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Novel Approach to Lightweight PLA Manufacturing Using Chemical Agents for Enhanced UAV Performance

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Abstract

In this paper, it is examined that the production and optimization of foamed filaments for Fused Deposition Modelling (FDM) based on mixing poly(lactic acid) (PLA) granules with different concentrations of foaming agents. The diameter of the produced filaments was set to 1.75mm. The melt mixing process of PLA and foaming agent was carried out at a ratio of 12%, 18%, and 24%. Later, filaments are used to print objects using a 3D printer to produce test samples. The process parameters for FDM, such as nozzle temperatures and printing speeds, were also varied during filament and sample printing. The mechanical and morphological analysis was done on the produced samples. The mechanical analysis entailed measuring tensile strength, elongation, breakage, and Young's modulus. Scanning electron microscopy (SEM) was used to test microstructures in the produced samples. On the other hand, the density test was used to determine the porosity of foamed filaments. Through optimizing foaming processes, it is aimed that to determine a combination of low material density with acceptable structural strength. The experimental results will enable us to understand how to make foamed PLA filaments for structurally optimized FDM.

Keywords: Additive Manufacturing, Polymeric composites, Chemical Foaming Agent, PLA Filament

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İHA Performansını Artırmak İçin Kimyasal Maddeler Kullanarak Hafif PLA Üretimine Yönelik Yenilikçi Bir Yaklaşım

Öz

Bu çalışmada, farklı köpürme ajanı konsantrasyonları ile kompozisyonlar oluşturulmuş polilaktik asit (PLA) granülleri kullanılarak Eriyik Yığma Modelleme (Fused Deposition Modeling – FDM) için köpürebilen düşük yoğunluklu filamentlerin üretimi ve optimizasyonu yapılmıştır. 1,75 mm çapında filamentler, PLA'ya köpürme ajanın %12, %18 ve %24 oranlarında eriyik karıştırma yöntemiyle katılması ile hazırlanmıştır. Bu filamentlerden daha sonra 3B baskı ile test numuneleri üretilmiştir. Filament ekstrüzyonu ve numune baskısı sırasında, meme (nozzle) sıcaklığı ve baskı hızı dahil olmak üzere FDM proses parametreleri sistematik olarak değiştirilmiştir. Elde edilen numuneler üzerinde mekanik ve morfolojik testler gerçekleştirilmiştir. Çekme dayanımı, kopma uzaması ve Young modülü gibi mekanik özellikler değerlendirilmiştir. Ayrıca, taramalı elektron mikroskobu (SEM) analizleri, basılmış numuneler içerisindeki mikroyapı ve gözenek dağılımı hakkında bilgi sağlamıştır. Köpüren filamentlerin gözenekliliğini nicelendirmek amacıyla yoğunluk testleri yapılmıştır. Köpürme davranışının optimize edilmesiyle, mekanik performans ile azaltılmış malzeme yoğunluğu arasında bir denge sağlanması hedeflenmiştir. Elde edilen bulgular, hafif ve yapısal olarak verimli FDM uygulamaları için PLA bazlı köpürebilen filamentlerin anlaşılmasına katkı sağlamaktadır.

Anahtar kelimeler: Eklemeli İmalat, Polimerik kompozit, Kimyasal köpürme ajanı, PLA filament

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1. Introduction

Fused Deposition Modeling (FDM) is a popular technique for producing complicated components with numerous features. The most usually used cloth in FDM is Polylactic Acid (PLA), which is preferred due to its low thermal shrinkage coefficient and correct adhesion to the printing plate. PLA is an environmentally friendly polymer as PLA decomposes into water and carbon dioxide due to its degradation. In addition, it's miles a biocompatible thermoplastic. It has negative aspects such as low thermal and mechanical energy. To triumph over those boundaries, composite structures can be produced by filling PLA with diverse substances. This can improve the residences of PLA and convey better satisfactory FDM published elements [1-2].

FDM is a extraordinarily successful technique that has a huge range of packages beyond UAV parts. It is mainly beneficial for accelerating prototype manufacturing. Using the FDM approach in UAVs can appreciably improve structural performance, mainly by way of increasing the strength/weight ratio. The FDM method become first utilized in wind tunnel studies to assess UAV designs in terms of aerodynamics. However, publish-production operations which include grinding and sprucing are required to reap the very last product for UAVs [3-7].

In recent years, there has been considerable interest in low-density polymeric systems that can be fabricated using FDM technology [8]. These structures have the potential to exhibit improved mechanical, thermal, and physical properties [9,10]. The study of these structures is important because of the need for such materials and their interchangeability with different materials. Polymers are usually composed of small gas molecules encapsulated in the material. This foam structure has been the subject of many studies over the years, and remains an active research area [11-14].

