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EXPLORING THE IMPACT OF ULTRAVIOLET RADIATION ON THE MECHANICAL PROPERTIES OF 3D-PRINTED PLA COMPONENTS

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ABSTRACT
In regions where sunlight is prevalent, ultraviolet (UV) radiation can negatively affect materials, especially polymers. As the use of 3D printing for part production grows, understanding how prolonged UV exposure impacts polymer-based products like polylactic acid (PLA) becomes crucial. This research investigates how UV radiation alters the mechanical characteristics of 3D-printed PLA. Specifically, it examines how different exposure durations influence properties such as tensile strength, flexural strength, and impact resistance. The study exposes twenty PLA samples to varying UV exposure times (one, two, and three weeks) and compares them to unexposed control samples. Through extrusion processes, the samples underwent UV exposure to simulate real-world conditions, revealing significant changes in mechanical properties. While most polymers showed reduced strength after UV exposure, PLA demonstrated a surprising increase in durability. The mechanical testing outcomes highlighted an improvement in strength for UV-exposed PLA compared to non-exposed ones, suggesting the material's potential to withstand UV-induced degradation.

INTRODUCTION
Additive Manufacturing and/or 3D printing, has revolutionized production across various sectors by offering unparalleled customization and flexibility compared to traditional manufacturing (Pandžić et al., 2023). This technology enables the construction of complex geometries without requiring costly tooling, making it vital in fields such as aerospace, healthcare, and construction (Gao et al., 2015). However, environmental factors, especially UV radiation, present challenges to the mechanical stability of 3D-printed parts. While much research has been conducted on printing parameters, studies addressing environmental influences like UV exposure remain scarce (González-González & Alonso, 2018).
Emerging research on the accelerated aging of 3D-printed materials like PLA and other thermoplastics highlights UV exposure as a significant cause of mechanical degradation (Rafiee et al., 2020). Studies have shown that exposure to UV radiation weakens PLA parts, compromising their durability (Balakrishnan et al., 2017). Similarly, UV radiation has affected materials such as ABS and polycarbonate, which emphasizes the need to understand the UV-induced degradation mechanisms (Balakrishnan et al., 2017).
Recent research has explored aging treatments and UV pre-printing impacts on PLA filaments, revealing that UV exposure interacts intricately with printing orientation and raster angles (Kulkarni et al., 2023). This area warrants further investigation to optimize the printing processes for better material durability.

Background of study
Additive manufacturing originated in the 1980s with the advent of 3D printing techniques, which introduced layer-by-layer fabrication (Molitch-Hou, 2018). Over time, advancements like stereolithography (SLA) and selective laser sintering (SLS) expanded the applications of 3D printing, revolutionizing prototyping, small-batch production, and mass customization.
Currently, additive manufacturing is widely adopted across industries, offering sustainability, customization, and material efficiency. Automotive manufacturers utilize it for prototyping and

producing custom jigs, while the medical field employs 3D printing for patient-specific implants and prosthetics.

Recent Development

Recent progress in additive manufacturing (AM) has significantly boosted its adoption across various industries, unlocking new opportunities and expanding the scope of what can be achieved. Key advancements include: (Gibson et al., 2021a)

- **Development of Advanced Materials:** Researchers and industry professionals are concentrating on creating a broader range of materials suitable for AM. (Gibson et al., 2021b) These materials include high-performance polymers, metal alloys, ceramics, and composites with customized properties such as strength, flexibility, conductivity, and biocompatibility. These innovations enhance the performance characteristics of manufactured parts, thereby broadening the potential applications of AM in different sectors (Gibson et al., 2021c).
- **Multi-Material Printing:** Advances in multi-material printing now enable the production of complex structures featuring varied material properties in a single process. This innovation allows for the creation of functional prototypes, customized products, and composite parts with smooth transitions between different materials. Multi-material printing increases design flexibility, facilitating the integration of multiple functions into a single component, and driving innovation in product development and engineering (Gibson et al., 2021c).
- **High-Speed Printing Technologies:** Improvements in printing speed and throughput have greatly enhanced the efficiency and scalability of additive manufacturing. Techniques like continuous liquid interface production (CLIP), selective laser melting (SLM), and binder jetting have shortened production times while maintaining high precision and quality. These advancements enable rapid prototyping, on-demand manufacturing, and mass customization, making AM more accessible and cost-efficient for industrial use (Kruth, Leu, and Nakagawa, 1998a).
- **Integration with Industry 4.0:** AM is increasingly being incorporated into Industry 4.0 ecosystems, using digitalization, automation, and connectivity to optimize manufacturing processes. (Kruth, Leu, and Nakagawa, 1998b) Technologies such as digital twins, real-time monitoring, and artificial intelligence (AI) algorithms enhance process control, quality assurance, and predictive maintenance within AM facilities. This integration boosts efficiency, productivity, and sustainability, promoting the adoption of AM in smart factories and digital supply chains.
- **Bioprinting and Tissue Engineering:** In biomedical engineering, bioprinting has made significant advances, allowing the creation of three-dimensional tissues, organs, and scaffolds for regenerative medicine and drug research. (Atala and Yoo, 2015) Researchers have developed bioinks containing living cells and biomaterials that replicate the native extracellular matrix, enabling precise control of tissue architecture and functionality. Bioprinting holds great promise for personalized medicine, organ transplantation, and in vitro disease modelling, revolutionizing healthcare, and patient care.

