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The Effect of Ultraviolet Radiation on Mechanical Properties of Fused Deposition Modeling 3D Printed Materials

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Abstract **– This study investigates the influence of ultraviolet (UV) radiation on the mechanical properties of Fused Deposition Modeling (FDM) 3D printed materials, specifically polycarbonate (PC) and polylactic acid (PLA) specimens. The research involves conducting experiments on five test specimens of each material exposed to UV radiation and comparing their mechanical properties to those of five control specimens that remain unexposed. The results reveal a significant mean difference between the mechanical properties of the control and UV-exposed materials. UV radiation caused a decrease in tensile strength for the PC material, while the PLA material exhibited an increase in tensile strength. The impact of UV radiation on PLA was more substantial compared to PC. Flexural strength testing showed an enhancement in strength for the UV-treated materials, with UV treatment having a greater influence on the flexural strength of PLA compared to PC. The mechanical properties of PLA were more significantly impacted by UV radiation than those of PC. The study findings suggest that PC and PLA materials exhibit different responses to UV exposure, which may have implications for their practical applications. Further research is needed to fully understand the underlying mechanisms governing these divergent responses and to optimize the performance of each material under UV radiation.**

Keywords **– Ultraviolet radiation, FDM, PLA, PC, AM materials, 3D print, tensile strength, flexural strength.**

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1. Introduction

Additive Manufacturing (AM), also known as 3D printing, is an evolving technology that constructs products by progressively adding materials layer by layer [1]. This method has demonstrated efficient performance across various materials, geometries, and manufacturing techniques, offering numerous advantages over traditional manufacturing processes. These advantages include the capability to create lighter products by adjusting infill density [7], manufacturing complex-shaped components without expensive tooling, reducing production time, and minimizing waste [2]. AM is well-recognized in medicine for personalized surgical guides and prosthetics where patient tomographic data are used to create custom 3D printed objects [3]. Novel materials like nanomaterial and fast drying concrete are also being explored for 3D printing [4]. AM potential by 3D printing shows transformative impact on aerospace, construction, energy, and electronic industries [3], [5]. Numerous studies have investigated the impact of various printing parameters on the mechanical properties of materials in additive manufacturing processes. These parameters encompass printing orientation, raster angle, layer thickness, infill shape and density, printing temperature, and nozzle diameter [6], [10]. The impact of environmental factors on printed products, such as prolonged exposure to high temperatures, sunlight, humidity, and marine environments, has received limited attention in existing studies [11]. Research related to the impact of environmental factors on printed products can contribute to improved product durability, optimized material selection and design considerations, enhanced product performance, and sustainable manufacturing practices within the AM field.

The study [12] aimed to investigate the impact of accelerated aging, specifically UV-B (λ = 280-315 nm) exposure, on the mechanical properties of specimens from polylactic acid (PLA) and from polyethylene terephthalate glycol-modified (PETG).

The findings revealed that PLA samples exposed to a 24-hour UV radiation exhibited a minor reduction in mechanical strength, while PETG samples experienced a considerable decrease in mechanical strength. Compressive strength of both materials decreased, where compressive strength of PETG exposed to UV radiation was found to be 38.6% lower compared to the control group. A tensile creep test demonstrated that the creep characteristics were maintained after UV exposure. Both materials exhibited comparable creep curves, with the offset attributed to the reduction in mechanical strength.

Study [13] investigated the effects of 24-hour of exposure to UV-B with $\lambda = 315$ nm and UV-C with $\lambda = 254$ nm, radiation on the mechanical properties of acrylonitrile butadiene styrene (ABS)-polycarbonate fibers (PC) copolymer specimens, produced using the material extrusion process (MEX) in 3D printing. After exposure to UV-C radiation, the ABS-PC specimens exhibited surface color changes consistent with ABS degradation, but there were no differences in dimensions between the exposed and control specimens. The study revealed that specimens exposed to UV-B radiation did not exhibit a statistically significant difference in tensile strength and stiffness when contrasted with the control group. Samples aged under UV-C radiation demonstrated a 1.86% lower tensile strength of the control samples. This difference was not statistically significant, meaning that it could have occurred due to random variation and not as a direct result of the UV-C radiation. Compressive strength tests revealed a decrease in the strength of ABS-PC parts after UV-C exposure, with aged parts exhibiting a 6.5% reduction in compressive strength. Overall, the results indicate a slight decline in the mechanical properties of 3D printed ABS-PC parts following irradiation treatment. Considering these minor alterations in mechanical properties and the established long-term stability of ABS-PC blends, these materials appear to be suitable for applications involving continuous tensile stress.