To create porous polymeric substances, CO2 and nitrogen are commonly used. The supercritical foaming behavior on this regard has been substantially studied [15-18]. In this technique, an out-of-equilibrium foam formation is completed the use of the partial gasoline saturation technique . Chemical foaming agents (CFA) are also an alternative to supercritical foaming and are extensively used within the automotive enterprise . The materials produced through this approach have lower density than trendy polymers. They additionally offer sound and heat insulation. In addition, they allow quicker manufacturing, reduce material intake, and lower fees . Research on CFA has shown that scaffold production for scientific packages can be done with FDM printing, however it isn't suitable for complex geometries at this degree [19].

This study investigates the production of PLA filaments with different CFA content and the production of lightweight PLA foams. The initial processing parameters are CFA ratio and printing temperature, which are expected to affect foam density and bubble shape. The effects of these parameters on the stiffness, tensile strength and morphological structure have been investigated. Optimization of these parameters enables calculation of volumetric expansion at a given temperature and CFA ratio. Based on this calculation, the flow rate of the 3D printing can be adjusted and the nose structure of the UAV can be printed. This research can contribute to further scientific progress by optimizing printing processes to produce lightweight PLA filaments [20].

2. Material and Method

2.1. Materials

A poly(lactic acid) (PLA) with grade Luminy® Lx175 was used as a matrix base polymer-grade to produce foamable filaments in this study. PLA, a biodegradable and biocompatible aliphatic polyester from renewable resources (corn starch or sugarcane), is an environmentally friendly alternative to petroleum-based plastics. Due to its good processability, low melting temperature and neat mechanical properties, PLA has found wide applications in Fused Deposition Modeling (FDM) and other Additive Manufacturing technologies.

A chemical foaming agent (CFA) such as Sukano® FA S632 was used to achieve controlled porosities of the PLA matrix. The foamable agent of the invention is suitable for thermoplastic molding and disintegrates by heat decomposition at high temperatures to produce gaseous substances. The nephrite gas bubble then comes into being and grows during the molten PLA while forming a cellular structure in consist of micro- and macro-scale pore with such a tiny solid volume fraction. This adoption allows for density decrease and material saving, with possibly influenced thermal and mechanical properties of the 3D-printed components.

2.2. Filament production

In this regard, in an attempt to monitor the effect of the chemical foaming agent (CFA) content on the morphology of the filaments as well as the foaming process, the foaming PLA filaments were made by melt mixing the PLA resin with varying weight percentages (12, 18, and 24 wt%) of the foaming agent. For this purpose, a single-screw extruder has been used for the melt mixing, which is sufficient to provide shear and heat energy to ensure that the foaming agent is dispersed in the PLA resin in an ideal manner. In addition, the single-screw extruder has a diameter of 30 mm, L/D ratio of 24, which contributes to a smooth melting process for the filaments. Further, there is also an automated closed system designed in Beta Laser diameter measurement devices, which is effective in monitoring the changes in diameters of the filaments.

Figure 1 *Filament Extrusion Process*

The temperature profile of the extruder, from the feed throat to the die, was carefully controlled at 165/170/178/175 °C, while the temperature of the water cooling bath was maintained at 43°C. This was the chosen temperature because it allows full melting and mixing of PLA but avoids degradation of the foaming agent, which might happen too early during the extrusion of filaments. The rotating speed of the screw was kept constant at 25 rpm, while the material feed rate was kept at 3 kg/h to maintain consistent processing conditions and quality of the filaments.

Table 1 *Produced Materials and Foaming Agent Ratios*

	Matrix	Additive	Additive ratio (%wt)
1	PLA	-	-
2	PLA	Sukano Fa s632	%12
3	PLA	Sukano Fa s632	%18
4	PLA	Sukano Fa s632	%24

2.3. Extrusion on 3D printer

PLA/CFA blends were extruded into filaments with a diameter of 1.75 mm to make them directly compatible with commercial FDM 3D printers. The extrusion parameters were optimized to prevent the foaming agent from activating during extrusion. Since the CFA remains unreacted within the filament, the foaming process takes place during the 3D printing process.

Foaming was meant to occur inside the FDM printer's heated nozzle. Higher temperatures help break down the CFA and form pores. It is analysed that the pore structure of the filaments before and after the thermofoaming process to see how the cellular structure developed. To assess how printing temperature affects pore nucleation, growth, and the overall foam structure, It is conducted thermofoaming experiments at 200 °C and 260 °C.

