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THERMAL AND MECHANICAL PROPERTIES OF IN-HOUSE-MANUFACTURED PLA AND PA FILAMENTS AT HIGH TEMPERATURE

TERMIČNE IN MEHANSKE LASTNOSTI DOMA IZDELANIH PLA IN PA FILAMENTOV PRI VISOKIH TEMPERATURAH

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Fused-filament fabrication using thermoplastic polymers such as polylactic acid (PLA) and polyamide (PA) is widely employed to fabricate high-quality products. However, at high temperature, filaments exhibit reduced mechanical performance because of their low thermal stability. This study aims to fabricate in-house PLA and PA filaments and evaluate their mechanical properties and printability in comparision with those of conventional filaments. Compression tests reveal that at 120°C, in-house PA achieves a high strength of 125.8 MPa, outperforming conventional PA and PLA with strengths of 50 and 102 MPa, respectively. The performance of in-house PA is better than that of in-house PLA because of the different polymer structure and chemical composition of PA. Flexural tests show that in-house PLA has a high Young's modulus of 2,675 MPa, which is 18 times higher than that of in-house PA at 144.5 MPa. Experimental data reveal improved performance when compared with finite-element analysis, with an increment of 23 times for in-house PLA and 63% for in-house PA. These findings indicate that in-house-fabricated PA filaments are on par with conventional PA filaments, especially when tested at a maximum temperature of 60°C. In-house-fabricated PLA and PA filaments demonstrate superior mechanical performance and thermal resilience, making them competitive alternatives to conventional filaments for high-temperature applications.

Keywords: polymer composites; additive manufacturing; mechanical properties; finite element analysis.

Za izdelavo visoko kakovostnih taljivih filamentov (tankih žičk različnih presekov) za varovalke se veliko uporabljajo termoplastični polimeri, kot sta polilaktatna kislina (PLA; angl.: polylactic acid) in poliamid (PA). Vendar pri visokih temperaturah ti filamenti izgubljajo svojo mehansko trdnost zaradi njihove slabe termične stabilnosti. V tem članku avtorji opisujejo študijo domače izdelave PLA in PA filamentov in ovrednotenje njihovih mehanskih lastnosti, ter natisljivosti v primerjavi s konvencionalnimi filamenti. Tlačni preizkusi so pokazali, da imajo doma izdelani PA filamenti pri 120°C visoko trdnost 125,8 MPa, ki presega trdnost konvencionalnih PA in PLA s trdnostjo 50 oz. 102 MPa. Kakovost doma izdelanih PA filamentov je boljša od doma narejenih PLA filamentov, ker imajo le-ti drugačno strukturo in drugačno kemijsko sestavo. Pregibni preiskusi so pokazali, da imajo doma izdelani PLA filamenti do 18-krat višji Youngov modul (2675 MPa) kot doma izdelani PA filamenti (144,5) MPa. Eksperimentalni preizkusi so odkrili boljše lastnosti tudi kot jih je napovedovala numerična simulacija na osnovi končnih elementov. Ta je napovedala 23-kratni prirastek za domače PLA in 63 % za domače PA filamente. Te ugotovitve kažejo, da so doma izdelani Pa filamenti primerljivi s konvencionalnimi, še posebej s tistimi,ki so bili testirani pri maksimalni temperaturi 60°C. Doma izdelani PLA in PA filamenti imajo superiorne mehanske lastnosti in termično odpornost in so zato lahko primerna alternativa konvencionalnim filamentom za visoko temperaturne aplikacije.

Ključne besede: polimerni kompoziti, dodajalne tehnologije, mehanske lastnosti, analiza na osnovi metode končnih elementov

1 INTRODUCTION

Fused-filament fabrication (FFF) has emerged as a pivotal technology in additive manufacturing because it enables the production of complex geometries with high precision and efficiency. This layer-by-layer fabrication technique is well-suited to thermoplastic materials, making it a popular choice in various industries, including automotive and biomedical engineering.[1] Recent advances in additive manufacturing have emphasised the need for material innovation to meet the demands of high-temperature applications, particularly in the aerospace sector, where thermal resilience is critical.[2] Among the numerous polymers used in FFF, polyamide (PA) and polylactic acid (PLA) stand out because of their unique properties and applications.[3,4] PA is a versatile engineering thermoplastic known for its excellent mechanical strength, durability, and resistance to chemicals and abrasion. A previous study reported that PA12 subjected to printing orientations by using multi-jet fusion and a selective laser sintering technique has an average tensile

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strength of 40–50 MPa.[5] Although the results reported by most researchers are promising, these techniques are varied and more costly than FFF. Furthermore, conventional filaments often lack tailored thermal stability, limiting their performance in high-temperature environments.[6] The materials used are typically conventional resin or filaments, which are difficult to control and tailor. Another study reported that the use of PA-12 in FFF presents challenges, including warping and distortion, especially when exposed to heat.[5] Elevated temperatures affect the samples by deteriorating the adhesion bond. These issues arise because of the inherent thermal properties of PA, which can lead to substantial shrinkage during the cooling phase of the printing process. Pre-drying materials to remove the moisture has been recommended in a prior study.[7] To address these challenges, researchers have investigated various strategies, including optimising processing parameters during filament fabrication and printing.[8]