The study [14] focuses on analyzing and discussing the aging treatment impact on the mechanical properties and failure modes of printed specimens made from polylactic acid (PLA) filament. The researchers examine how the UV treatment applied to the PLA filament prior to printing impact the performance and characteristics of the printed specimens. The research investigates the impact of UV radiation exposure for three different time periods: 24, 48, and 72 hours. Specimens are printed with varying raster angle and printing orientation.

Tensile testing is performed on specimens with two raster angles (90° and 0°) and two printing orientations (on edge and flat). The evaluation of mechanical properties is based on Young's modulus. The results reveal that the raster angle has the most significant effect on the specimens mechanical properties. Specimens with a 90° raster angle and edge orientation exhibit the highest Young's modulus, with a 33% decrease observed after aging treatment. On the other hand, specimens with a raster angle of 0° and flat orientation show the smallest Young's modulus, with a 30% increase after aging treatment. Therefore, it is evident that Young's modulus of the treated specimens follow a trend of decrease and increase with a raster angle of 90° and 0°, respectively, for different printing orientations.

In the study [15] the impact of natural aging on the mechanical properties of polymer materials is investigated. Specimens are produced using PolyJet Matrix technology and two photocurable resins: FullCure 720 and VeroWhite. The specimens were manufactured in period from December to June using these resin types. Some specimens were immediately tested after printing, while others were stored in laboratory conditions from 8 to 8.5 years to evaluate the impact of natural aging on their mechanical properties. The findings of these experiments provide valuable insights into the durability and performance of these materials, specifically regarding their tensile strength. The results indicate that aging had a noticeable effect on the tensile strength, with greater changes observed in the FullCure 720 compared to the VeroWhite specimens. Additionally, both types of 3D-printed polymers retained their anisotropic nature, exhibiting variations in mechanical properties depending on the printing orientation. The decrease in tensile strength due to aging suggests a potential reduction in the overall duration of a product's usability of the 3D printed polymer products. However, this limitation can be mitigated to some extent during the design phase by carefully selecting the orientation of the model on the build tray.

The findings of the presented studies suggest that UV radiation influences the mechanical properties of 3D printed materials. The results indicate that, depending on the specific printing conditions and materials used, thermal aging caused by UV radiation can lead to either improvements or deteriorations in mechanical properties. This study aims to analyze the impact of UV radiation on two materials, printed as solid structures with 100% infill. The specimens are manufactured and tested in accordance with relevant standards. Using statistical analysis, mechanical properties of tested materials are assessed.

2. Experimental Methodology

In present study, a series of experiments utilizing polycarbonate (PC) and polylactic acid (PLA) are performed. PC is an amorphous and transparent thermoplastic polymer that possesses remarkable characteristics including high toughness, fire resistance, suitability for elevated temperatures up to 100°C, strong interlayer bonding, and excellent adhesion to the work surface. It offers a unique combination of toughness, strength, transparency, and thermal resistance [16], [17], [18]. PLA is a biodegradable and renewable linear aliphatic thermoplastic polymer known for its favorable printability, biocompatibility, and surface finish. It provides several advantages such as safety, non-toxicity, and versatility in a wide range of applications. However, PLA applicability is limited by its low coefficient of thermal stability, with restricting usage for temperatures higher than 50°C. Additionally, PLA exhibits relatively low elongation, impact toughness, and brittleness [18], [19]. While PC surpasses PLA in terms of flexibility and durability, it is accompanied by a higher price point. Mechanical properties of Fused Deposition Modeling (FDM) 3D printed PC and PLA materials [8], defined by Ultimaker manufacturer are presented in Table 1.

Table 1. Mechanical properties PC and PLA materials

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

A total of twenty specimens are printed using the Ultimaker S5 3D printer, with ten specimens made of PC and ten specimens made of PLA material. All samples were 3D printed in the XY plane, also known as the flat orientation, employing the "normal profile" parameters in CURA 5.2.1 slicer for Ultimaker PC and PLA materials.

