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EVALUATING THE PLA AGING EFFECTS ON THE MECHANICAL PERFORMANCE OF 3D-PRINTED COMPONENTS

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The aging influence on the mechanical performance of bio-degradable polymers holds significant importance in additive manufacturing, particularly in structural applications. Understanding the changes in mechanical properties over time is crucial for ensuring the long-term sustainability and reliability of polymer-based structures. Thus, this study aims to comprehensively evaluate the effects of aging on polylactic acid (PLA) by analyzing its failure mechanisms of 3D-printed samples subjected to compression load. To achieve this goal, specimens of PLA were exposed to natural environmental conditions for varying periods. Subsequently, the mechanical characteristics of the additively produced component were assessed after each exposure, providing valuable insights into its performance at different stages of aging. By quantifying the material's ability to withstand applied forces, the study enables the prediction of its long-term structural integrity. In addition, the investigation of failure mechanisms aids in understanding the modes of failure that PLA may undergo as it ages. This knowledge is essential for developing strategies to prevent structural failures and enhance the overall reliability of PLA-based applications. The findings contribute to advancing the field of additive manufacturing, enabling PLA's sustainable and reliable application in various industries.

Keywords: Polylactic acid, Aging procedure, Strain, Additive manufacturing.

1 INTRODUCTION

Additive Manufacturing (AM), colloquially known as three-dimensional (3D) printing, has emerged as a transformative technology with widespread applications across various industries such as aerospace, electronics, automotive, healthcare monitoring, and construction (Kong *et al.* 2019, Li *et al.* 2020, Khosravani *et al.* 2020a). The versatility and adaptability of AM have fueled extensive research into its engineering aspects, leading to significant advancements and innovations in the field (Chen *et al.* 2019, Khosravani *et al.* 2020b, Gribniak *et al.* 2022, Rimkus *et al.* 2022). Mechanical components produced through AM technologies are crucial in numerous applications and are subject to various loading conditions. Understanding the fracture behavior of these components is essential for ensuring their reliability and performance (Shkundalova *et al.* 2018, Russ *et al.* 2020, Somireddy *et al.* 2020). Consequently, extensive studies have been conducted to characterize the fracture mechanics of 3D-printed structural components using experimental techniques and numerical methods (Aliheidari *et al.* 2017, Tkac *et al.* 2020).

Polylactic acid (PLA) stands out among the polymers commonly used in fused deposition modeling (FDM) 3D printing due to its minimal warping issues, biodegradability, and ease of use. However, despite its favorable properties, PLA-based 3D-printed parts often exhibit inferior mechanical properties compared to those fabricated using conventional processes like injection molding and compression molding. Environmental exposure, such as sunlight, heat, and atmospheric agents, can induce natural aging processes that deteriorate materials' physical and chemical characteristics over time. Numerous studies have investigated the effects of temperature, moisture, UV exposure, impurities, and catalysts on the degradation of PLA (Mitchell *et al.* 2015, Karamanlıoğlu *et al.* 2019). Understanding how aging affects the mechanical properties of 3D-printed components is crucial for predicting their long-term performance and structural integrity under real-world conditions.

Structural components are exposed to various loads and environmental conditions, leading to changes in strength and stiffness over time. Despite the significant potential of 3D printing, there remains a gap in understanding the effects of aging on the mechanical behavior of 3D-printed parts. This study aims to address this gap by evaluating the influence of aging on the mechanical performance of 3D-printed PLA components.

2 EXPERIMENTAL SETUP AND AGING PROCEDURE

The specimens were produced from PLA using the FDM additive manufacturing method. The selection of sample type and geometry was guided by prior research (Gribniak *et al.* 2022) on the local stability of aluminum profiles incorporating low-modulus stiffeners. Ten polymeric prisms were included in the experimental program. Each specimen measured 10 mm in thickness, 40 mm in height, and 40 mm in width. Fig. 1c illustrates the cross-section of the specimen.

For printing, a *Prusa i3 MK3* printer (Fig. 1a) was utilized, maintaining consistent parameters: extrusion nozzle temperature set to 215 °C, printing bed temperature at 60 °C, and print speed at 28 mm/s. *Prusament* PLA filament with a density of 1240 kg/m3 and a diameter of 1.75 mm was used. Mechanical properties of the PLA were determined in previous studies (Shkundalova *et al.* 2018, Gribniak *et al.* 2023) as follows: yield strength f_y = 42.1 MPa, modulus of elasticity E_p = 2.21 GPa, ultimate strain ε_u = 4.35%.