By contrast, PLA is a biodegradable thermoplastic derived from renewable resources, making it suitable for sustainable manufacturing practices. Its eco-friendly nature, good printability and easy processing, make PLA one of the most widely used materials in FFF.[9] PLA exhibits favourable mechanical properties, including a compression strength between 4.6 MPa and 15.8 MPa for FFF printed parts, so it is suitable for applications requiring flexibility when mixed with additive materials.[10] However, PLA has limitations, such as a lower impact resistance and thermal stability compared with conventional engineering thermoplastics (e.g., PA). These shortcomings can restrict its use in applications where high strength and durability are critical, and thus require further research.[11] A study that used conventional PLA achieved a maximum flexural strength of ≈140 MPa, which was attributed to the high degree of crystallinity and favourable processing conditions.[12] Theoretically, a high degree of crystallinity leads to improved material stiffness and strengths.[1] Moreover, filament-fabrication parameters, such as extrusion temperature and speed, considerably influence the final material properties. A prior study reported that variations in extruder temperature ranging from 240 °C to 255 °C and printing speed ranging from 60 mm/s to 80 mm/s influence the modulus and elongation at break.[13] Other processing parameters, including filament making and printing parameters, are also crucial, because these inputs directly affect the output properties. A study on FFF revealed that adjusting the layer height between 0.05 mm and 0.25 mm alters wettability performance because high layer heights promote anisotropic behaviour, thereby improving the mechanical performance.[14] Recent research efforts have focused on developing in-house filaments to overcome the limitations of commercial filaments and enable precise control over the polymer composition and processing conditions.[15] Various approaches, particularly the development of in-house filaments as an alternative to conventional filaments, have been explored to enhance the performance of PA and PLA in FFF applications.[16]

This study focuses on fabricating in-house PLA and PA filaments and assessing their thermal and mechanical performances under elevated temperatures (up to 120 °C). In contrast to prior studies that primarily relied on commercial filaments, this research highlights the influence of in-house processing parameters such as extrusion speed, temperature control and moisture removal on the printability and final properties of the materials whilst integrating experimental data with finite-element analysis (FEA) to validate performance. The integration of PA and PLA in FFF presents opportunities for the development of advanced materials with tailored properties. By addressing the challenges associated with these polymer and leveraging their unique characteristics, researchers can pave the way for innovative applications that meet the evolving demands of modern manufacturing. The results of this study not only benchmark the performance of in-house filaments against their commercial counterparts but also contribute to a growing body of knowledge on customisable filament fabrication for high-temperature applications.

2 MATERIALS AND CHARACTERISATION

2.1 Materials

One of the materials used in this study was pure PA (grade PA2200) in powder form with a density of 0.45 gcm^{-3}. PA powder with a specific tensile modulus and tensile strength of 1,620 and 48 MPa, respectively, was supplied by Sigma Aldrich Sdn. Bhd. Pure PLA with a density of 1.24 gcm^{-3} was also provided by Sigma Aldrich Sdn. Bhd.

2.2 Filament fabrication and printing

Both polymer materials were dried using a vacuum oven (Thermo VY 6060M) for a minimum of 5 h to remove all moisture.[17,18] The dried materials were fabricated into filaments using a 3Devo filament maker (450 Precision). The filament diameter was maintained at

Table 1: Parameters for the filament making process of PA and PLA by using the 3Devo machine.

Materials	Zone	Extrusion Temperature
PLA	Zone 1	156 °C
	Zone 2	190 °C
	Zone 3	190 °C
	Zone 4	170 °C
	Extrusion speed	3.1–3.5 min^{-1}
PA	Zone 1	225 °C
	Zone 2	235 °C
	Zone 3	237 °C
	Zone 4	231 °C
	Extrusion speed	3.0 min^{-1}

1.75 mm. The detailed parameters involved in this process are shown in **Table 1**. The extrusion temperature was obtained through a thermogravimetric analysis (TGA) of the materials used in this study. For comparison, a conventional PLA filament with a similar diameter of 1.75 mm was used; it was supplied by Pebblereka Sdn. Bhd. (brand Polymaker). The fabrication process was similar to the manufacturing method reported in our previous study.[19,20]

The prepared filament was dried (5 h minimum) before being printed using a FunmatHT printer. This printer corresponded to the FFF technique. The temperature during the printing process was subjected to thermal analysis via TGA and differential scanning calorimetry (DSC) by using a Mettler Toledo machine at a temperature 30 °C to 900 °C. Meanwhile, to print the samples, a drawing was created in accordance with the standard applied and converted to g-code using NX Siemen software. The file was sliced using INTAMSYS slicer software to control the infill density and other geometrical structures used to print the samples. On the basis of the thermal analysis, the printing parameters, which are given in **Table 2**, were inputted during the slicing process. With regard to the printing speed and infill pattern, because this study focused on bulk-printed materials, the infill pattern was not a critical factor and was standardised as a line pattern. Meanwhile, the printing speed was set between 30 mm/s and 50 mm/s. The printed samples were presented in a similar manner as those shown in **Figure 3**.

Table 2: Printing parameters for PLA and PA materials

Parameter	Value
Nozzle temperature	240 °C
Bed temperature	75 °C
Layer height	0.1mm
Infill density	100%

2.3 Characterisation

For a detailed analysis, a flexural test (ASTM D790) and a compression test (ASTM D695) were performed using a universal testing machine, (Instron 5567) with a crosshead speed of 5mm/min at various temperatures of 60 °C, 90 °C and 120 °C. The data obtained from the analysis were compared with those from FEA conducted with Ansys software under the Static Structural category. Meanwhile, the fracture-surface samples were analysed using a scanning electron microscope. The setups for the compression and flexural tests are shown in **Figure 1**.