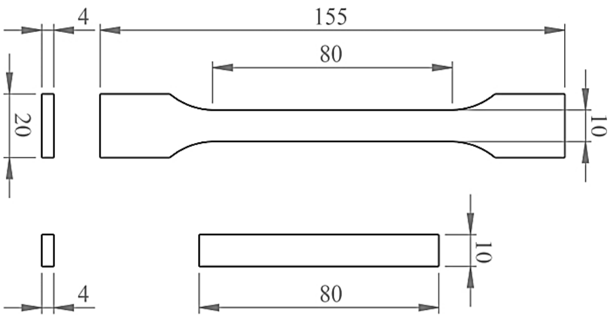
The FDM printing parameters utilized for this process are shown in Table 2.

Table 2. FDM printing parameters for PLA and PC materials

Parameters	PLA material	PC material
Layer Height	0.15 mm	0.15 mm
Printing Temperature	200 °C	280 °C
Build Plate Temperature	60 °C	110 °C
Print Speed	70 mm/s	50 mm/s
Fan Speed	100%	0 %
Infill Density	100%	100%

Test specimens for tensile strength analysis are designed in accordance with ISO 527-2 [20], and ISO 178 for flexural tests [21]. Visual representation and schematic of test specimens are presented in Figure 1.

a)



b)

Figure 1. Test specimen design: a) visual presentation; b) schematic of specimens according to ISO 527-2 and ISO 178

Specimens made of PC and PLA materials are divided into two groups: five test specimens not exposed to UV radiation (control group) and five test specimens exposed to UV radiation (treatment group). All specimens are printed using a 100% infill density, ensuring a solid structure.

UV radiation testing is performed according to ISO 4892-3 [9], Method B; Artificial accelerated weathering, with continuous 24 h exposure to UV radiation. The temperature of the chamber is set to 50 °C during the testing period. Irradiation chamber used for this analysis is Formlabs cure, shown in Figure 2.

Figure 2. Irradiation chamber with testing specimens

A comparative analysis is conducted to evaluate the impact of accelerated aging on the tensile and flexural strength of the specimens exposed to UV radiation and the control specimens.

a)

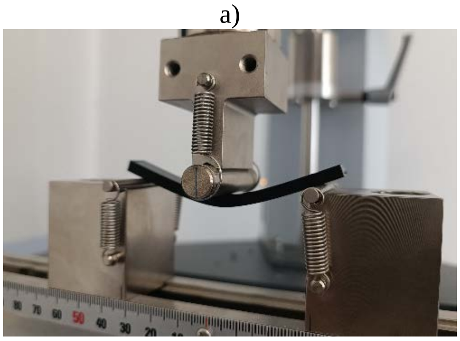


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Figure 3. Mechanical properties testing process: a) tensile strength; b) flexural strength

The specimens underwent tensile and flexural tests, according to the ISO 527-1 and ISO 187 standards, respectively, using a Shimadzu AGS-X universal testing machine (Figures 3a and b), with a testing speed of 5 mm/min. Tensile and flexural strength data were collected and recorded in the Shimadzu Trapezium-X software.

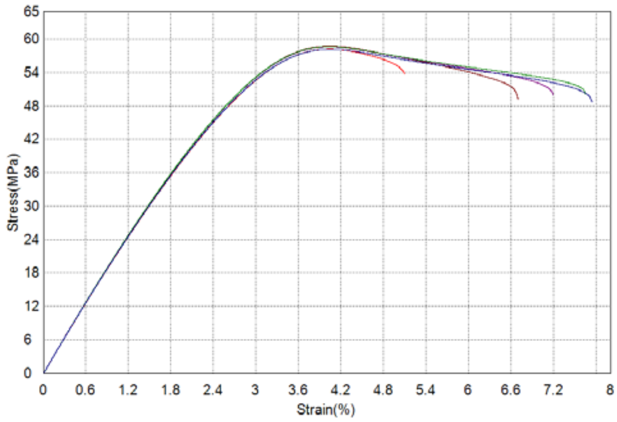
Experimental data are statistically analyzed using t-tests. For each material, t-tests are performed to detect significant differences between control and treatment groups.