Before printing, the PLA filament dried for 6 hours at 50 °C using the dryer depicted in Fig. 1b. This process aimed to enhance printing quality and mitigate the adverse effects of moisture, such as bubbling, popping, or inconsistent extrusion, which could compromise surface finish and structural integrity. The specimens were printed horizontally (Fig. 1c), with each printing layer having a thickness of 0.2 mm. Two continuous 'shells' with 100% density were printed around the perimeter of each specimen. The inner part of the samples was constructed with a rectilinear raster orientation inclined at 45°, a common practice for prototyping purposes.

The age of the printed specimens was a variable in this study. The results presented in this manuscript encompass two series of specimens aged 2 and 200 days. Five specimens were tested after 2 days of production, and another set of five specimens were tested after 200 days. The latter test specimens were maintained under controlled laboratory conditions, with an average temperature of 20 °C and a relative humidity of 50%.

A compression test was employed to determine the deformation behavior, focusing on understanding the failure mechanism. These tests were conducted using a 75 kN electromechanical machine, the H75KS (Tinius Olsen, Norway), operating under displacement control at a rate of 0.25 mm/min. Vertical displacements were measured using linear variable displacement transducers (LVDT) with a precision of 0.001 mm, while an applied load of up to

50 kN was constantly monitored using a load cell. The tests continued until failure, with the setup shown in Fig. 2a.

To monitor deformations on both the front and back surfaces of the specimens, the digital image correlation (DIC) technique was employed. High-contrast random patterns were applied to the monitoring surfaces using spray paint, as Fig. 2b shows. Digital images were then captured using a *Canon EOS 77D SLR* camera equipped with an 18–135 mm *Canon EF-S* lens, mounted on a tripod 0.4 m from the monitored surface. These high-resolution images, sized at 6000 × 4000 pixels, were captured at load increments of 0.25 kN, with camera settings including an exposure time of 1/200 s, an aperture of f/4.5, ISO sensitivity set to 100, and a focal length of 24 mm. A remote-control device was utilized to prevent any unexpected movements.

The relative strain distribution maps were determined by utilizing *GOM Correlate* software, aiding in the analysis of deformation monitoring results, as exemplified in Fig. 3. Notably, the observed uniform distribution of strains is a characteristic feature of compressive samples until the ultimate load capacity is reached. Furthermore, the relationship between load and vertical displacement is shown in Fig. 4, while Fig. 5 demonstrates the various failure modes observed during testing.

Fig. 1. Additive production: a) 3D printer, b) filament dryer, c) cross-section of the specimens.

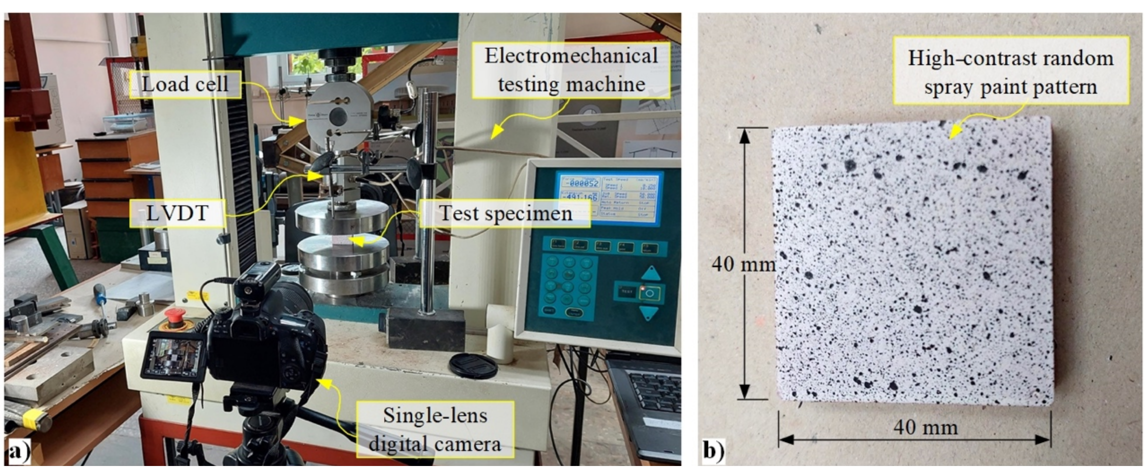

Fig. 2. Experimental setup: a) loading scheme of the compression test, b) specimen cross-section.