2.4 FEA

This study performed FEA via Ansys 2024 student version (Static Structural Module) to simulate the mechanical response of FDM-printed PA and PLA under temperatures of 60 °C, 90 °C and 120 °C. The simulations focused on compression and three-point bending tests and were in line with physical experiments conducted in accordance with ASTM D695 and ASTM D790-17 standards. A linear elastic - isotropic elasticity material model was used for both polymers. 3D models of cubic (12.7 mm^3) and rectangular (150 mm × 12.7 mm × 3.5 mm) samples were constructed based on the physical experimental geometry. The models were discretised using hexahedral elements with a mesh size of 1.05 mm and, optimised through convergence studies to balance accuracy and computational efficiency. The boundary conditions utilised to mimic the universal testing machine included a fixed support with bonded contact on the bottom surface; the top surface incorporated frictional contact (friction coefficient = 0.2) by using a load cell of 29420 N with a displacement control value of 1.3 mm/min for compression and 2 mm/min for bending. The temperature was controlled in the simulation to evaluate its effects on total deformation, equivalent stress and equivalent strain, which will be used to calculate the

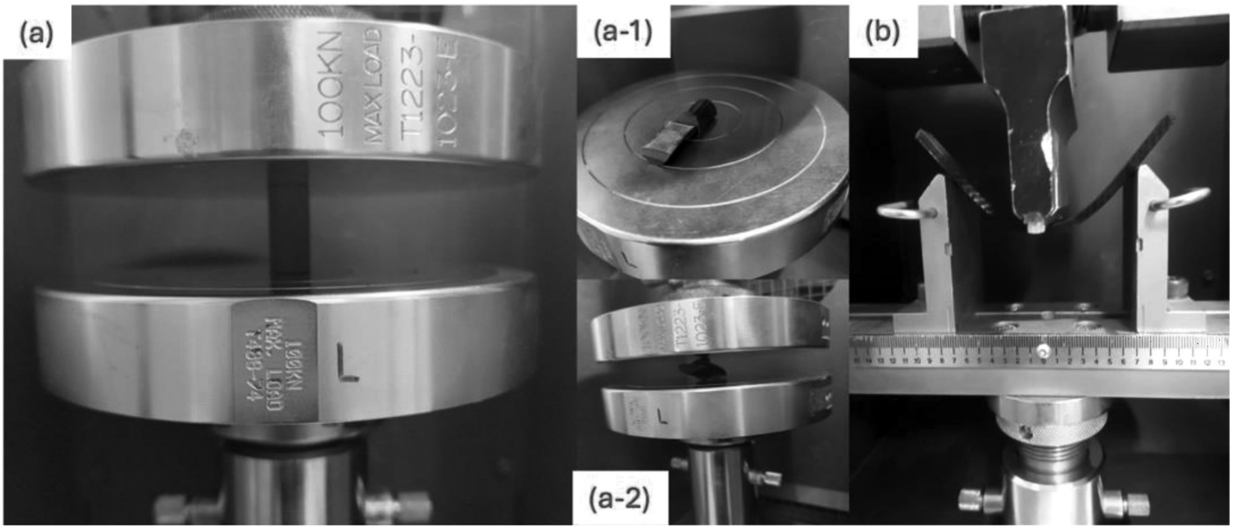

Figure 1: Setups of the compression and flexural tests on printed PLA and PA samples

Young's modulus. The results were compared with the experimental data to verify the accuracy of the model and to analyse the potential errors resulting from fabrication or environmental factors. This analysis aims to validate the relationship between the FDM processing temperature and the mechanical performance of the material through an efficient computational approach.

3 RESULTS AND DISCUSSIONS

3.1 Thermal properties of printed PLA and PA

The correlation between the mechanical properties and micrograph images when subjected to anisotropic behaviour was determined for in-house PLA and in-house PA in terms of strength. With the aim of processing deep printed materials, the relationship between the displacement and applied force of the in-house-fabricated samples was identified. The filament underwent thermal analysis to ensure that the parameter setting was accurate during the printing process and to investigate the mechanical performance of the printed samples. **Figure 2** shows TGA and DSC analysis. The weight loss of the polymer was studied at increasing temperature. The degradation of the in-house PLA and PA samples was a one-stage degradation process and all the samples showed a minimal difference in curvature at a constant heating rate of 20 °C/min. Both materials exhibited thermal stability up to 380 °C and 400 °C according to the one-stage degradation pattern. For in-house PA, moisture evaporated at the early stages (<200 °C). Degradation began to occur dramatically at temperatures of 380 °C to 900 °C for in-house PLA and at 400 °C to 900 °C for in-house PA, and weight losses of about 92% to 98% caused by chain dissociation were observed in this temperature range. A previous study that used pure PLA and PA obtained a similar results, that is, molecular weight decreases during exposure to test temperatures of 60 °C, 90 °C, and 120 °C.[21]

The DSC analysis revealed the glass transition temperature (T_g) of in-house PLA. In **Figure 2b**, a transition characterised by a change in the slope of the heat-flow curve occurs between 60°C and 70°C for in-house PLA. A previous study also found that a polymer changes from a glassy state to a rubbery state.[22] The first small endothermic peak at 150 °C suggests the possible presence of residual solvent moisture or the release of adsorbed water released, an observation that is similar to that derived by a prior study that recorded a prominent endothermic peak at 150 °C to 200 °C, which represents the melting temperature of PLA.[14] The sharp increase indicates the melting of the crystalline regions in the PLA polymer. The melting temperature of PLA usually ranges from 160 °C to 180 °C, which is parallel to the observed peak.[14] In the region after the melting peak at 200 °C to 300 °C, the heat flow stabilises briefly, indicating that the polymer is now fully molten. **Figure 2b** demonstrates that in-house PA has a small endothermic peak at around 50–100 °C, suggesting the evaporation of moisture or other volatile components. A cooling trend was observed at 100 °C to 350 °C, proving that the sample absorbed heat. This value may correspond to the T_g of in-house PA, at which the material transitions from a brittle and glassy state to an elastic state. This trend continued with slight fluctuations up to around 350 °C. The intermediate temperature region (350 °C to 600 °C) showed notable dips and small peaks, which may be due to further physical changes in the polymer structure, such as secondary crystallisation processes. The high-temperature region at 600 °C to 850 °C presented an endothermic peak, peaking at around 800 °C. This peak corresponded to the melting point (T_m) of in-house PA. This material absorbed a large amount of heat when it changed from solid to liquid.