3. Results and Discussion

The evaluation of experimental data, for both materials and tested mechanical properties, are shown in this section. The dimensions of PC specimens have remained relatively constant, whereas of PLA have decreased approximately 1.27%, indicating that no significant change in specimen's dimensions is observed.

3.1. Tensile Strength

The stress-strain diagrams from the tensile tests of PC and PLA materials are shown in Figures 4a-d and Table 3. The PC material treatment group exhibits a marginally lower tensile strength in comparison to the control group. However, the PLA specimens exhibit the opposite trend, showing a slight increase in tensile strength after the treatment.



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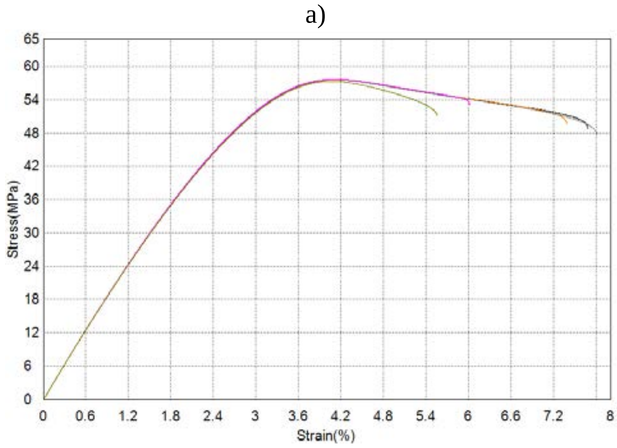

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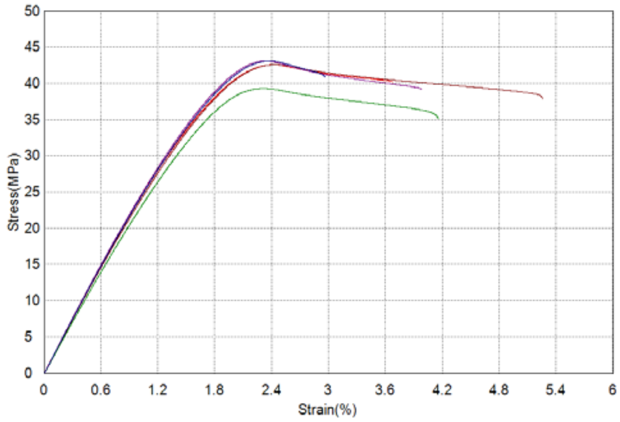

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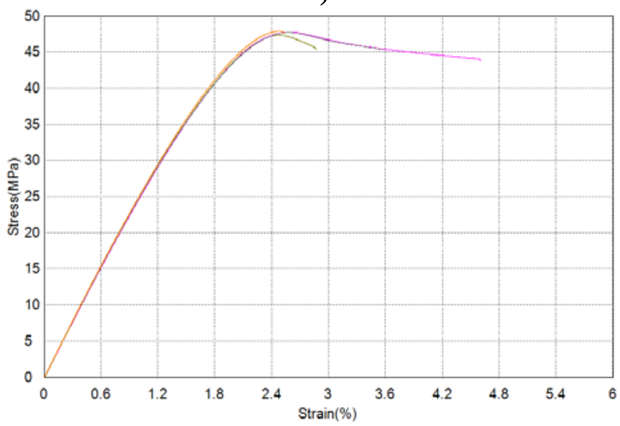


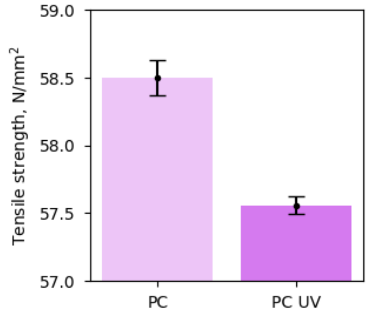
d)

Figure 4. Stress-strain diagrams (tensile tests) of tested materials: a) PC control group; b) PC UV treated; c) PLA control group; d) PLA UV treated

In Figure 5 and Table 3, the average tensile strength for both PC and PLA materials is presented, which is calculated from the data of five samples for each material. Mean tensile strength of PC is significantly larger than of PLA material. Additionally, the calculated standard deviation and standard error for the tensile strength of both materials are shown. Standard deviation and standard error of control and treated PC materials are significantly smaller than of PLA.