Challenges and Opportunities

While examining the impact of ultraviolet (UV) exposure on the mechanical properties of 3D-printed PLA parts is important, it represents just one facet of the broader challenges and opportunities facing additive manufacturing (AM) as a whole. Understanding and addressing these issues is key to advancing the field and unlocking its full potential across various industries (Francois et al., 2017).

- **Scalability:** One of the foremost challenges in AM is scaling production to meet the demands of mass manufacturing. Although 3D printing excels in flexibility for both design and production, achieving high-volume output with consistent quality remains a significant challenge. Recent innovations, such as large-scale additive manufacturing (LSAM) and continuous printing technologies, offer promising solutions for overcoming these scalability hurdles.

- **Quality Control:** Maintaining consistent quality and reliability in 3D-printed parts presents another major challenge. Variations in material properties, printing parameters, and post-processing methods can result in inconsistencies that impact the performance of the final product. To ensure high standards, it is critical to develop rigorous quality control processes, industry standards, and advanced monitoring techniques.
- **Regulatory Considerations:** As AM technologies gain wider adoption, regulatory frameworks and standards are becoming increasingly crucial for ensuring product safety, reliability, and compliance. Challenges in this area include navigating complex certification processes, addressing intellectual property issues, and adhering to industry-specific regulations. Collaboration between industry leaders, regulatory bodies, and standards organizations is necessary to establish clear guidelines for the implementation of AM technologies.
- **Integration with Existing Manufacturing Processes:** Incorporating AM into traditional manufacturing workflows presents both challenges and opportunities. While 3D printing offers benefits such as on-demand production, faster lead times, and greater design flexibility, integrating it with conventional processes requires addressing obstacles like material compatibility, workflow optimization, and workforce training. Hybrid manufacturing approaches and digital twinning technologies can help overcome these challenges, facilitating smoother integration and maximizing AM’s benefits.

Despite these challenges, additive manufacturing has demonstrated its transformative potential through a myriad of real-world applications. In healthcare, 3D printing is revolutionizing patient care by enabling the production of personalized implants, prosthetics, and surgical guides tailored to individual anatomy. For example, medical researchers have utilized AM to create custom implants for cranial reconstruction or orthopedic surgeries, improving patient outcomes and reducing surgical complications (Reddy K *et al.*, 2016).

Addressing the challenges and opportunities within the additive manufacturing landscape requires a comprehensive approach that combines technological innovation, regulatory collaboration, and strategic planning. By resolving issues related to scalability, improving quality control, navigating regulatory challenges, and integrating AM with traditional processes, the potential for AM to transform industries and foster innovation is immense. By viewing these challenges as opportunities for growth, the AM industry can advance and unlock new possibilities for future applications.

Aims and Hypotheses

The key goals of this research are:

1. To systematically assess the effect of UV exposure duration on the mechanical properties of 3D-printed PLA.
2. To quantify changes in tensile strength, flexural strength, and impact resistance under varying UV exposure times.
3. To uncover the mechanisms driving UV-induced degradation in PLA and propose strategies to mitigate its effects.

The primary objective is to understand how UV exposure alters PLA's mechanical properties, addressing how environmental conditions could impair the performance and durability of PLA in various applications.

Experimental Methodology

PLA samples were prepared for testing by following specific standards for tensile, flexural, and impact tests. These samples were produced using a Stratasys F170 3D printer, printed in the XY orientation with 100% infill density. The samples were divided into control and UV-exposed groups and subjected to UV radiation for one, two, and three weeks.

The UV-exposed samples were tested using an Instron 3367 testing device to measure tensile and flexural strength, following the ISO 527-2 and ISO 178 standards. A comprehensive analysis of the mechanical properties was conducted to evaluate changes in tensile strength, Young's Modulus, and elongation after exposure to UV radiation (See Table 1 & 2).