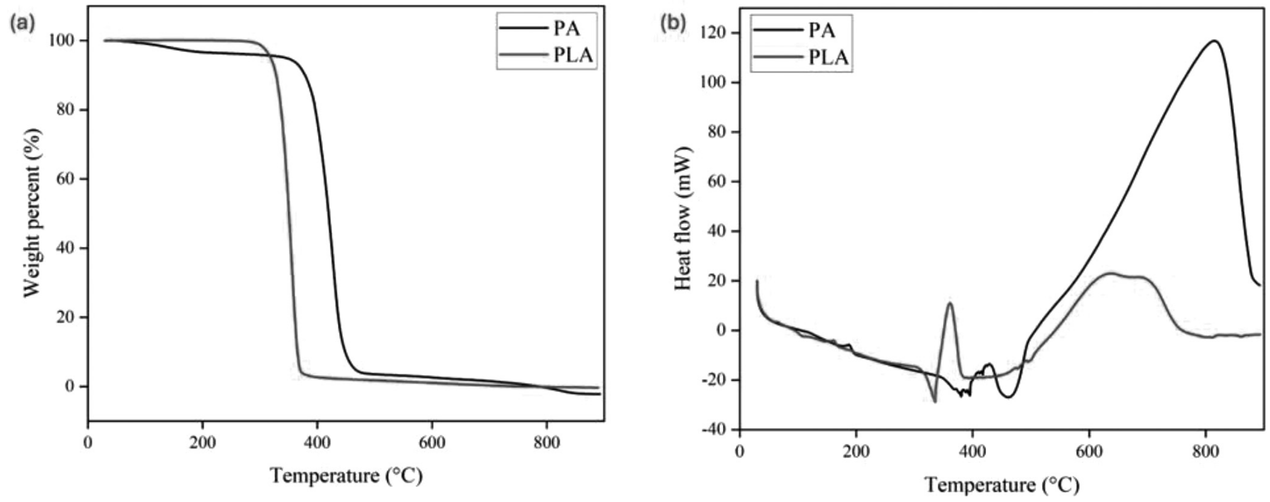

Figure 2: Thermal analysis of in-house PLA and PA: a) thermogravimetric and b) DSC curves

3.2 Compressive strength of conventional PLA-Polymaker

Compression tests are used to determine the compressive strength of a material or its resistance to breaking, cracking or disintegrating. **Figure 3a** shows the results of the compression test performed on the conventional PLA-Polymaker at different test temperatures of 60 °C, 90 °C and 120 °C. The results showed that the temperature increase of 120 °C produced the lowest compressive strength, with an average Young's modulus of 102.270 MPa, compared with temperatures of 90 °C and 60 °C that had average tension rates of 109.3 MPa and 118.9 MPa, respectively. High temperatures can cause PLA molecules to split or rearrange, changing the molecular structure of the material.[23] This alteration can affect the bond between the layers, leading to reduced mechanical properties.[24] High temperatures can increase the moisture absorption by PLA, which can further degrade its mechanical properties as reported by a similar study that used 3D-printed polymer and discovered that moisture affects the material degradation.[25] The study revealed that moisture can weaken the bonds between molecules, making the material susceptible to deformation and failure.[25] The increase in molecular mobility and polymer softening is closely related to the decrease in Young's modulus under increasing temperature.[26] At room temperature and temperatures above the T_g of PLA, the polymer chains become mobile, causing a deterioration in stiffness; the same finding has been obtained for other polymer filaments.[27] Meanwhile, as the temperature approaches or exceeds T_g, the material behaviour transforms to an elastic state, characterised by high molecular mobility and reduced stiffness.[28] As a result, at 120 °C, which is well above T_g, PLA exhibits considerably reduced stiffness, with a decrement of 6.4 % compared with that at the temperature of 90 °C as shown in **Figure 3a**. The detailed temperature degradation experienced by the samples in this study is shown in **Figure 3b**. The samples at 120 °C deformed more compared with those at 60 °C and 90 °C because their thermal degradation and changes in crystallinity may have reduced their compression strength.[29] Understanding this thermal behaviour is important for applications where PLA is exposed to fluctuating temperatures, because it directly affects the mechanical performance and durability of the material.

3.3 Compressive strength of in-house PLA

In-house PLA was fabricated and compared with conventional PLA-Polymaker, as shown in **Figure 3a**. The compressive-strength profile is shown in **Figure 3c**. When the sample was pressed at a temperature of 60 °C, it began to deform, similar to the trend exhibited by conventional PLA-Polymaker in **Figure 3a**. The compressive strength of the in-house PLA was drastically reduced by 96 % compared with the test samples at 60 °C. The samples fabricated in-house had poor thermal stability probably because the particle size was not controlled in this study and because the geometrical structure of PLA is uneven, hence the thermal softening of the PLA material at high temperatures.[30] The data obtained in this study presented a similar trend to that reported in a prior study that used PLA materials; in this previous work, the Young's modulus decreased considerably as the temperature increased.[31] The researchers recorded a decrease of up to 90 % when the temperature increased to 90 °C because the mobility of the polymer chains led to a considerable reduction in material stiffness and load-bearing capacity. **Figure 3d** indicates that when the temperature