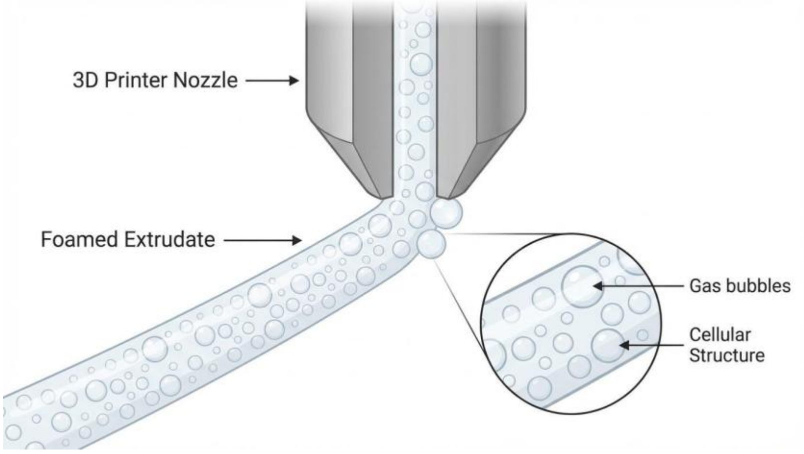

Figure 2 Foaming at 3d printing nozzle

The materials were extruded through a 3D printer nozzle at temperatures between 200 and 260 °C, with a constant feed rate after filament production. Then, after gathering the extrudates obtained for each of those temperatures, their densities were measured to quantify the foaming ratio and investigate volumetric expansion behaviour. A device based on Archimedes' principle was used for the accurate determination of bulk density of the samples. The buoyancy force was measured by submerging the sample in a reference fluid. For these measurements, a Precisa XB 3200 precision balance was used. The influence of processing conditions, such as extrusion temperature and content of foaming agents, on foam expansion was further investigated on the basis of calculated density values.

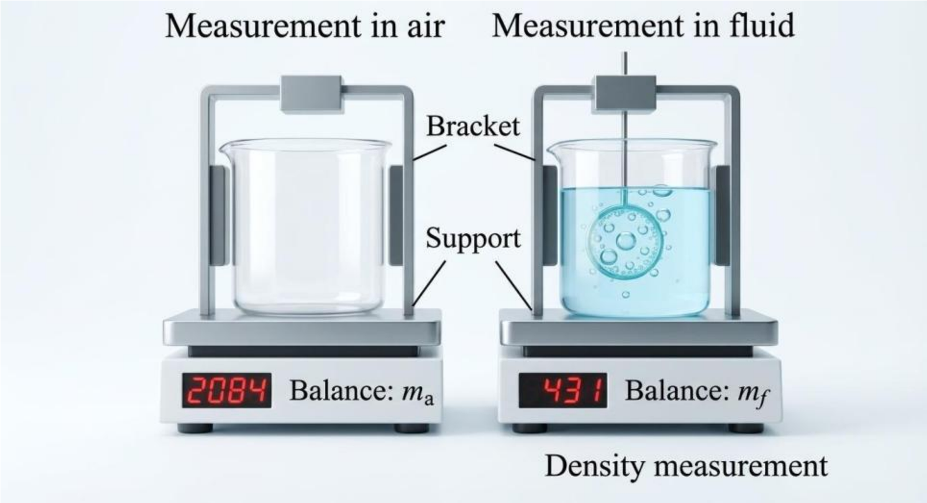

Figure 3 Density Measurament

The degree of volumetric expansion caused by the foaming process was measured in our experiment was the degree of expansion that occurred in the material when it went through the foaming process. It is measured this degree of expansion by the value of the foaming ratio, or expansion ratio. Essentially, the foaming ratio determines the degree to which the density is reduced by the creation of pores within the material. To better explain, there are two densities that are measured in a given experiment. These are the density of the solid PLA (or PLA/CFA filament), which is measured prior to the foaming process, and the density of the foamed sample after the foaming process.

$$Foaming\ Ratio\ (FR) = \frac{\rho_{solid}}{\rho_{foam}} \tag{1}$$

In this formula, a description of density for unfomed or solid PLA and PLA/CFA is given as ρ_{solid} and is measured in units of g/cm3, while a description of density for a foamed sample is given as ρ_{foam}. This ratio shows a higher level of pore development and expansion as a high value is indicated.

Density measurements carried out using the principle of Archimedes were utilized to establish the porosity of the foamed samples. Relative densities between the foamed and unfoamed samples were utilized to calculate the porosity of the sample, which is the volume of the voids that exist.

$$Porosity\ (\%) = 100 \times \left(1 - \frac{\rho_{solid}}{\rho_{foam}}\right) \tag{2}$$

Where; ρ_{solid} is the unfoamed (solid) PLA or PLA/CFA material's density, and ρ_{foam} is the foamed sample's density, both in g/cm^3.

The foamed sample's density A higher volumetric expansion ratio and lower bulk density of the material are correlated with higher values of porosity, indicating a greater volume fraction of gas voids produced during the foam formation process.

2.4. Tensile test

ASTM D638 Type V tensile test specimens were printed using an FDM 3D printing technique by Bambulab P1S Combo 3d printer with a nozzle diameter of 0.4 mm, and the specimens have a nominal thickness of 3.2 mm and 0,2 mm layer height to meeting the standard requirements. To reduce anisotropy effects resulting from print layers, concentric raster orientation in each printed layer was adopted, which coincides with the direction of loading. The printing temperature was varied for the test specimens, keeping the temperatures at 200 °C, 220 °C, 240 °C, and 260 °C. However, the other conditions were remained constant for all the test specimens prepared for evaluation. For this investigation, the printing speed for all test samples was 30 mm/s.