Property	**Test method**	**Typical value for XY (flat) specimen printing orientation** PC	PLA
Tensile strength	ASTM D3039 (5 mm/min)	53,3 MPa	52,5 MPa
Tensile elastic modulus	ASTM D3039 (1 mm/min)	2,39 GPa	3,25 GPa
Strain at brake	ASTM D3039 (5 mm/min)	6,1 %	7,8 %
Flexural strength	ISO 178 (5 mm/min)	89,4 MPa	96,8 MPa
Flexural modulus	ISO 178 (1 mm/min)	1,62 GPa	3,02 GPa
Flexural strain at brake	ISO 178 (5 mm/min)	No break (>10%)	4,8 %
Charpy impact strength (at 23 °C)	ISO 179-1/1eB (notched)	11,6 kJ/m^2	3,9 kJ/m^2
Hardness	ISO 7619-1 (Durometer, Shore D)	81 Shore D	84 Shore D
Tensile strength	ASTM D3039 (5 mm/min)	53,3 MPa	52,5 MPa
Tensile elastic modulus	ASTM D3039 (1 mm/min)	2,39 GPa	3,25 GPa

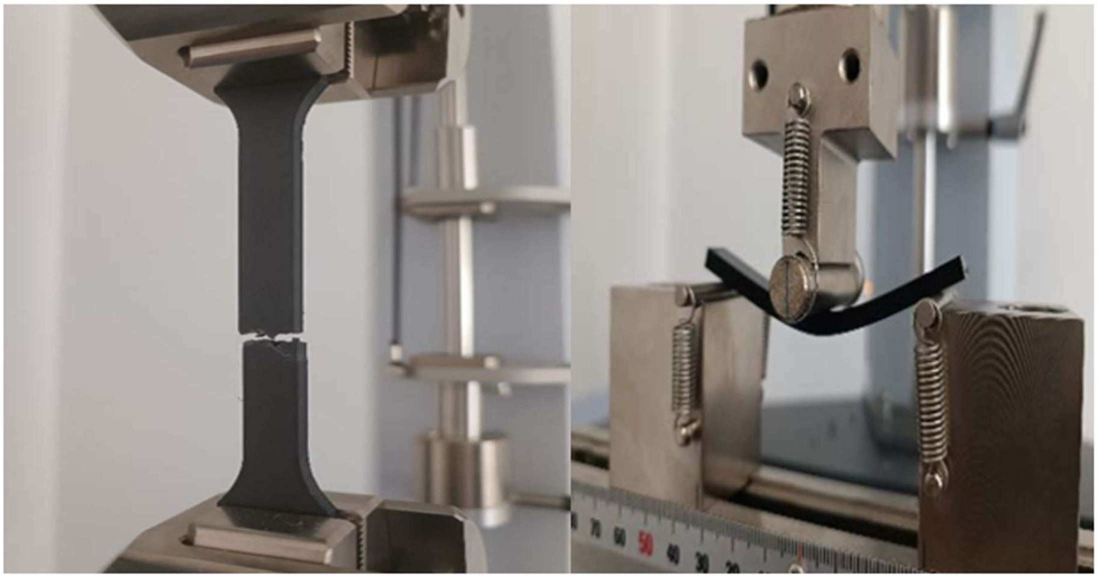
Table1. Mechanical properties PLA materials

Parameters	PLA material
Layer Height	0.15 mm
Printing Temperature	200 °C
Build Plate Temperature	60 °C
Print Speed	70 mm/s
Fan Speed	100%
Infill Densitv	100%

Table 2. FDM printing parameters for PLA

Figure 1.(a) Stratasys F170printer. Test specimen design; (b)visual presentation

The samples underwent tensile and bending tests in accordance with ISO 527-1 and ISO 187 standards, respectively, using an Instron 3367 testing machine (refer to Figures 3a and b) at a test speed of 5 mm/min. The results for both tensile and bending strength were recorded and processed using the Instron 3367 X software. The experimental data were then analyzed using t-tests to identify any differences between the control and treatment groups for each material.(Figure 2 & 3).



a) flexural strength *b) tensile strength*

Figure 2. Mechanical properties testing process.

