Study of compressive strength and water absorption in 3D printed PLA scaffolds for bone regeneration

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Abstract: This work investigates the use of polylactic acid (PLA) scaffolds manufactured by 3D printing (FDM) for bone tissue engineering, in order to overcome the limitations of treatments for bone defects. The aim was to evaluate the influence of different extrusion temperatures (180°C and 200°C) and filling rates (40%, 60% and 80%) on the water absorption and compressive strength of the structures. For this purpose, PLA scaffolds were printed and subjected to water absorption (ASTM D570) and compressive strength tests (ASTM D695-10). The results showed a clear inverse correlation between the properties: increasing the filler increased the mechanical strength but reduced the water absorption capacity. Scaffolds with 40% filler showed the highest absorption (up to 90.48%), while those with 80% exhibited the highest strength and lowest absorption (10.69%). The temperature of 200°C promoted a slight increase in mechanical strength due to better fusion between the layers. It is concluded that adjusting the printing parameters allows the properties of scaffolds to be modulated, balancing mechanical support and functional porosity to optimize performance in specific biomedical applications.
Keywords: Tissue engineering. Bone regeneration. Scaffolds. FDM.
Abbreviations: (PLA), Polylactic acid. (FDM), Fused Filament Deposition. (Ww), Wet sample. (Wd), Dry sample. (ASTM), American Society for Testing and Materials.

1.Introduction

The high incidence of bone defects caused by infections, tumors and bone loss due to trauma, which significantly affect patients' quality of life and impact society as a whole, means that bone tissue is more commonly used for transplantation and treatment of bone defects worldwide [1]. This tissue is metabolically active and, depending on the defect, is capable of selfhealing without surgical intervention [2], as it is made up of collagen, the mineral hydroxyapatite, a mixed organic component (type 1 collagen, lipids and non-collagenous proteins) and water [1-3], [4]. However, studies show that larger bone defects require invasive surgical intervention to aid the healing process. To overcome these challenges, tissue engineering has advanced in studies aimed at developing scaffolds produced from biomaterials by 3D printing, with the aim of helping to regenerate bone tissue [2-5]. Tissue engineering depends on understanding the biological mechanisms that regulate cell proliferation and differentiation, and the use of scaffolds is fundamental for providing structural and functional support to cells in this process. Conventional scaffold manufacturing techniques have limitations in terms of the precision of pore size and geometry, as well as interconnectivity and mechanical strength. 3D printing has emerged as a promising technique, enabling the production of complex biomimetic structures with high precision. Advanced 3D printing strategies make it possible to manufacture platforms ranging from the millimeter to the nanometer scale, although production time increases as the complexity of the project grows. 3D structures can be created, called scaffolds, capable of mimicking the extracellular matrix, promoting an ideal microenvironment for cell adhesion, proliferation and differentiation, with the potential to form functional tissues [4-5]. The ideal scaffold for bone fracture recovery must be produced from a bioactive, biodegradable, biocompatible biomaterial with adequate mechanical strength for the implantation site and osteogenic potential. One of the successful polymers to meet these properties is the use of polylactic acid (PLA). PLA is a thermoplastic, biocompatible and biodegradable biopolymer, widely used in biomedical applications for tissue regeneration and controlled drug release. It also has low elasticity and high tensile strength. However, it is hydrophobic, non-bioactive and has a low degradation rate [1-3]. The main objective of this research is to present a study on the use of PLA in the manufacture of scaffolds by 3D printing, intended for application in injured or fractured bone tissue, using two melting temperatures (180 °C and 200 °C) in order to evaluate the influence on the formation of the scaffolds and three filling rates (40, 60 and 80%) in order to study the influence on the rate of water absorption and compressive strength.

2. Methodology

For the production of the scaffolds, we used polylactic acid (PLA) filament, purchased from 3D Slim Tecnologia Comercio De Equipamen, with a density of 1.24 g/cm3 , a melting temperature of 185 °C and a glass transition temperature (Tg) of 60 °C.