Figure 4 Scheme of printing parameters and infill type and printed specimens

The flow of the material was precisely regulated with respect to each printing condition based on the measured density values for the foamed filaments. As a result of the effect of thermofoaming on the density of the material, it was essential that this regulation be done to compensate for the possibility of under-extrusion experienced when handling highly foamed filaments. Through this regulation based on the control of flow rates based on density differences, it was possible for us to ensure that each specimen had a given mass per unit length.

The infill density of each of our physical sample copies was 100% and had a raster orientation following the loading direction. Our aim was to ensure that the results of the tensile test would not be affected in any way from the layer anisotropy. Once they had been produced, the samples underwent 48 hours of conditioning in an atmosphere of 23 ± 2 °C and 50 ± 5% RH before undergoing the mechanical test.

For the tensile testing, universal testing machine is used which having a 5 kN load cell. In tensile testing, it is maintained a crosshead speed of 5 mm/min, which is in line with the requirements given in ASTM D638 standards. In each processing condition, it is been carried out the tensile test on at least five specimens (n = 5), and the average values, along with the standard deviation, were provided.

3. Results

In our experiment, some interesting trends was found with regards to chemical foaming agents and extrusion temperatures. In our experiment where various percentages of chemical foaming agents such as 12%, 18% was tried, and 25%, found that with each increase in temperature from 200°C to 230°-240°C, the density values for our extruded samples went down. That is, temperatures really seem to increase the positives of foam expansion. It appears that adding more heat is assisting CFAs in decomposing effectively [16,20].

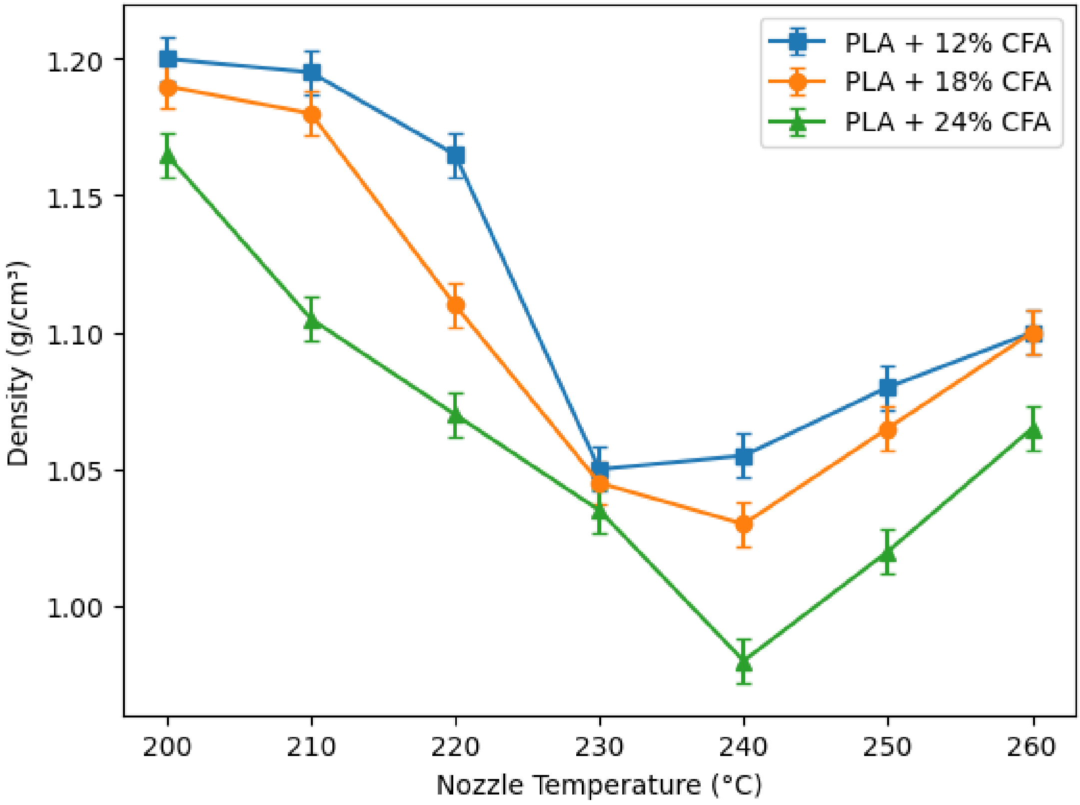

Figure 5 Density variation of foamed PLA samples as a function of nozzle temperature for different CFA contents.