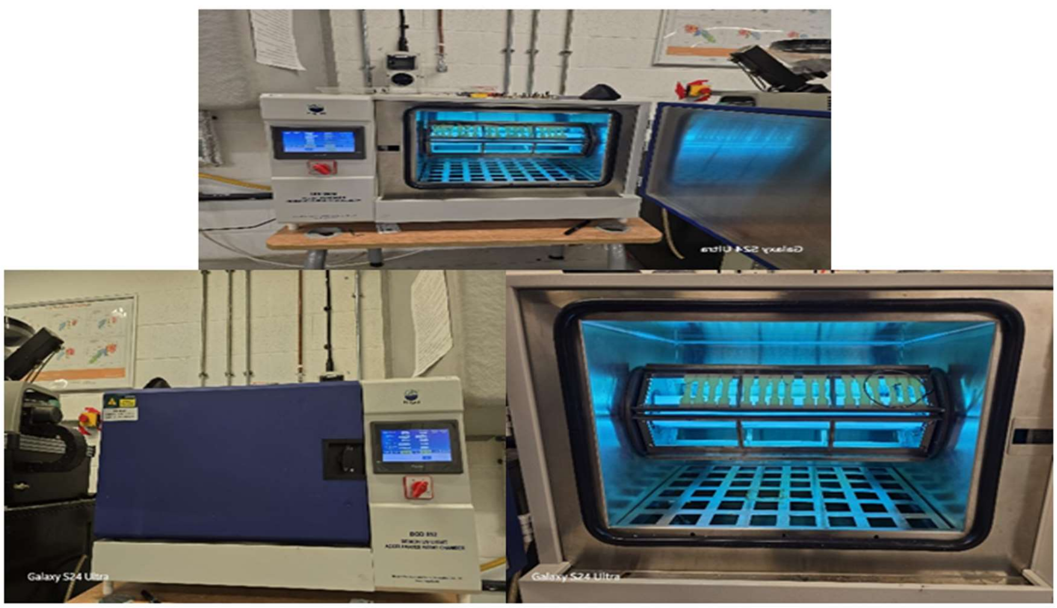


Fig 3. BGD 852 accelerated aging chamber

RESULTS AND DISCUSSION

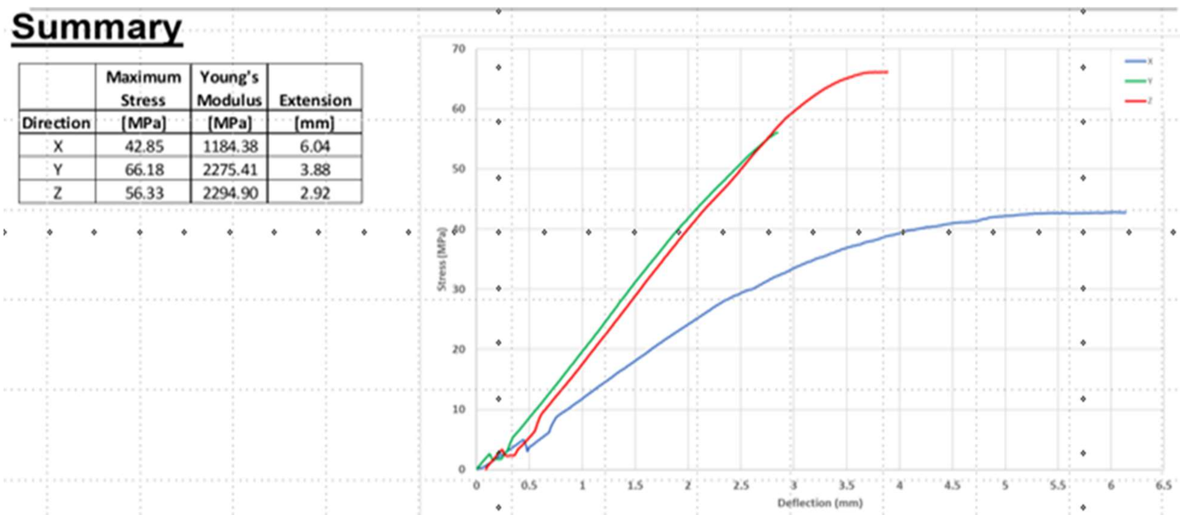
a. Tensile Strength and Stiffness

An analysis of the failure mechanism revealed that the PLA samples fractured along the polymer filaments, resulting in a zigzag failure pattern. This pattern was observed in both the control group and the samples exposed to UV-B radiation (see Figure 4). The fracture behaviour can be attributed to the properties of components produced through MEX 3D printing. The anisotropy arises from the tensile strength along the filaments, which is stronger than the adhesion between adjacent filaments. This is influenced by factors such as print orientation, infill type and density, raster angle, and layer height. The consistent failure modes across all test groups indicate that any effects of the irradiation treatments were evenly distributed throughout the parts. Additionally, post-irradiation, all samples exhibited discoloration of the ivory-colored material, with a similar degree of discoloration in the UV-B exposed samples.

(a) (b)

