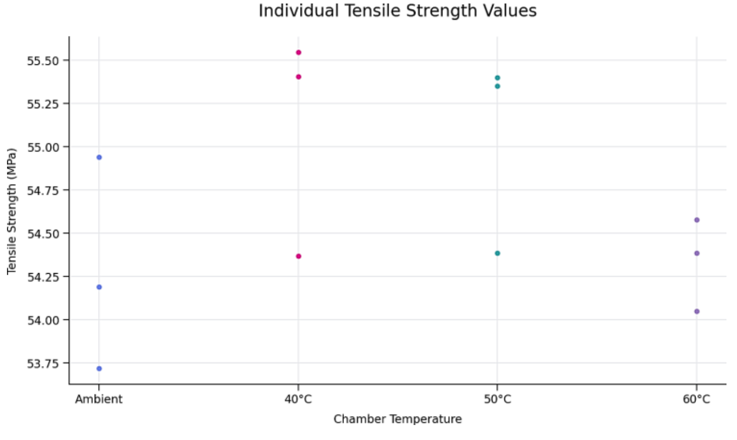

Figure 7: Individual value plot

The statistical distribution of tensile strength is further illustrated in Figure 8 using a box plot. The median tensile strength values for the 40°C and 50°C conditions are higher than those of the ambient condition, while comparable interquartile ranges are observed across all groups. This suggests that moderate chamber heating improves mechanical stability without introducing additional variability. In contrast, the reduced median value at 60°C indicates the onset of thermal softening under excessive thermal exposure.

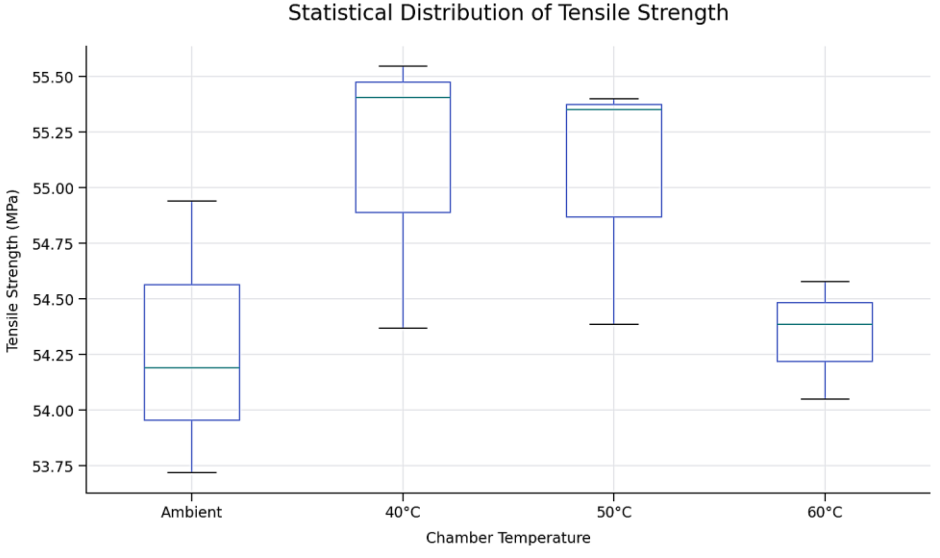

Figure 8: Box plot

A one-way analysis of variance (ANOVA) was conducted to examine statistical differences among the four chamber conditions. The results indicated no statistically significant difference ($F(3, 8) = 1.98$, $p = 0.196$), which may be attributed to the limited sample size in this study. However, the absence of statistical significance does not negate the consistent trend observed in the experimental data, particularly as the objective is to identify a practical thermal processing window rather than to demonstrate intrinsic material modification.

In desktop FDM systems, where mechanical performance is inherently constrained by interlayer adhesion and thermal history, incremental yet consistent improvements are meaningful from a process optimisation perspective. Therefore, the statistical findings support the selection of a moderate chamber temperature range of 40–50°C as a

stable thermal window that enhances tensile performance relative to ambient conditions.
The results demonstrate that moderate chamber heating at 40°C and 50°C leads to a consistent improvement in tensile strength compared to the non-heated condition, whereas further heating to 60°C results in mechanical degradation. This behaviour reflects the competing influence of enhanced interlayer diffusion and thermo-viscoelastic softening during FDM processing. The improvement observed at 40°C is consistent with previous findings, where auxiliary heating enhances interlayer bonding by reducing cooling rates and promoting polymer chain diffusion across adjacent layers [8]. In FDM processes, rapid cooling typically limits molecular interdiffusion, resulting in weak interfacial bonding and anisotropic mechanical performance [9-10]. By increasing the ambient chamber temperature, the cooling rate is reduced, allowing more time for chain mobility and entanglement, which contributes to improved tensile strength.