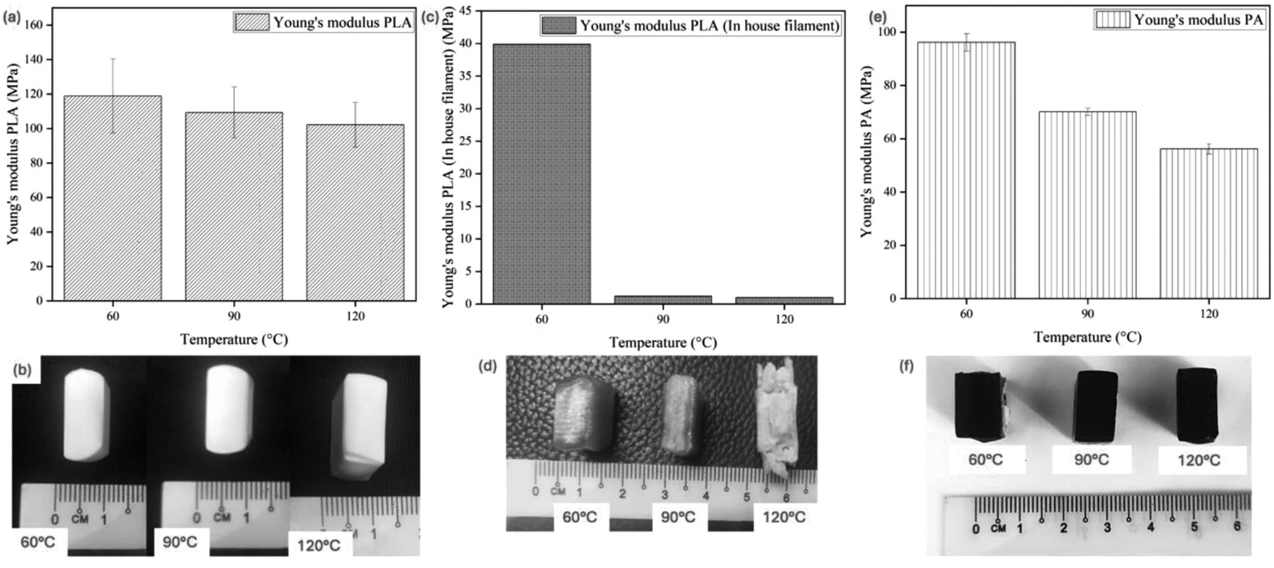

Figure 3: Compression strength of PLA-Polymaker: a) Young's modulus and b) deformed samples tested at various temperatures (60 °C, 90 °C and 120 °C). In-house PLA compression strength ; c) Young's modulus and d) test samples tested at 60 °C, 90 °C and 120 °C. In-house PA compression strength; e) Young's modulus and f) compression test samples at temperatures of 60 °C, 90 °C and 120 °C

increased to 120 °C, the sample failed to retain its original shape and scatted. A difference in behaviour was observed between the in-house PLA and PLA-Polymaker at 120 °C. The value recorded for the PLA-Polymaker was 102 MPa which is higher that the value for in-house PLA (1 MPa). This phenomenon was due to the full deformation and degradation at the temperature of 120 °C, as shown by the optical images in **Figure 3d**.

3.4 Compressive strength of in-house PA

For the reference samples, the in-house PA material was fabricated into a compression test piece, as shown in **Figure 3e** and **Figure 3f**. It achieved a lower compressive strength at 120 °C with an average Young's modulus of 56.2MPa compared with the samples at temperatures of 90 °C and 60 °C, which had average stress rates of 70 MPa and 96.2 MPa, respectively. Compared with the in-house PLA, the in-house PA had higher heat resistance and mechanical strength, a result that was also reported by another study.[32] The PA filament can withstand temperatures up to 90°C and has a tensile strength between 50 MPa and 100 MPa, which is ≈50 % higher than the tensile strength of the in-house PLA. A previous study also mentioned that an increase in material homogeneity could result from changes in the ratio of amorphous and crystalline, which is directly affected by temperature increments.[33] In the present study, the in-house PA showed better performance compared with in-house PLA because of the different polymer structure and chemical composition of PA. In-house PA is stronger than in-house PLA at high temperatures because of the high thermal resistance of in-house PA, as reported by Hadi et. al.[34] Meanwhile, comparison of **Figure 3f** and **Figure 3d** clearly indicates that in-house PA deformed less compared with in-house PLA. When the temperature rose, the energy channelled to the polymer chain increased. Unlike the PLA, the PA exhibited viscoelastic properties, which caused it to behave as a viscous and elastic materials as the temperature increased.[35] As a result, the PLA material changed its shape easily under pressure. In a previous study, PLA could deform up to a maximum strain of 10.2 % at the highest strain rate possible under the tested pressure as it reached T_g making it change from a glassy state to a rubbery or elastic state.[36] In the elastic state, the material becomes increasingly flexible and less rigid, resulting in a reduced Young's modulus.[37]

3.5 Flexural strength of in-house PLA

A three-point bending test was conducted to obtain the bending strength, bending modulus and deformation of the sample at different test temperatures of 60 °C, 90 °C and 120 °C. The results are shown **Figure 4**. Increasing the test temperature reduced the bending strength of the PLA and PA. For the in-house PLA material, no readings were available for the test temperatures of 60 °C, 90 °C and 120 °C. Therefore, the test was performed at room temperature for one of the samples. When the temperature exceeded 60 °C, the sample deformed as shown in **Figure 4b-1**. The samples became elastic and dropped from the jig before testing when it was heated at post-processing temperatures of 60 °C, 90 °C and 120 °C. The sample was extremely bent, as demonstrated in **Figure 4b-1**. With regard to the in-house PLA sample, room temperature produced a reading of bending strength with an average rate of Young's modulus of 2,675 MPa compared with the temperatures of 60 °C, 90 °C and 120 °C that had no reading. The sample tested at room temperature was the only sample that fractured. As expected, in-house PLA became deformed and flexible at temperatures above 60 °C. This phenomenon is due to the fact that the PLA's mechanical properties deteriorate at temperatures above T_g. These properties are also influenced by external factors such as element geometry, printer-work platform and nozzle temperature. Moreover, the shrinkage phenomenon caused a large loss of molar mass during the experiment.[38] The unexpected shrinkage observed after post-processing heat treatment in materials made from PLA or containing PLA is a notable material defect. This issue is especially critical in specific applications, particularly biomedical.[38]