The study found that when samples with different amounts of CFA are investigated(chemical foaming agent) and set them to a specific extrusion temperature, those with higher CFA content tended to have lower density values. This suggests that more foaming agent leads to a greater ability to generate gas, which is important in the foaming process. The density of the samples that contained 25 wt% CFA and were printed at a temperature of 240 °C showed the least density, which indicates the highest volume expansion. Nevertheless, when the temperature increased marginally between 250-260 °C, there was a slight increase in the density of all the samples. This confirms that the foam-forming efficiency had reduced at higher temperatures [16–18,20].

Considering porosity, which was calculated on the basis of density measurements, similar trends were followed. With an increase in content of CFA and extrusion temperature, porosity up to a certain limit was noticed to increase. Peak porosity values up to 22% were measured at intermediate to high temperatures during extrusion, especially at 240 °C. However, there was a slight decrease in porosity with an increase in temperatures above 240 °C, indicating that too much heat may hinder the development of healthy cells within the material [16-18].

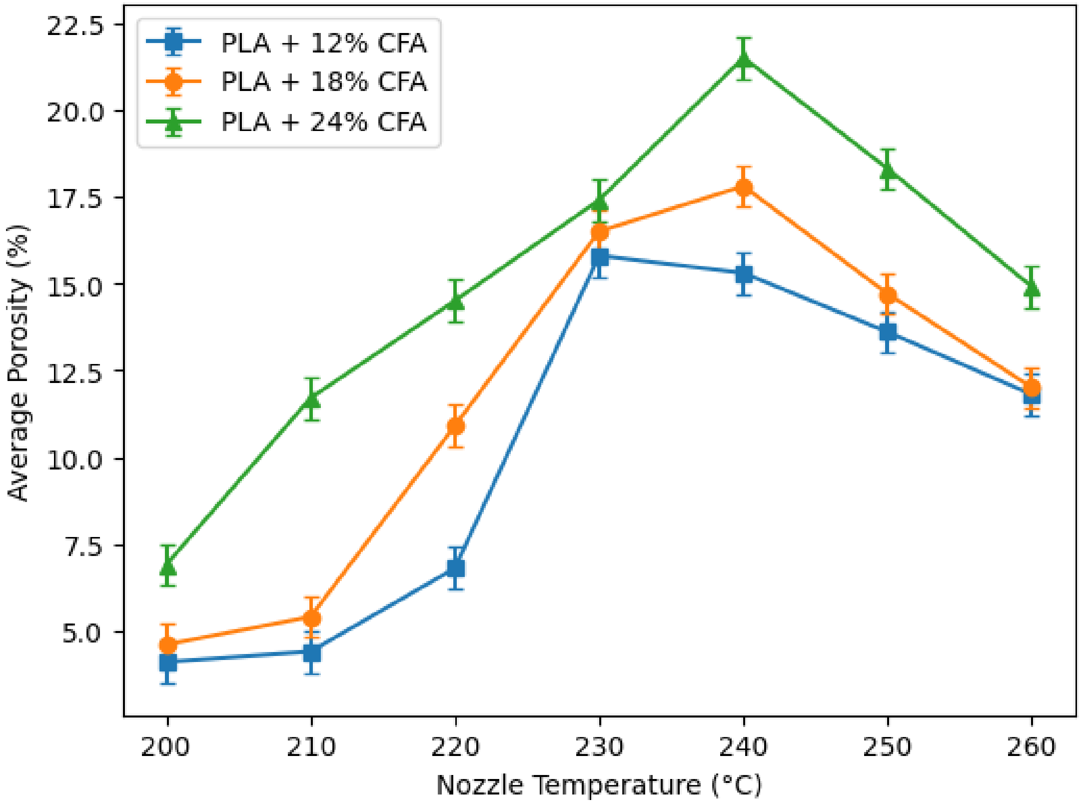

Figure 6 Porosity variation of foamed PLA samples as a function of nozzle temperature for different CFA contents.

On analyzing the density and porosity properties, the role of the chemical foaming agent (CFA) content and the extrusion temperature was observed to be significant. For all the compositions, an increase in the extrusion temperature from 200 °C to around 230-240 °C resulted in a corresponding decrease in density. This can be explained by the observation that an increase in extrusion temperature leads to an enhanced foaming reaction by increasing the amount of gases being produced. Also, an increase in the content of the chemical foaming agent at a specific constant density value points to an increase in the amount of material expansion.