This behaviour is further supported by thermo-mechanical studies demonstrating that PLA exhibits strong temperature dependency even below its glass transition temperature ($T_g \approx 65°C$), where increasing temperature promotes molecular mobility while still maintaining the material in a glassy state [11]. As such, the 40–50°C range represents a condition where sufficient chain diffusion occurs without significant loss of stiffness, resulting in improved interlayer bonding and mechanical consistency.

The plateau observed at 50°C suggests that once a critical thermal threshold is reached, further increases in chamber temperature do not result in proportional improvements in tensile strength. Similar diminishing returns have been reported in studies on FDM thermoplastics, where interlayer bonding reaches a saturation point beyond which additional thermal input does not yield further mechanical benefits [12-13]. This indicates that interlayer diffusion alone cannot continuously enhance tensile performance once adequate bonding has been achieved.

Moreover, as the temperature approaches the upper boundary of the glassy region, reductions in stiffness begin to offset the benefits gained from diffusion. Thermo-mechanical characterisation of PLA shows a significant decrease in elastic modulus and yield strength with increasing temperature, even below Tg [11]. This explains the stabilisation of tensile strength observed at 50°C, where competing thermal effects reach equilibrium. In contrast, specimens fabricated at

60°C exhibited a noticeable reduction in tensile strength despite improved thermal exposure. This behaviour aligns with thermo-viscoelastic studies showing that PLA experiences reduced stiffness and load-bearing capability as temperature increases, due to molecular relaxation and softening effects [14]. Furthermore, temperature-dependent studies confirm that mechanical strength decreases significantly as the material approaches the glass transition region [11, 15].

Additionally, similar degradation behaviour has been reported in studies investigating thermal aging and prolonged thermal exposure, where elevated temperatures lead to reduced mechanical strength and structural integrity in polymer components [16-17]. This further supports the observation that excessive chamber heating may introduce adverse thermal effects, counteracting the benefits of improved interlayer bonding.

From a broader perspective, the influence of temperature on mechanical performance is not only governed by interlayer diffusion but also by intrinsic material-level thermal sensitivity. Previous work has shown that thermal exposure can alter crystallinity, stiffness, and failure behaviour in additively manufactured polymers [18-19]. In particular, ambient temperature control during printing has been identified as a key factor influencing fracture behaviour and mechanical reliability of FDM parts [20]. Recent studies have also shown that ambient temperature variations directly affect material deposition stability and structural integrity in FDM processes, further highlighting the importance of controlled thermal environments during printing [21].

Furthermore, in-process temperature evolution plays a critical role in determining final part performance, as thermal gradients and heat accumulation influence residual stresses and deformation behaviour during printing [14]. Even moderate increases in thermal exposure can result in viscoelastic relaxation, reducing the material's ability to sustain load under tensile conditions. The findings of this study are also consistent with literature on thermal post-processing techniques such as annealing, where controlled heating improves mechanical properties only within a limited temperature range [11-12]. Beyond this range, excessive thermal energy promotes molecular relaxation and leads to degradation of mechanical performance.

4.0 CONCLUSION

The objective of this study was to investigate the tensile performance of FDM-printed virgin PLA using a custom-built heated chamber and to identify a practical chamber temperature range for desktop FDM systems. The results showed that specimens printed at moderate chamber temperatures of 40°C and 50°C exhibited higher tensile strength compared to ambient conditions, while printing at 60°C reduced mechanical performance. These findings demonstrate that controlled chamber heating enhances mechanical properties by stabilising the thermal environment during fabrication. A temperature range of 40–50°C was identified as an effective thermal window for improving tensile performance without inducing thermal softening. In addition, this study validates the performance of the developed heated chamber and provides baseline tensile data for virgin PLA under controlled thermal conditions. Future work is recommended to extend this investigation to recycled and modified PLA materials, incorporate a larger sample size to strengthen the statistical significance of the findings, and evaluate finer chamber temperature increments to more precisely define the optimum thermal window. Further studies may also assess the scalability of the developed heated chamber for industrial-scale desktop FDM applications.

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AUTHOR CONTRIBUTIONS

F.A. Muhammad Fakri: Experimental Works, Data Analysis and Original Draft Preparation; R.A. Hamid: Reviewing, Final Draft Preparation and Supervision; N.W. Mafazi: Data Curation, Software Validation, L. Abdullah: Conceptualization; W.S. Wan Harun: Reviewing; C. Bilgen: Proof-reading.

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the manuscript, agree with its submission, and declare no conflict of interest on the manuscript.

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