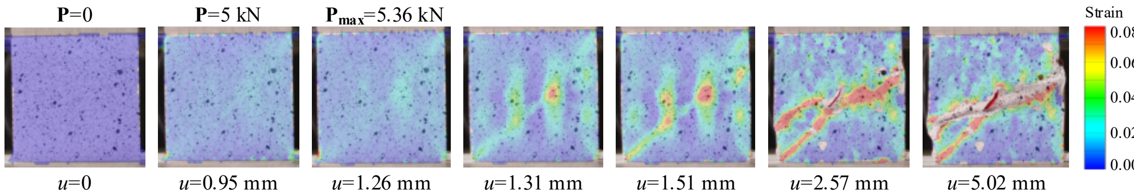

Fig. 3. Strain distribution maps of the specimen *N2*.

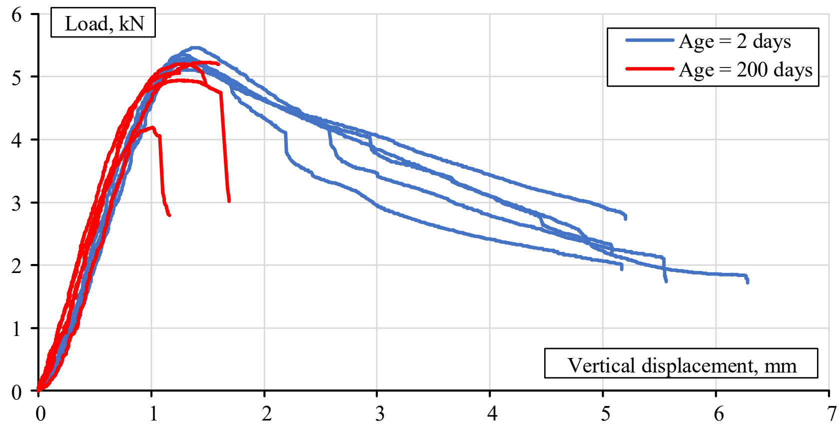

Fig. 4. Load and vertical displacement relationship of tested specimens.

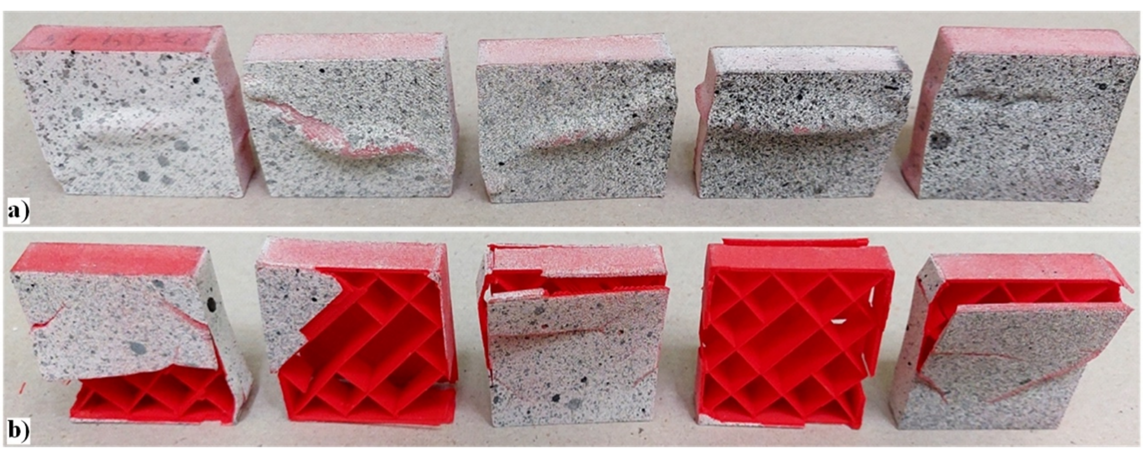

Fig. 5. Failure modes of specimens tested after a) 2 days and b) 200 days after specimen production.