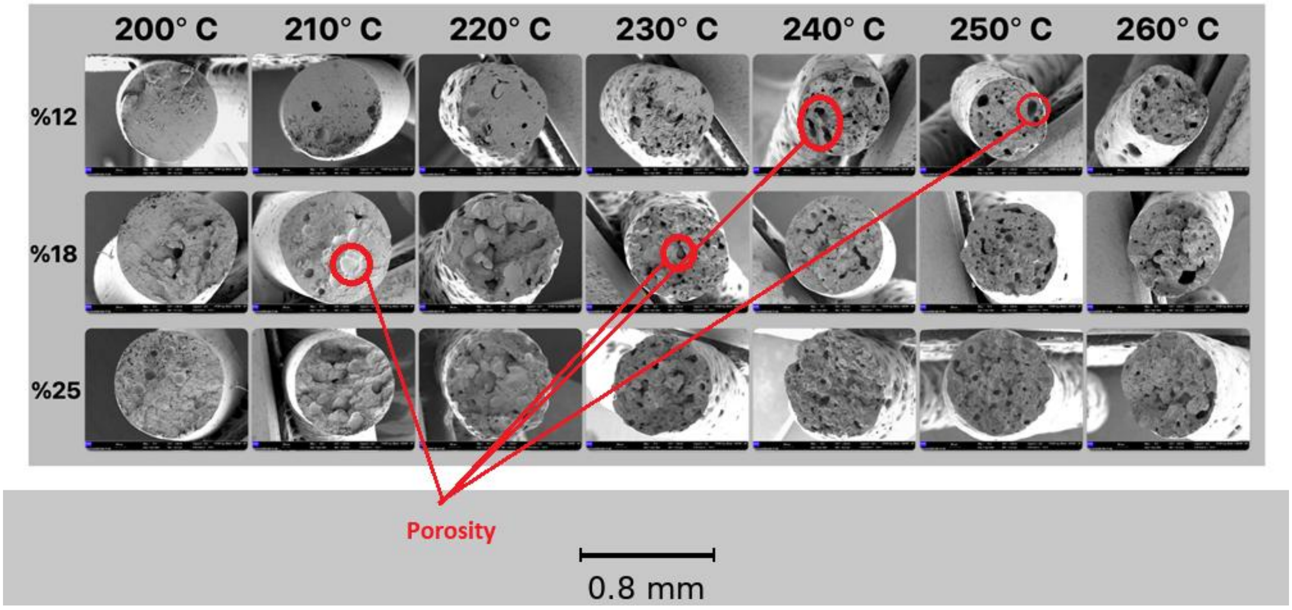

Figure 7 Cross-sectional SEM images illustrating the evolution of cellular morphology in foamed PLA samples as a function of extrusion temperature and foaming agent content.

The analysis of porosity value data obtained from the density measurement showed the following interesting results: as the amount of CFA (Chemical Foaming Agent) and the extrusion temperatures increased, the porosity also showed a corresponding increase. The maximum porosity of up to 22% occurred when the temperatures oscillated close to 240 °C in specimens containing higher quantities of CFA. But when the temperatures surpassed the optimal range, a slight reduction in porosity occurred, indicating that excessive temperatures might prevent the proper formation of the pores [16–18].

The results obtained from SEM (scanning electron microscopy) studies further proved these trends. These results showed highly distinct variations in cellular structure depending on CFA content and processing temperature. Samples with low CFA had irregular cellular distributions and irregularities in cellular structure, while samples with high CFA had regular cellular structure with tighter control over cellular and/or pore sizes.

Both CFA content and printing temperature showed a strong influence on the tensile behaviour of the foamed PLA filaments, in direct correlation with the density and porosity trends discussed in the previous section [1,2,20].