Fig 4. PLA Samples

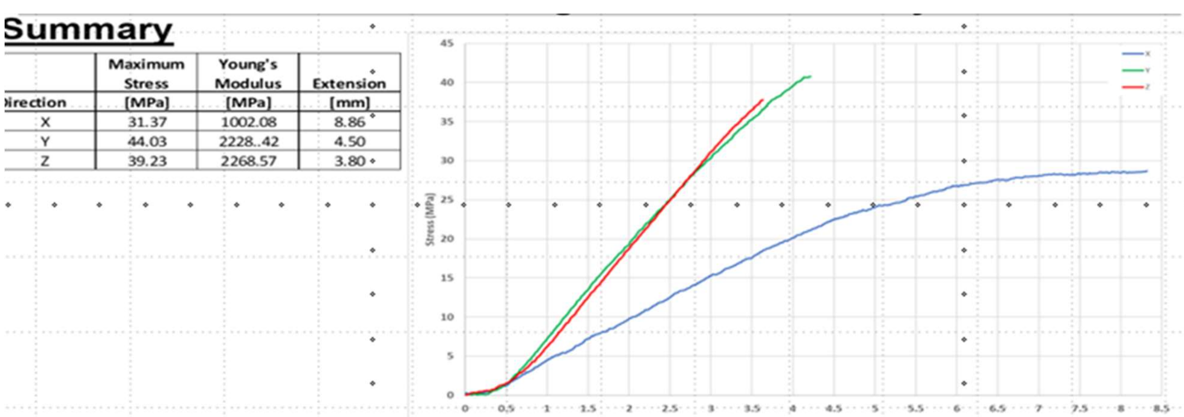
b. Tensile Strength and three-point bending test.



Summary

Direction	Maximum Stress [MPa]	Young's Modulus [MPa]	Extension [mm]
X	42.85	1184.38	6.04
Y	66.18	2275.41	3.88
Z	56.33	2294.90	2.92

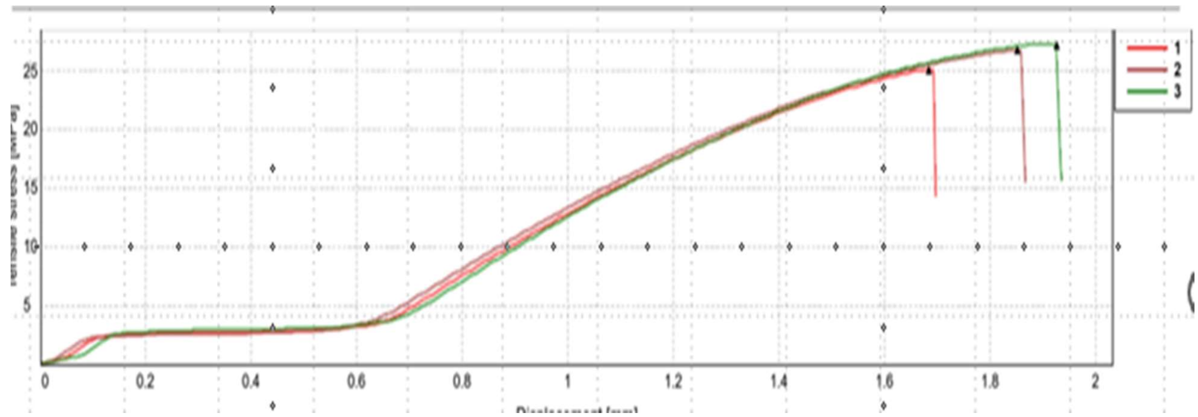
(a)



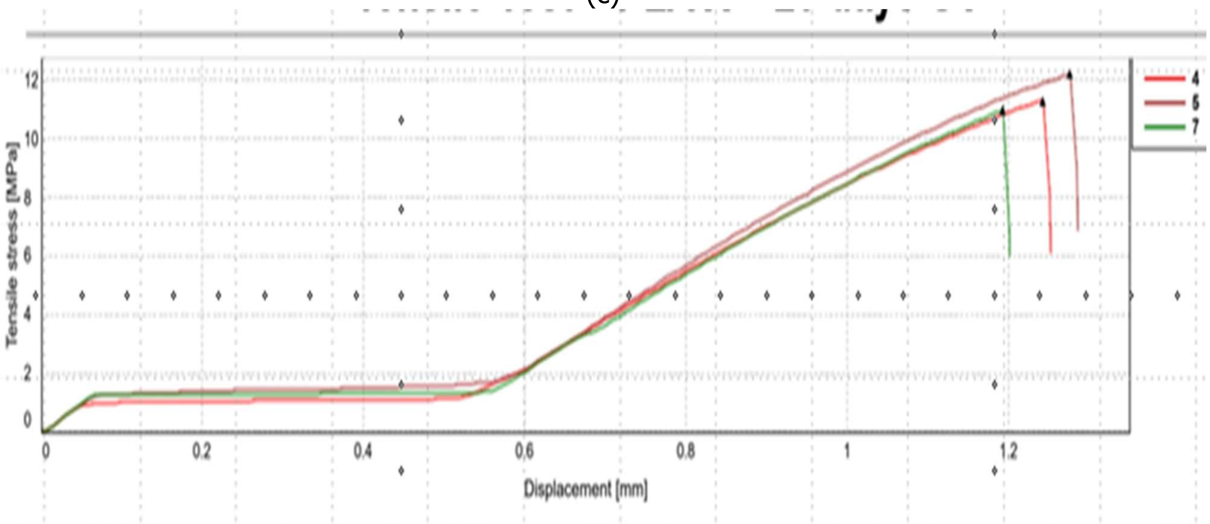
Summary

Direction	Maximum Stress [MPa]	Young's Modulus [MPa]	Extension [mm]
X	31.37	1002.08	8.86
Y	44.03	2228..42	4.50
Z	39.23	2268.57	3.80