Table 3. Tensile strength of PC and PLA materials

Material	Sample size	Mean	St. Dev.	St. error
PC	5	58.500	0.283	0.126
PC UV	5	57.560	0.152	0.068
PLA	5	42.140	1.607	0.719
PLA UV	5	46.760	2.059	0.921



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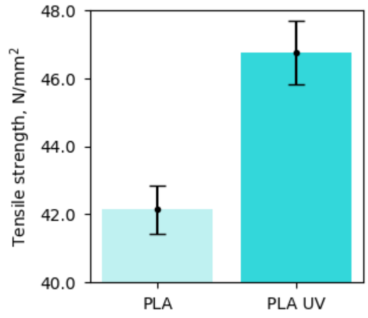


b)

Figure 5. Tensile strength of tested materials: a) PC and b) PLA

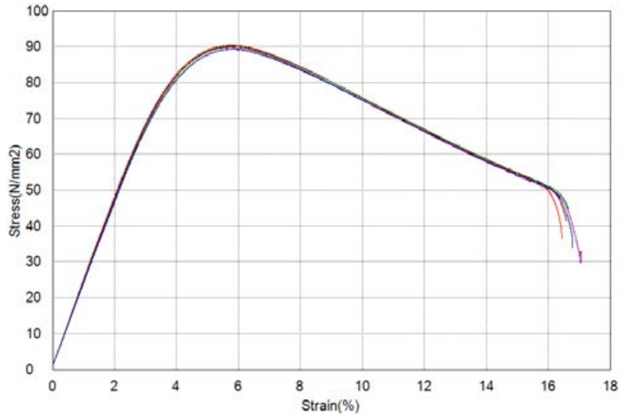
Results of t-test for tensile strength of PC and PLA materials are shown in Table 4. The mean difference of PC material is 0.939 MPa, and is statistically significant (t=6.549, p=0.000), indicating significant difference between control and treated materials tensile strength. The mean difference of PLA materials is -4.620 MPa, and is statistically significant (t=-3.955, p=0.004), also indicating significant difference between control and treated materials tensile strength. Therefore, obtained values indicate decrease in tensile strength of PC material, and increase in tensile strength of PLA material, with greater influence of UV radiation on PLA than PC material.

Table 4. T-test for tensile strength of PC and PLA materials (α= 95.0%)

	PC vs PC UV	PLA vs PLA UV
Mean difference	0.939	-4.62
t-statistic	6.549	-3.955
p-value	0.000	0.004
Lower CI	0.609	-7.313
Upper CI	1.271	-3.955

3.2. Flexural Strength

Stress-strain graphs obtained from flexural testing for PC and PLA materials are given in Figures 6a–d. The treated PC and PLA materials demonstrate an increase in flexural strength.



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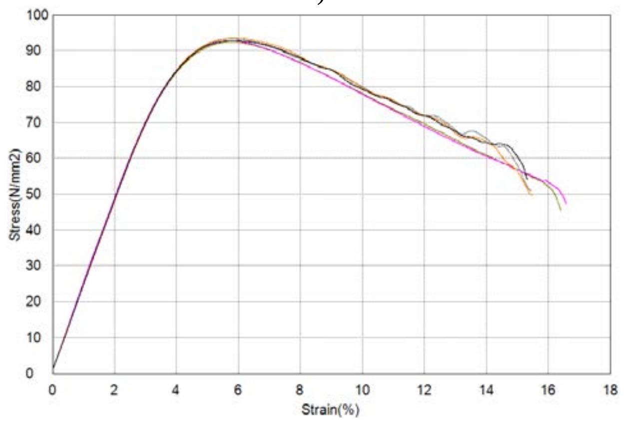