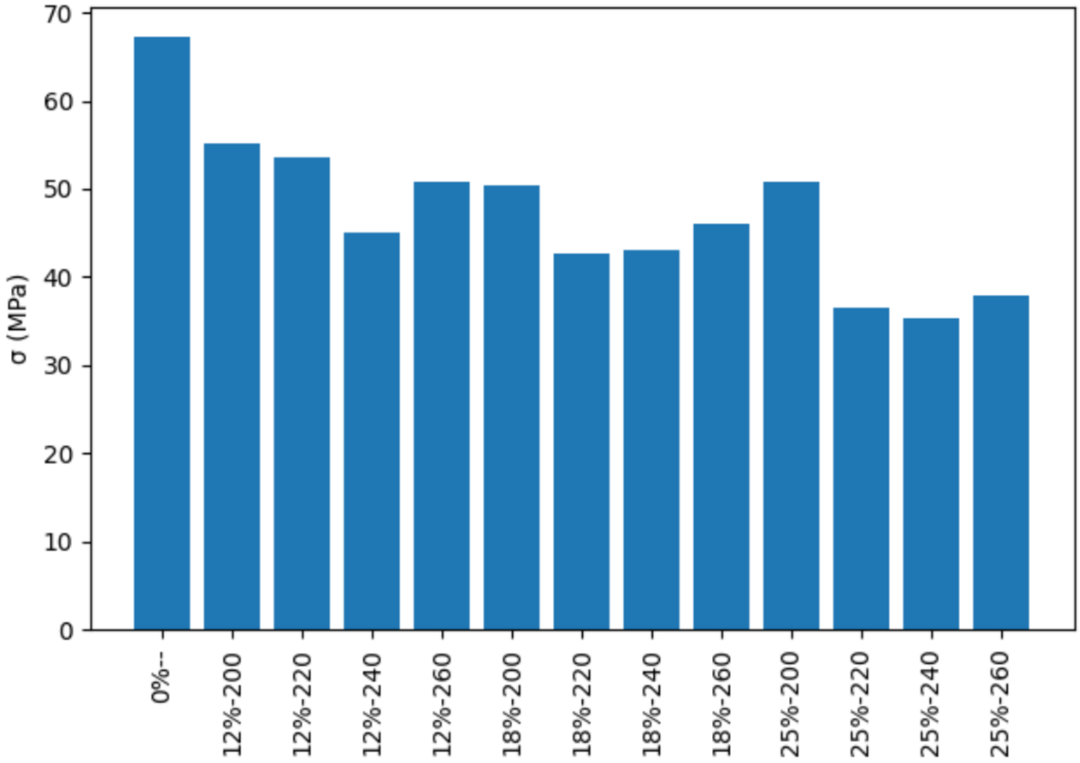

Figure 8 Comparison of maximum tensile stress (σ, MPa) of foamed PLA filaments printed at different CFA contents and temperatures.

Figure 8 illustrates the comparison of the maximum tensile stress (σ, MPa) of all samples that were processed at various contents of CFA and printing temperatures. Overall, adding CFA resulted in a reduction of the tensile strength of the samples compared to solid PLA, which can be interpreted by taking into account the higher porosity of the samples created by the foaming process [12,20].

In all CFA concentrations, a reduction in the tensile strength of the CFA-based foam was found with the increase of the printing temperature from 200°C to 240°C. That trend corresponds to the density reduction found in Figure 8, where a higher level of foaming at intermediate temperatures increased the porosity of the porous network. The reduction in density and development of the cellular structure reduced the mechanical resistance of the foam against the tensile load.

Among the foamed samples, those containing 12 wt.% CFA printed between 200-220 °C showed relatively higher values of tensile strength compared to other samples containing higher amounts of CFA. This showed that to a certain extent, foaming allowed a certain degree of retention of continuity of the matrix, thereby leading to better stress distribution in the matrix. Samples containing 25 wt.% of CFA, especially those that were printed at higher temperatures, had lower values of tensile strength [12,20].

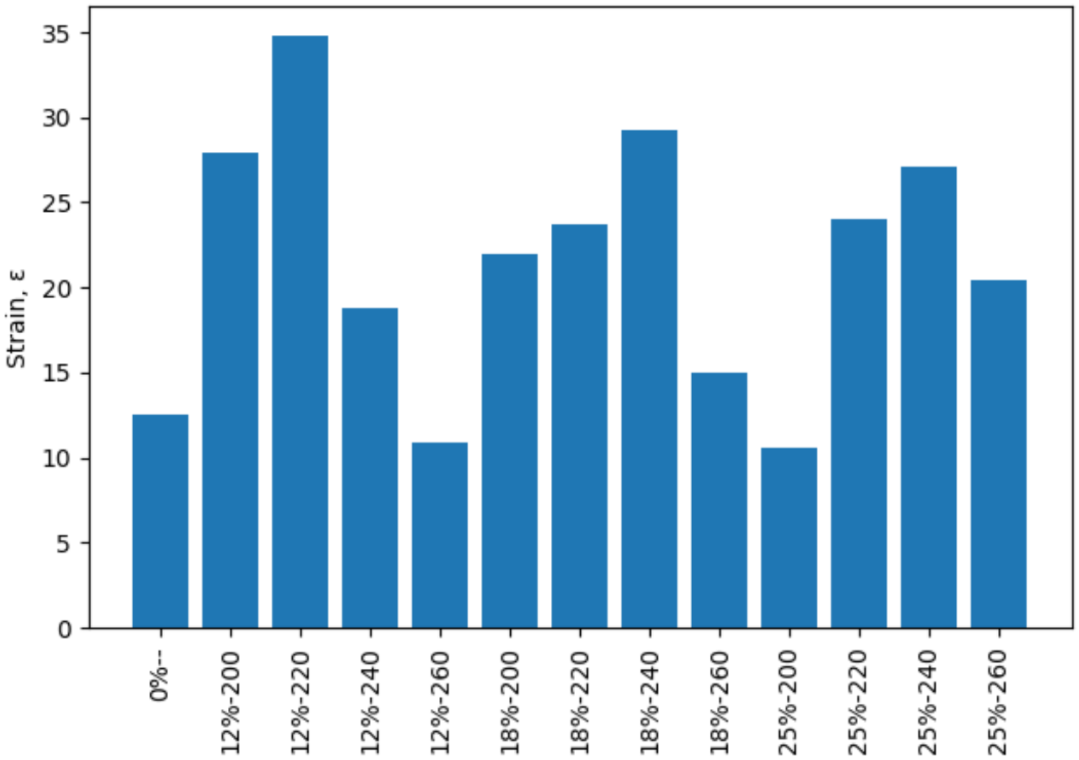

Figure 9 Maximum tensile strain (ε) values of PLA foams as a function of CFA content and printing temperature.