(b)



(c)



(d)

Fig. 5.(a-d). ***Tensile Strength and three-point bending test graphs***

The graphs in Figure 5 (a-d) present the results from both tensile and 3-point bend tests, illustrating the effects of UV exposure on the mechanical properties of PLA materials. In cases where there was no UV exposure, PLA samples showed higher stress and Young's Modulus values compared to those exposed to UV radiation. In the tensile tests, the highest stress observed in the control group (without UV) was 25.15 MPa. However, after UV exposure (W2 and W3), the stress levels decreased to 11.92 MPa and 7.05 MPa, respectively. Similarly, in the 3-point bend tests, the control group exhibited a stress level of 42.85 MPa, while UV-exposed samples (W2 and W3) showed reduced stress levels of 23.17 MPa and 16.44 MPa, respectively.

Additionally, both elongation during tensile testing and deflection in the 3-point bend tests decreased with UV exposure, indicating a reduction in the flexibility of the PLA materials. A comparison between W2 and W3 samples suggests that the deterioration in mechanical properties due to UV exposure is more severe in W3 than in W2, indicating differences in how PLA responds to varying durations or intensities of UV exposure. Overall, UV exposure negatively impacts PLA by reducing stress and Young’s Modulus while increasing elongation and deflection.

c. Flexural Strength

Specimen Label	Maximum Stress (MPa)	Flexure Displacement at Break (mm)	Modulus (MPa)
Week 1	23.71	4.63	738.03
Week 2	14.51	3.36	829.55
Week 3	27.06	5.20	895.27

Table 3. ***Flexural strength of the specimen***

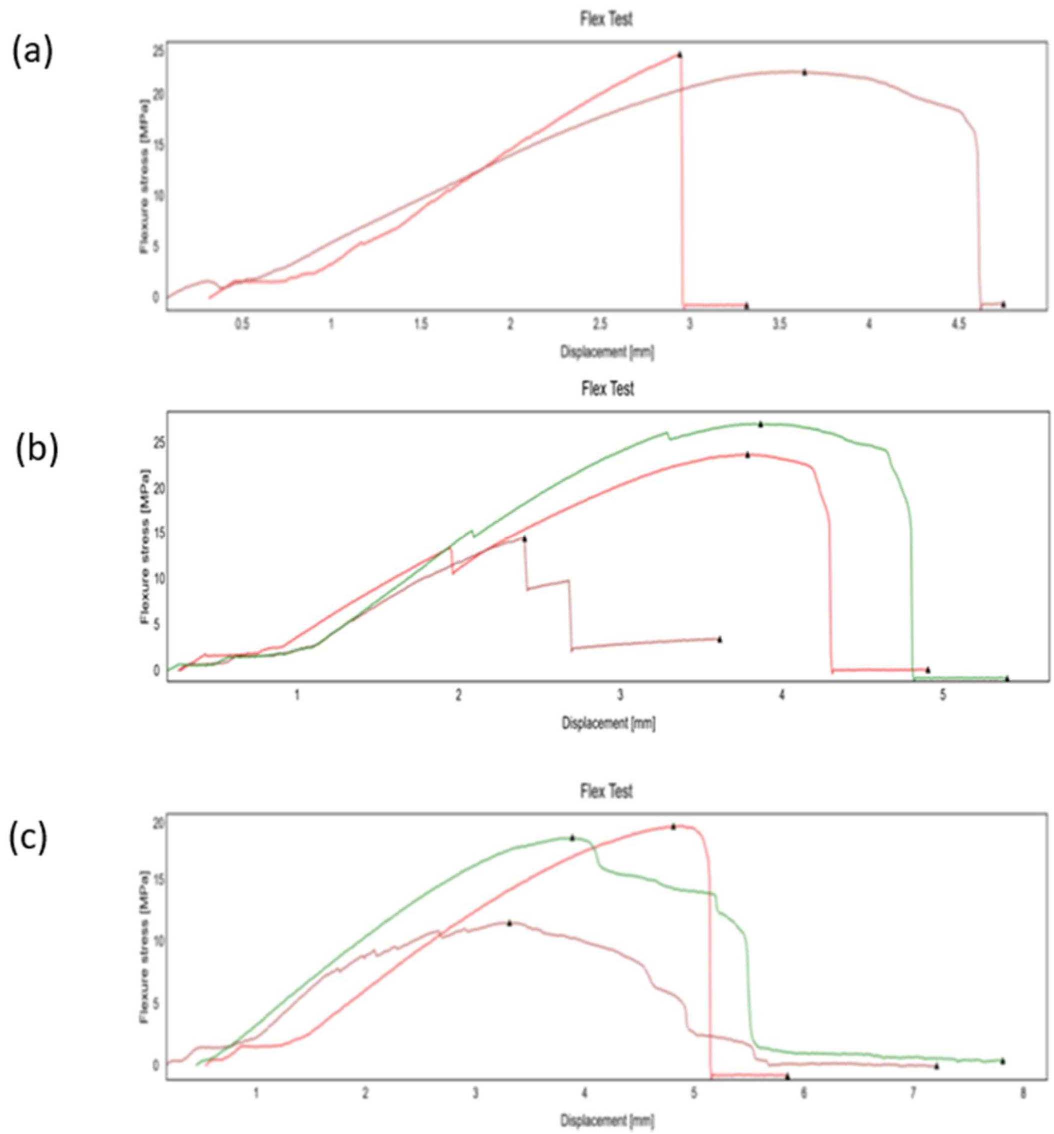
From Table 3., the results from the flexure test conducted in week three provided valuable insights into the mechanical behaviour of PLA specimens. Among all the tested samples, the stress in week one was recorded at 27.06 MPa, indicating its ability to withstand higher loads before failure compared to weeks one and two. This suggests that the week three samples may have greater strength under bending stress.