3 MECHANICAL PERFORMANCE

The conducted compression test aimed to evaluate the specimens' deformation behavior and failure mechanism. Table 1 presents an overview of the test results, highlighting key parameters such as load-bearing capacity (**P**), the corresponding vertical displacements (u), and ultimate vertical displacement (u_{lim}). These results suggest that the duration of exposure did not notably affect the load-bearing capacity of the specimens, implying that the material's ability to carry loads remained relatively consistent regardless of the sample age. For instance, the average load-bearing capacity was 5.3 kN for specimens tested after 2 days and 4.93 kN for those tested after

200 days, indicating minimal variation; still, the aging raised scatter of the results (compare the standard deviation values of 0.13 and 0.43). However, the crucial aspect impacted by exposure duration was the ductility of the specimens. Ductility refers to the material's ability to undergo significant deformation before failure. The study revealed a substantial decrease in ductility for specimens exposed to longer durations. Specifically, the vertical displacement values decreased nearly fourfold, from 5.46 mm to 1.44 mm, indicating a significant reduction in the material's ability to deform before failure.

Fig. 5 makes apparent the ductility increase after 200 days of aging. These samples exhibited brittle failure, proclaiming a sudden and catastrophic failure without significant deformation. In contrast, specimens aged 2 days displayed viscoelastic behavior, suggesting a more gradual deformation process before failure. These distinct failure modes highlight the influence of exposure duration on the material's mechanical properties and failure behavior.

Fig. 6 provides additional insights into the deformation evolution of characteristic specimens using the DIC technology, which enables precise measurement and visualization of surface deformations, allowing the evolution of deformation patterns to be tracked over the performed test. The images associated with vertical displacement (*u*) reveal how the specimens deform under applied loads after 2 and 200 days of production.

Table 1. Load bearing capacity and corresponding vertical displacement of the test specimens.

Age, days	**P, kN**					***u*, mm**					**u_{lim}, mm**				
2	5.35	5.36	5.46	5.29	5.12	1.29	1.27	1.35	1.28	1.30	5.08	5.16	5.56	6.28	5.20
	5.32 ± 0.13 (*)					1.30 ± 0.03 (*)					5.46 ± 0.50 (*)				
200	5.21	5.07	4.19	5.23	4.94	1.29	1.24	1.01	1.43	1.22	1.48	1.25	1.16	1.59	1.69
	4.93 ± 0.43 (*)					1.24 ± 0.15 (*)					1.44 ± 0.23 (*)				

(*) Mean ± standard deviation.

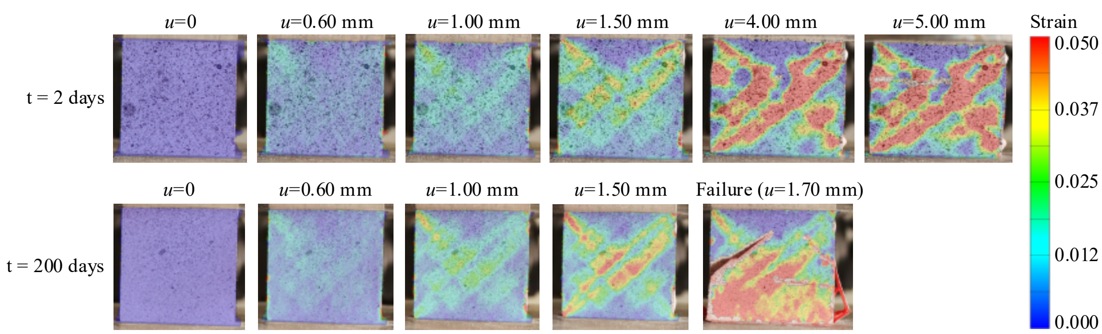

Fig. 6. Strain distribution maps of the characteristic specimens after 2 and 200 days of production.

4 CONCLUSIONS

This study evaluated the mechanical performance of PLA-based 3D-printed components under varying aging conditions. The effects of aging on load-bearing capacity, ductility, and failure modes were investigated through compression testing and analysis of failure mechanisms.

The results indicate that the load-bearing capacity of PLA specimens remained consistent over time. However, there was a significant decrease in ductility with time. Specimens aged for 200 days exhibited brittle failure, contrasting with the more gradual deformation observed in specimens tested at 2 days. These findings highlight the importance of understanding the aging effects on PLA's mechanical behavior for predicting long-term structural integrity. The digital image correlation (DIC) technique provided valuable insights into specimen deformation evolution, further enhancing understanding of PLA's mechanical response to aging.

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