Figure 9 shows the maximum tensile strain (ε) values obtained from the tensile tests. Unlike tensile strength, the strain at break demonstrated an opposite trend with respect to CFA content and printing temperature.

The tensile strain was seen to increase when the content of CFA increased and when the printing temperature got closer to the optimal foaming temperature (220-240 °C). The highest strain was obtained when the 12wt% of CFA was printed at 220 °C (ε = 34.77), revealing the substantial enhancement in ductility. The strain can be largely associated with the development of a homogeneous and stable cellular structure at an intermediate level of porosity, according to the findings obtained from the density and SEM analyses presented in the foregoing discussion [12,20].

In samples containing 18 wt% CFA, there was improved ductility at 220-240°C, which can again be related to the greater capacity of the foam structure to deform under tensile loading by cell wall flexibility and cell collapse mechanisms. However, at higher temperatures (250-260°C), there was a definite reduction in tensile strain in samples containing all concentrations of CFA. This correlates well with the small increase in density and the reduction in porosity measured at higher temperatures, which indicates a certain cell collapse or gas release during the process of extrusion [16,20].

A combination of density, porosity, and tensile strength data clearly reveals that a trade-off between tensile strength and ductility exists for foamed PLA materials. From figures 4, 7, and 8, lower density with higher porosity is preferable for higher tensile strain values but at the cost of tensile strength [12].

The results illustrate that at an intermediate printing temperature of around 220-240 °C, there was a good gas formation cell stabilization and polymer melt strength such that an optimal cell structure was formed. This ensured improved plasticity without a pronounced degradation of tensile strength, especially when samples containing 12-18 wt% CFA. Conversely, the presence of a large amount of CFA and high temperatures encouraged an unstable cell formation that yielded poor mechanical properties [16,20].

4. Discussion and Conclusion

In this study, the influence of the chemical foaming agent content and the extrusion temperature applied during the FDM method on density, structural characteristics, and tensile properties of PLA-based foamed filaments was largely investigated, with the results clearly showing the importance of these characteristics to the bubble development process.

It was identified that an optimum processing window exists between 230 and 240°C where adequate gas evolution and cell growth were obtained without compromising melt strength significantly. Within this window, a balanced cell structure with moderate level porosity was obtained to afford an effective compromise between weight loss and integrity. Although weight loss was further enhanced by increasing the level of CFA because of increased porosity and density reductions, excessive foam evolution resulted in cell coalescence and wall thinning..

These findings have verified that the optimal mechanical properties are not necessarily achieved at levels of maximum porosity but within a regime where homogeneity is maintained. Nevertheless, the porous structure remains a unique advantage with great potential as a lightweight material while still allowing for good tensile properties.

In summary, thus, it is found that while considering the tensile properties of these foamed PLA filaments, certain extrusion parameter conditions govern this phenomenon based not only on stability but also homogeneity, as far as the cellular structure is concerned, to achieve a particular level of mechanical properties within a given window rather than keeping it a function of foam expansion, as excessive porosity is associated with a reduction in mechanical properties by creating a particular type of cell coalescence; however, porosity is one feature that provides a significant advantage with respect to weight reduction.

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Declarations:

1. Statement of Originality:

This work is original.

2. Author Contributions:

Concept: ÖBY; ***Conceptualization:*** ÖBY; ***Literature Search:*** ÖBY; ***Data Collection:*** ÖBY; ***Data Processing:*** ÖBY; ***Analysis:*** ÖBY; ***Writing – original draft:*** ÖBY; ***Writing – review & editing:*** ÖBY.

3. Ethics approval:

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5. Competing Interests:

The author declares no competing interests.

6. GenAI Usage Statement:

AI tools (such as ChatGPT) were used only for language editing and improvement. The authors take full responsibility for the content.

7. Sustainable Development Goals:

☐ 1 NO POVERTY	☐ 2 ZERO HUNGER	☐ 3 GOOD HEALTH AND WELL-BEING	☐ 4 QUALITY EDUCATION	☐ 5 GENDER EQUALITY	☐ 6 CLEAN WATER AND SANITATION	☐ 7 AFFORDABLE AND CLEAN ENERGY
☐ 8 DECENT WORK AND ECONOMIC GROWTH	☒ 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	☐ 10 REDUCED INEQUALITIES	☐ 11 SUSTAINABLE CITIES AND COMMUNITIES	☐ 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	☐ 13 CLIMATE ACTION	☐ 14 LIFE BELOW WATER
☐ 15 LIFE ON LAND	☐ 16 PEACE AND JUSTICE STRONG INSTITUTIONS	☐ 17 PARTNERSHIPS FOR THE GOALS	THE GLOBAL GOALS For Sustainable Development			

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