2.1 Scaffolds design and printing

The scaffolds were designed using 3D modeling software (CAD) with dimensions of 10×10 mm. The internal filling pattern selected was zigzag. The model file was then exported in STL format and processed in Ultimaker Cura slicing software. The specimens were additively manufactured on a Creality CR-10 3D printer using the Fusion Deposition Modeling (FDM) technique. During printing, the table temperature was kept constant at 50 °C and the printing speed was set at 50.0 mm/s. Two nozzle extrusion temperatures were tested, 180 °C and 200 °C, and three different fill rates: 40%, 60% and 80%.

2.2. Water absorption test

The water absorption test was carried out in triplicate for each group of samples according to ASTM D570. The specimens were immersed in water at a temperature of 24 °C for a period of 48 hours. The absorption capacity was calculated as the ratio of the difference between the weight of the wet sample (Ww) and the weight of the dry sample (Wd), and the weight of the wet sample, shown in equation 1.

$$Water\ absorption\ (\%) = \frac{W_w - W_d}{W_w} \times 100\% \quad (1)$$

2.3. Compression resistance test

The mechanical properties of the scaffolds were assessed using compression tests in accordance with ASTM D695-10. The tests were carried out on an EMIC universal testing machine, model DL10000, equipped with a 10 kN load cell. The load application speed during the test was 1.0 mm/min. The results were analyzed in order to correlate the maximum stress withstood and the relative deformation with the different printing parameters (temperature and filling percentage).

3. Results and Discussion

3.1. Scaffolds printing

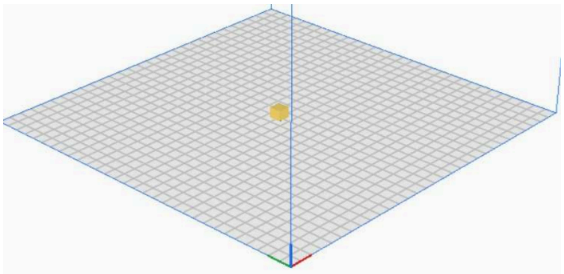
The three-dimensional images generated in the slicing software allowed a detailed spatial analysis of the geometry designed in all directions and planes. The qualitative evaluation indicated that the spatial architecture modeled for the samples was reproduced with high fidelity during most of the manufacturing process. However, it was observed that the upper layers tended to "close" the pores. To guarantee the functionality of the scaffold, which depends on a porous and interconnected structure, the printing process was intentionally interrupted when it reached between 90% and 94% of its completion, thus preserving the desired architecture.

Figure 1. printer producing the specimens (a), image of the Ultimaker Cura during slicing (b), the parts with 40%, 60% and 80% printed at .180°C (c) and 200°C (d)

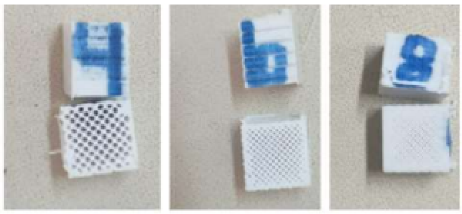
a)

ISSN: 2357-7592
XI INTERNATIONAL SYMPOSIUM ON INNOVATION AND TECHNOLOGY
Quantum Technologies: The information revolution that will change the future - 2025

b)



d)



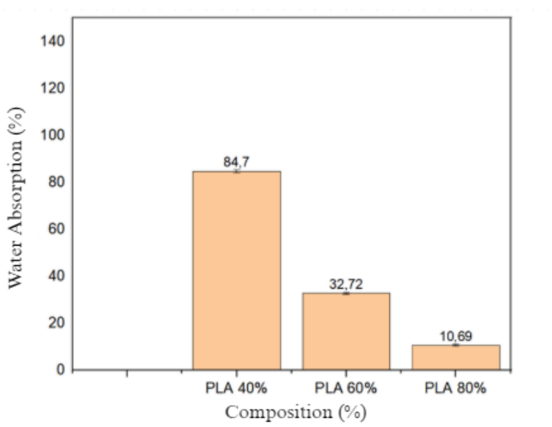
c)