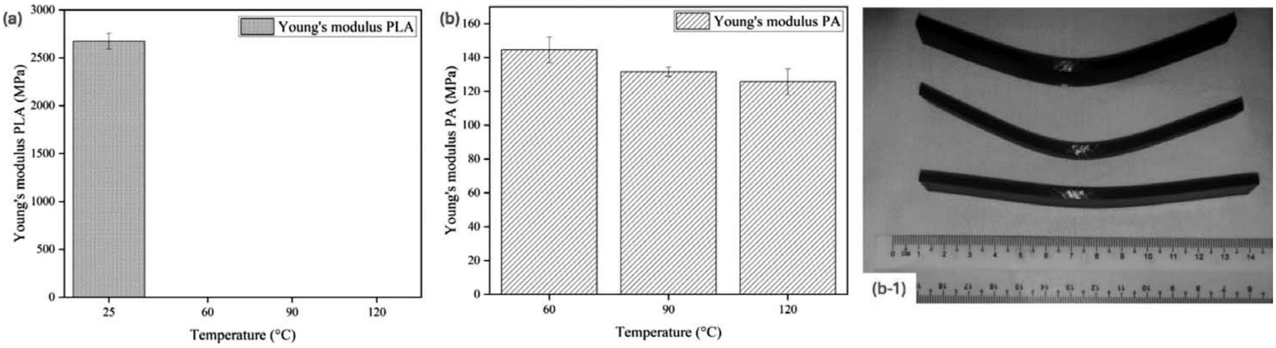

Figure 4: Flexural strength of in-house: a) PLA and b) PA at different temperature of 60 °C, 90 °C and 120 °C

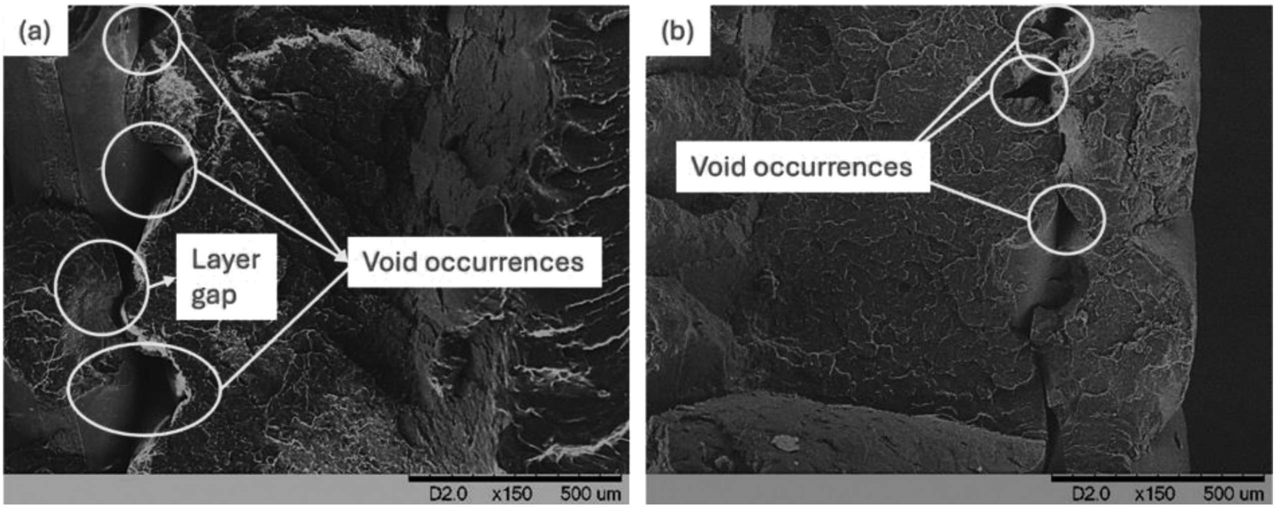

Figure 5: Micrograph analysis of in-house: a) PLA and b) PA at a temperature of 60 °C

3.6 Flexural strength of in-house PA

As shown in **Figure 4b**, for the in-house PA, the temperature of 120 °C produced the lowest flexural strength with an average Young's modulus of 125.8 MPa, compared with the temperatures of 90 °C and 60 °C, which had an average flexural strength of 131.6 MPa and 144.6 MPa, respectively. As expected, in-house PA was stronger than in-house PLA at high temperatures because of the high heat resistance of the in-house PLA material. At high temperatures, the intermolecular forces of the polymer chains weaken, and the chains can move past each other easily. This increase in chain mobility leads to a decrease in material stiffness, which is measured by Young's modulus, as exhibited in **Figure 4b-1**.[33] The specific Young's modulus values of PA-12 obtained by Pszczólkowski et al. [33], at different temperatures are consistent with the values obtained in this study. **Figure 4b** demonstrates that when the temperature rose from 60 °C to 90 °C and 120 °C, the Young's modulus plummeted slightly at an average of 6 % to 8 %. This phenomenon is due to the fact that the material becomes increasingly flexible and less resistant to bending forces when the temperature increases.[39]