In terms of flexibility, specimen S3 showed a bending value of 5.20 mm, indicating its ability to deform more before breaking. This implies that the week three samples may exhibit greater ductility or flexibility compared to both S1 and the week two samples, allowing them to endure more deformation under stress.

For modulus, S3 displayed a value of 895.27 MPa, higher than S1's 738.03 MPa but lower than the week two sample, which was 829.55 MPa. Modulus reflects a material's stiffness or rigidity, and these values indicate resistance to deformation. Therefore, S3 appears to strike a balance between stiffness and flexibility compared to the samples from weeks one and two.

Overall, the week three flexure test results highlight the differences in the mechanical properties of the PLA specimens, emphasizing the importance of comprehensive testing and analysis to fully understand material behaviour and optimize additive manufacturing processes. Further research is needed to explore the underlying causes of these variations and refine printing settings to improve material performance and reliability. The stress-strain graphs of the materials are shown in Fig. 6(a-c) below.

Fig. 6(a-c). Stress_Strain Graph of tensile materials



Understanding how UV radiation affects the quality and performance of PLA parts is crucial to ensuring their reliability and durability in real-world applications. The color changes observed on the surface of PLA parts after exposure to UV A radiation indicate the early stages of degradation. This color shift suggests that chemical changes are occurring within the polymer structure, which could eventually impact its strength over time. However, despite this change, the tensile strength of the tested PLA samples showed resistance to UV A exposure, demonstrating a certain level of stability under these conditions. On the other hand, UV C radiation, with its shorter wavelength and higher energy, posed a different set of challenges. Although there was no significant difference in strength between PLA samples exposed to UV C for three weeks and those not exposed, a noticeable reduction in stiffness was observed. This loss of rigidity can be attributed to the breakage of bonds within the PLA structure.

Test results provide further insight into how PLA components respond mechanically to UV exposure. While the elongation time curves for both control and irradiated groups show patterns indicative of creep behaviour, a more detailed examination of the mechanisms behind creep resistance is needed. Variations in printing parameters could also influence material properties, highlighting the importance of testing under different conditions to optimize performance and reliability. The impact of UV radiation on degradation mechanisms, including the formation of radicals and peroxides, underscores the complex relationship between polymer chemistry and environmental stress. These molecular changes not only affect the material's mechanical properties but also lead to alterations in its optical characteristics, such as discoloration and yellowing.

CONCLUSION

This research enhances the understanding of how UV radiation affects the mechanical properties of 3D-printed PLA. Our results reveal that while PLA is resilient to short-term UV exposure, extended exposure leads to mechanical degradation. Future research should explore UV stabilizers and alternative printing settings to extend PLA's durability in environments with high UV exposure. The findings of this study have implications for industries such as outdoor signage, automotive components, and architectural models, where prolonged UV exposure is inevitable.

REFERENCES

Ahmed, W., Zaneldin, E. and El Hassan, A. (2023) 'Investigating the Integrity and Failure Characteristics of Deteriorated Polymeric 3D-Printed Components as Candidates for Structural and Construction Applications', *Buildings,* 13(10), pp. 2402.

Atala, A. and Yoo, J.J. (2015) *Essentials of 3D biofabrication and translation.* Academic Press.

Balakrishnan, P. *et al.* (2017) 'Morphology, transport characteristics and viscoelastic polymer chain confinement in nanocomposites based on thermoplastic potato starch and cellulose nanofibers from pineapple leaf', *Carbohydrate Polymers,* 169, pp. 176-188.