3.2. Water absorption tests

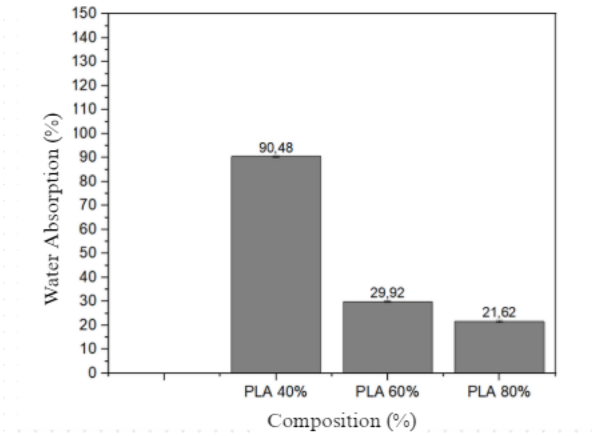
The water absorption test is essential for assessing a scaffold's potential to interact with the biological environment, influencing cell adhesion and nutrient transportation. Figure 2 shows the results of this test, graphically illustrating how varying the percentage of filler and the printing temperature impacted on the water retention capacity of PLA scaffolds.

Figure 2. : Percentage of water absorption of scaffolds printed at: (a) 180° C and (b) 200° C.

a)



b)



Analysis of the water absorption tests showed a inverse correlation between the percentage of filling and the water absorption capacity. The scaffolds with 40% filling, the lowest density tested, had the highest average water absorption values, registering $84.7 \pm 0,59\%$ for the 180°C temperature and $90.48 \pm 0,41\%$ for 200°C. This behaviour is to be expected, since a lower fill density results in greater internal porosity and a more significant volume of interconnected voids, maximizing the surface area available for interaction with water and, consequently, its retention. As the filling percentage increases to 60% and 80%, water absorption progressively decreases, as evidenced by the values of $32.72 \pm 0,46\%$and $10.69 \pm 0,34\%$ and $29.92 \pm 0,35\%$and $21.62 \pm 0,48\%$, at 180°C and 200°C, respectively. The increase in material density creates more compact structures, with a smaller pore volume and less accessibility to water penetration, which naturally restricts capillarity and reduces water retention capacity. The influence of printing temperature was also observed, as scaffolds printed at 200°C generally showed slightly different absorption than those produced at 180°C. This can be attributed to better cohesion and fusion between the layers at higher temperatures, which can alter the surface roughness and internal morphology of the pores, influencing the interaction with water. Just as fill density has been shown to be a determining factor for mechanical properties [6-7], it is clear that this same structural parameter dictates physical properties, such as fluid absorption.

3.3. Compressive strength test

Figures 3 and 4 show the test being carried out on the scaffolds and the visual aspect after the test, allowing a qualitative analysis of the deformation and failure mode of the structure, which complements the quantitative stress and strain data.

Figure 3. Compressive strength test of scaffolds.

Figure 4. Samples after the compression test: (a) 180 °C e (b) 200 °C.

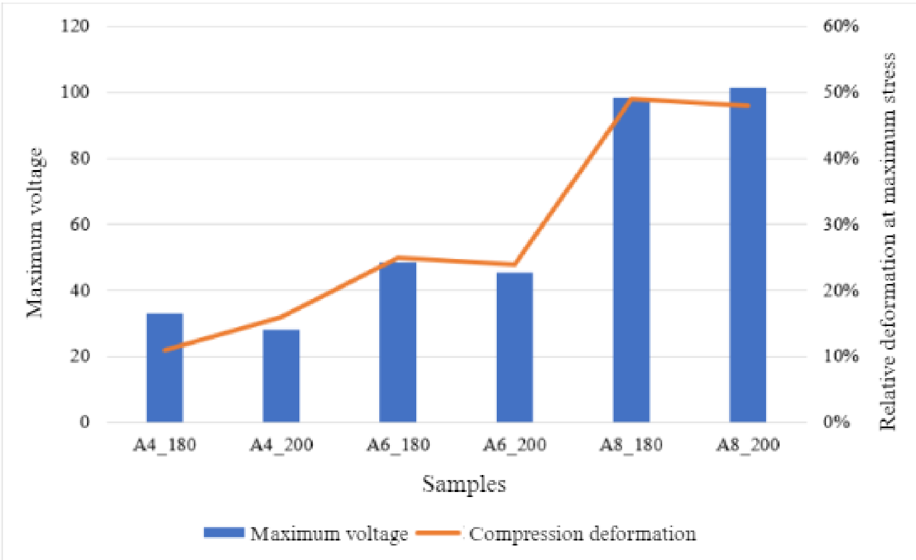
a)

b)

The results obtained showed that the compressive strength of PLA scaffolds increased significantly with the increase in the percentage of filler, ranging from 40% to 80%, as pointed out by works such as Dave et al.