3.7 Fracture surface analysis of printed in-house PLA and PA

The fracture surface of flexural samples for in-house PLA and in-house PLA were analysed using micrograph images as shown in **Figure 5**. The microstructural analysis was performed on the flexural in-house PLA sample tested at 60 °C for comparison with an in-house PA sample. **Figure 5a** indicates that the sample layer at room temperature separated without melting and did not leave any residual material on the edge of the layer after being subjected to bending loads. The absence of any temperature in this bending test caused the sample layers to separate easily. The in-house PLA samples tested at the study temperatures of 60 °C, 90 °C and 120 °C melted and slipped from the surface of the jig before being pressed until it broke in the middle. Given that no data were recorded for in-house PLA at temperatures above 60 °C, the micrograph images were analysed at 60 °C for comparison with in-house PA. Compared with in-house PA, the in-house PLA do had a huge layer gap and an obvious void which caused the samples to have a lower Young's modulus compared with the in-house PA samples. The thermal resistance and melting point of in-house PA were higher than those of in-house PLA. The in-house PA samples tested at the study temperatures of 60 °C, 90 °C and 120 °C did not break, but bent when pressed showing high in-house PA strength at high temperatures. **Figure 5b** presents the small void found on the fractured surface of the in-house PA sample. The layered structure and the presence of air gaps between the deposited filament layers caused the formation of small voids or holes in the printed in-house PA part. These small holes are produced in the FFF printing process and are commonly observed in 3D-printed in-house PA samples. The mechanical properties of 3D-printed PLA, including its bending strength, can be affected by printing parameters such as layer thickness. Thick layers tend to produce high flexural strength but can cause large voids or holes between layers.[40] With increasing temperature, plastic resistance decreases, leading to a gradual decrease in voids in the amorphous phase and low strain softening. After the elastic deformation stage, the sample starts to orient and shear along the drawing direction.[41] The results of both tests in this study show that the higher the temperature was, the lower the strength of the polymer was, resulting in an increased deformation capacity as proven in **Figure 2d** and **Figure 2f**. The intermolecular bonds weakened, and polymer crystallinity decreased as the temperature increased. This situation resulted in the loss of elasticity, which reduced the polymer's ability to return to its original shape.

3.8 Simulation analysis of printed in-house PLA and PA

FEA was verified by the experimental work conducted in this study. An ASTM-D695 compression test and an ASTM-D790 bending test were performed at the same temperatures of 60 °C, 90 °C and 120 °C in accordance with the FEA simulation. The compression simulation was conducted using the usual commands 'fixed support' and 'force' as shown in **Figure 6a**. Three-point bending simulation (flexural test) was performed using the 'remote displacement' command, as presented in **Figure 6b**. Simulation of the compression test was performed at various temperatures and presented in **Figure 6c**, which shows the decreasing trend of the graph with increasing temperature (within the range 19.8 %–27 %), similar to the actual test. At the temperature of 60 °C, the Young's modulus was 113.5 MPa. When the temperature increased to 90 °C, the Young's modulus decreased to 112.3 MPa, indicating a decrement

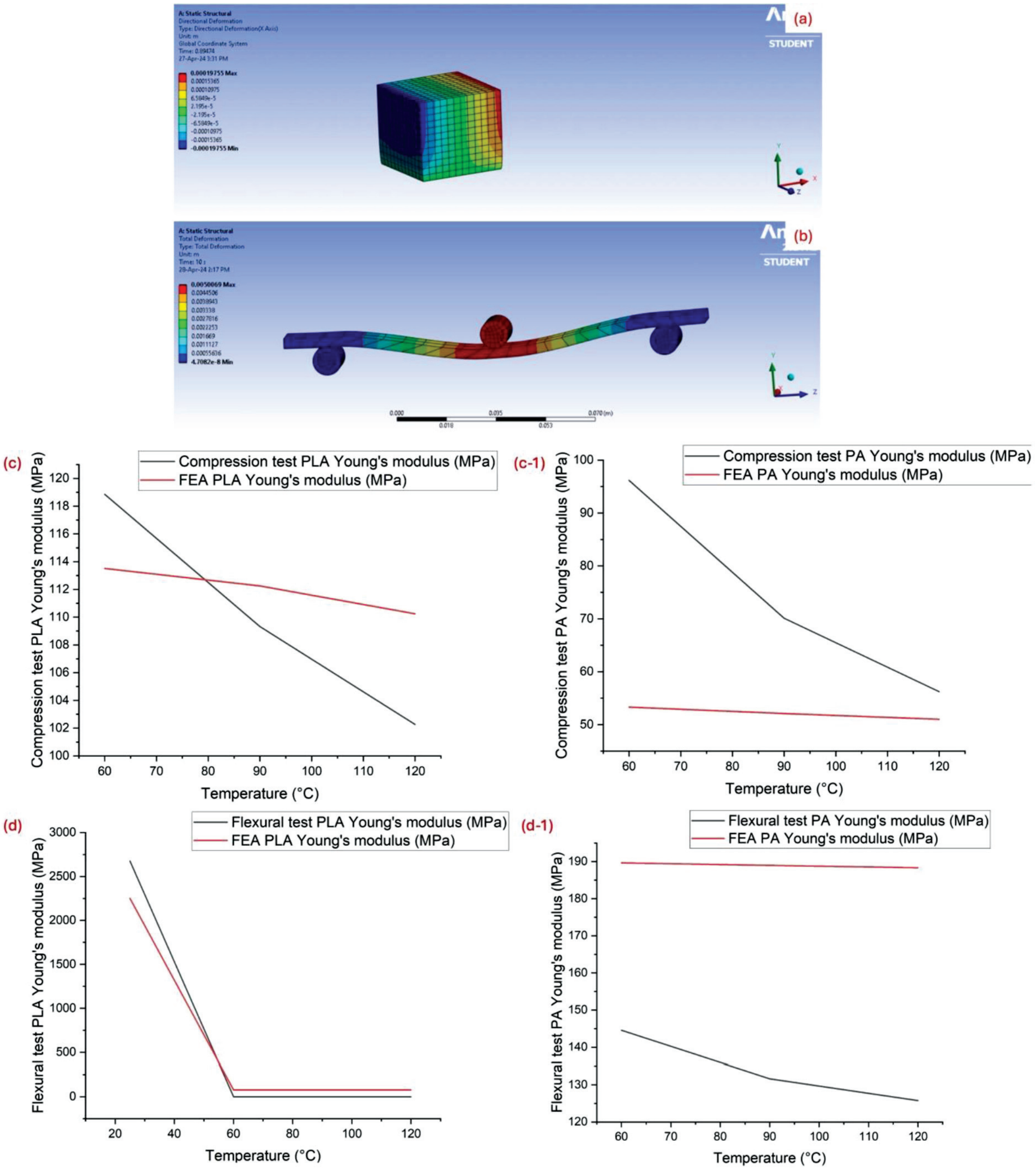

Figure 6: Simulation using FEA of: a) compression and b) flexural samples. Comparison of compression experimental and simulation data obtained at different temperatures of c) PLA and (c-1) PA; Flexural experimental and simulation data of d) PLA and (d-1) PA.