Francois, M.M. *et al.* (2017) 'Modeling of additive manufacturing processes for metals: Challenges and opportunities', *Current Opinion in Solid State and Materials Science,* 21(4), pp. 198-206.

Gao, W. *et al.* (2015) 'The status, challenges, and future of additive manufacturing in engineering', *Computer-Aided Design,* 69, pp. 65-89.

Gibson, I. *et al.* (2021a) *Additive manufacturing technologies.* Springer.

Gibson, I. *et al.* (2021b) *Additive manufacturing technologies.* Springer.

González-González, L. and Alonso, J. (2018) 'Periostin: a matricellular protein with multiple functions in cancer development and progression', *Frontiers in Oncology,* 8, pp. 225.

ISO, E.N. (2012) '527-2; Plastics—Determination of Tensile Properties—Part 2: Test Conditions for Moulding and Extrusion Plastics', *Organization of Standardization: Geneva, Switzerland,*

Kruth, J., Leu, M. and Nakagawa, T. (1998a) 'Progress in additive manufacturing and rapid prototyping', *Cirp Annals,* 47(2), pp. 525-540.

Kruth, J., Leu, M. and Nakagawa, T. (1998b) 'Progress in additive manufacturing and rapid prototyping', *Cirp Annals,* 47(2), pp. 525-540.

Kulkarni, V.R. *et al.* (2023) 'Veering to a Continuous Platform of Fused Deposition Modeling Based 3D Printing for Pharmaceutical Dosage Forms: Understanding the Effect of Layer Orientation on Formulation Performance', *Pharmaceutics,* 15(5), pp. 1324.

Molitch-Hou, M. (2018) 'Additive manufacturing: Materials, processes, quantifications and applications',

Pandžić, A. *et al.* (2023) 'The Effect of Ultraviolet Radiation on Mechanical Properties of Fused Deposition Modeling 3D Printed Materials.', *TEM Journal,* 12(4)

Rafiee, M., Farahani, R.D. and Therriault, D. (2020) 'Multi-material 3D and 4D printing: a survey', *Advanced Science,* 7(12), pp. 1902307.

Reddy K, S.N. *et al.* (2016) 'Topology optimization software for additive manufacturing: A review of current capabilities and a real-world example', *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* American Society of Mechanical Engineers

Standard, I. and Iso, B. (2019) 'Plastics—Determination of flexural properties', *ISO Geneva, Switzerland,*

Wu, H. *et al.* (2020) 'Recent developments in polymers/polymer nanocomposites for additive manufacturing', *Progress in Materials Science,* 111, pp. 100638.

Souissi, S., Bennour, W., Khammassi, R., & Elloumi, A. (2022). Mechanical properties of 3D printed parts: Effect of ultraviolet PLA filaments ageing and water absorption. Journal of Elastomers and Plastics, 1–17. Doi: 10.1177/00952443221144736.

Bochnia, J. (2023). A Study of the Mechanical Properties of Naturally Aged Photopolymers Printed Using the PJM Technology. Materials, 16(1).Doi: 10.3390/ma16010400.

Gibson, I., Rosen, D., Stucker, B., & Khorasani, M.(2021). Chapter 14: Materials for additive manufacturing. In Additive Manufacturing Technologies, 379–428. Springer Nature Switzerland AG 2021. Doi: 10.1007/978-3-030-56127-7_14.

Wu, H., Fahy, W. P., Kim, S., Kim, H., Zhao, N.,Pilato, L., Kafi, A., Bateman, S., & Koo, J. H. (2020).Recent developments in polymers/polymer nanocomposites for additive manufacturing. Progress in Materials Science, 111.Doi: 10.1016/j.pmatsci.2020.100638

Dizon, J. R. C., Gache, C. C. L., Cascolan, H. M. S.,Cancino, L. T., & Advincula, R. C. (2021). Post-Processing of 3D-Printed Polymers. Technologies,9(3), 61. Doi: 10.3390/technologies9030061.

Pandzic, A., & Hodzic, D. (2021). Mechanical properties comparison of PLA, tough PLA and PC 3D printed materials with infill structure – Influence of infill pattern on tensile mechanical properties. IOP Conference Series: Materials Science and Engineering, 1208(1), 012019.Doi: 10.1088/1757-899x/1208/1/012019.

International Organizational for Standardization.(2012). ISO/TC 61/SC 2 Mechanical behavior.Plastics — Determination of tensile properties — Part2: Test conditions for moulding and extrusion plastics.ISO. Retrieved from:https://www.iso.org/committee/49272.html.[accessed: 17 July 2023].

International Organizational for Standardization.(2002). ISO EN ISO 178 Plastics -- Determination of flexural properties. Retrieved from:http://www.iso.org/iso/catalogue_detail.htm?csnumber=45091 [accessed: 20 July 2023].