(2019) [6] and Silva et al. (2019) [7], the density of filler is one of the most influential parameters in the mechanical behavior of parts manufactured by FDM. A higher percentage of filler results in a more solid internal structure with a smaller volume of voids, giving greater rigidity and, consequently, a greater capacity to withstand compressive loads [8-9].

Figure 5. Comparative graph of the compression test results for PLA scaffolds. The bars represent the Maximum Stress supported by each specimen, while the line indicates the Relative Deformation at Maximum Stress. The nomenclature of the samples on the horizontal axis specifies the percentage of fill (A4 = 40%, A6 = 60%, and A8 = 80%) and the printing temperature (180°C or 200°C).



Analysis of the compression test graph (Figure 5) shows that the maximum stress values increased progressively as the fill went from 40% to 80%. For the samples printed at 200°C, the maximum stress was noticeably higher in the parts with 80% fill compared to those with 40% and 60%. This behavior is crucial for bone tissue engineering, where scaffolds must offer mechanical support similar to bone tissue in order for there to be adequate cell regeneration. The ability to modulate mechanical strength by adjusting the filler, as demonstrated, is essential for mimicking the properties of specific tissues, such as trabecular bone, as discussed by Baptista and Guedes (2021) [10]. The influence of printing temperature, a critical parameter in additive manufacturing, proved to be complex. The data obtained suggests that the extrusion temperature of 200°C favored the integrity of the layers, resulting in slightly higher mechanical strength values compared to 180°C. This phenomenon is attributed to better fusion between the filaments, which reduces voids and improves adhesion between the layers, a behavior validated by Baptista and Guedes (2021) [10] in their studies. However, the same authors warn that excessively high temperatures can compromise the dimensional accuracy of the part, which reinforces the observation that this parameter must be strictly controlled to guarantee both the mechanical stability and geometric fidelity of the scaffold. It is important to note the inverse correlation observed between the compression and water absorption results. The data shows that the scaffolds with the lowest filling (40%), which had the lowest compressive strength, were the ones with the highest water absorption capacity (up to 90.48% at 200°C). On the other hand, the scaffolds with 80% filling, which withstood the highest compressive stress, showed the lowest rate of water absorption (10.69% at 180°C). This inverse relationship is a direct consequence of the microarchitecture of the scaffolds, which is dictated by the percentage of filling. A structure with high porosity (low filling) has a large volume of interconnected voids, which facilitates the penetration and retention of fluids, but at the same time represents a structural discontinuity that reduces the ability to withstand mechanical loads. Conversely, a dense structure (high fill) offers greater integrity and cross-sectional area to resist compression, but has fewer pores available for water absorption. Applications that require high load-bearing may need denser scaffolds, while applications that prioritize maximum cell-material interaction and nutrient transport may benefit from greater porosity, albeit with lower mechanical strength. The ability to modulate this balance by adjusting printing parameters, such as filling, is one of the main findings of this work and is in line with the literature exploring the customization of scaffolds for biomedical purposes [7],[9-10].

4. Conclusion

Based on the results, it can be concluded that the filling percentage of scaffolds has an inverse influence on water absorption and compressive strength. Structures with less filling (40%) showed greater porosity and, consequently, greater water absorption, but lower mechanical strength. On the other hand, denser scaffolds (80%) had lower absorption capacity and higher compressive strength. The printing temperature also affected performance, with 200 °C favoring a slight increase in mechanical strength. These findings reinforce the importance of adjusting the filler and printing temperature to balance mechanical and absorption properties, according to the specific demands of biomedical applications.

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