of 27 %. This substantial decrease in modulus means that PLA becomes less stiff and highly susceptible to deformation at high temperatures, which is identical to the trend obtained in the experimental study. At the temperature of 120 °C, the Young's modulus continued to decrease to 110.2 MPa, manifesting a decrease of ≈20 % compared with the value at 90 °C. This continuous decrease in modulus indicates that the PLA material becomes less rigid and highly susceptible to deformation at high temperatures.[42] Meanwhile, a trend similar to that observed in the experimental results is shown in **Figure 6c-1** for the compression test.

Compression tests and FEA were performed at different temperatures, which may have affected the mechanical properties of the material. Young's modulus values from compression tests reflect the actual change in material stiffness at different temperatures. **Figure 6c-1** indicated that the test slope is lower that that in FEA. FEA may not fully consider this temperature effect, leading to differences in calculated values as suggested by a prior study.[29] For the PA materials, the simulation showed that the Young's modulus values at 60 °C and 90 °C were 53.3 MPa and 52.1 MPa, respectively, manifesting a decrement of 2.25 %. This decrease in modulus was likely due to the increase in thermal energy at high temperatures, causing the molecular structure of the PA material to become less rigid and prone to deformation.[43] The simulation also revealed that the value recorded at 120 °C was 51 MPa, which represents a decrease of 2.11 %. This result is in line with the expected trend of decreasing stiffness with increasing temperature. The difference in Young's modulus reading between the experimental test and the FEA simulation is shown in **Figure 6c-1**. The strength in the test is higher than that in FEA because of factors, such as the size of the fixture plate and possible misalignment during testing.[43] The mechanical properties of PA, such as tensile and compressive Young's modulus, can vary depending on part orientation and manufacturing conditions. This anisotropy is not fully captured by FEA models, leading to discrepancies between FEA predictions and experimental data.[44]

Figure 6d shows the FEA simulation results of the flexural test for PLA in comparison with the experimental results. The substantial decrease in Young's modulus at high temperatures (60°C, 90°C and 120°C) observed in the experiment indicates that the properties of 3D-printed PLA materials are highly dependent on temperature. However, the FEA may not accurately capture the thermal softening and deterioration of material properties at high temperatures, leading to discrepancies between experimental and simulated results.[45] In this study, the FEA may have assumed linear-elastic behaviour of the material, failing to accurately captured the complex deformations and failure modes observed in the experiments. According to **Figure 6d-1**, the flexural test results of PA assumed a uniform material behaviour without considering the effect of temperature. Hence, discrepancies rose between the test and the FEA results, especially at higher temperatures.

4 CONCLUSIONS

This study successfully fabricated in-house 3D-printed samples by using pure PA and PLA, under the influence of different temperatures. The compression and flexural properties were determined, and experimental and FEA results were compared. The results showed that increasing the temperature of the compression and flexural tests affected the mechanical properties of the in-house PLA and PA.

Among the studied test temperatures, the temperature of 120 °C produced the lowest compressive and flexural properties, with an average decrease of 27 % for in-house PA and 96 % for in-house PLA. This results were obtained because of the weak bond between the layers, resulting in a decrease in material strength. By contrast, the bonding and adhesion at room temperature minimised the void occurrences, indicating that temperature affected the performance of the in-house polymer, as reflected by the layer gap within the printed samples.

The moisture content of in-house PA evaporated at the early stages (<200 °C). Degradation occurred dramatically between 380 °C and 900 °C for in-house PLA and between 400 °C and 900 °C for in-house PA. Weight losses of approximately 92 % to 98 % were observed in this temperature range and attributed to chain dissociation.

PLA-Polymaker (commercial) had a Young's modulus of 102.270 MPa at 120 °C, but the values were 109.3 MPa and 118.9 MPa at temperatures of 90 °C and 60 °C, respectively. Drastic reductions (96%) in the compressive strength of in-house PLA were observed compared with the PLA-Polymaker samples at 60 °C. Meanwhile, the temperature of 120 °C produced a low compressive strength with an average Young's modulus of 56.2 MPa compared with the temperatures of 90 °C and 60 °C, which had average stress rates of 70 MPa and 96.2 MPa, respectively.

At 120 °C the in-house PA had the lowest flexural strength with an average Young's modulus value of 125.8 MPa compared with the average Young's modulus values of 131.6 MPa and 144.6 MPa at 90 °C and 60 °C respectively.

Future analysis involving simulation is required, especially when the samples cannot be experimentally tested because of failure during testing. A prediction will allow researchers to adjust the printing parameters and refine the homogeneity of polymer materials during the filament-making process.

The FEA simulation confirmed the experimental results, showing a decreasing trend in Young's modulus with increasing temperature for PLA and PA. The flexural tests further confirmed that PLA's mechanical properties are highly temperature-dependent, with substantial modulus reductions at high temperatures. However, the discrepancies between the experimental and the FEA results suggest that the FEA may not fully capture nonlinear deformations, thermal softening, and anisotropic effects. These findings highlight the importance of refining simulation models to fully account for temperature-induced material behaviour in 3D-printed polymers.

These remarks underscore the importance of future studies, particularly in controlling the powder geometrical form and studying the printing orientation. Doing so will enhance mechanical performance and broaden applications which that can be tailored in the near future.

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