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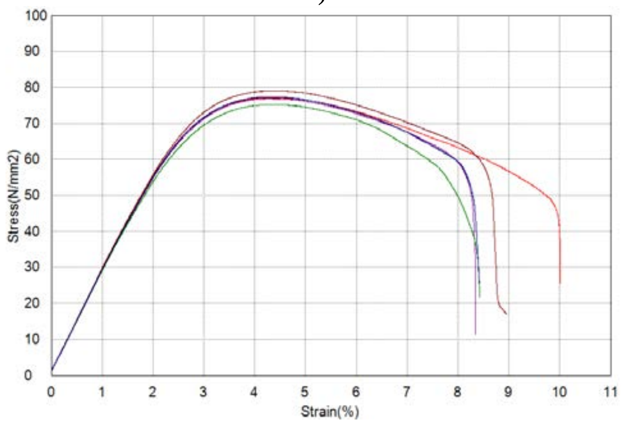

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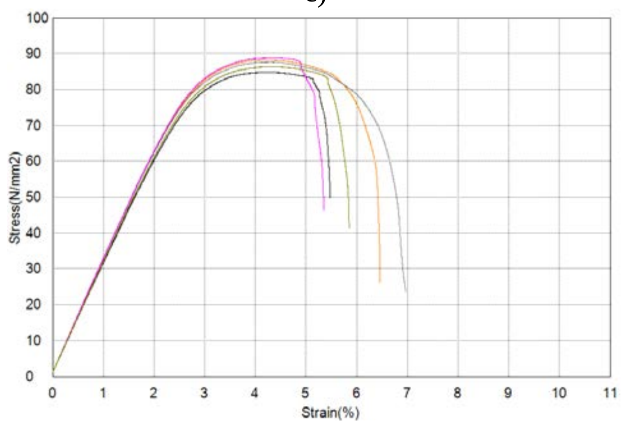


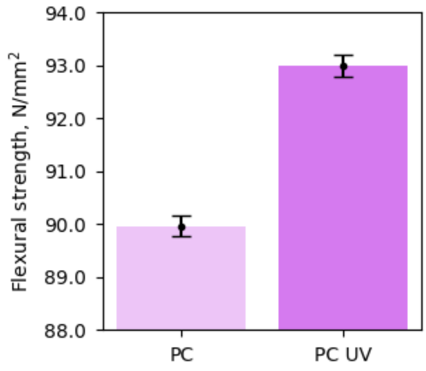
d)

Figure 6. Stress-strain graphs of tested materials: a) PC control group; b) PC UV treated; c) PLA control group; d) PLA UV treated

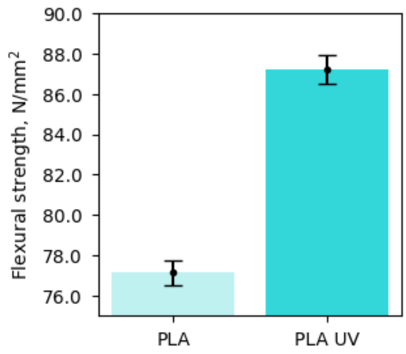
Figure 7 and Table 5 show the mean values of flexural strength for PC and PLA materials, obtained by averaging the values of five samples. The calculated standard deviation and standard error for the flexural strength of both materials are shown. Standard deviation and standard error of control and treated PC are smaller than of PLA.

Table 5. Flexural strength of PC and PLA materials

Material	Sample size	Mean	St. Dev.	St. error
PC	5	89.956	0.439	0.196
PC UV	5	92.986	0.473	0.212
PLA	5	77.140	1.366	0.611
PLA UV	5	87.239	1.614	0.722



a)



b)

Figure 7. Flexural strength of tested materials: a) PC and b) PLA

Table 6 presents the results of the t-test for flexural strength of PC and PLA materials. For the PC, the mean difference is -3.032 MPa, which is statistically significant (t=-10.501, p=0.000). This implies significant difference in flexural strength between the control and treated PC materials. Similarly, for the PLA material, the mean difference is -10.098 MPa, also statistically significant (t=-10.955, p=0.000). These values indicate an increase in flexural strength for the treated materials, with greater impact of UV radiation on the PLA compared to PC material.

Table 6. T-test for flexural strength of PC and PLA materials (α= 95.0%)

	PC vs PC UV	PLA vs PLA UV
Mean difference	-3.032	-10.098
t-statistic	-10.501	-10.955
p-value	0.000	0.000
Lower CI	-3.696	-12.279
Upper CI	-2.365	-7.918

4. Conclusion

This study examined the effects of UV radiation on the mechanical properties of PC and PLA materials created through FDM printing. The samples were divided into two groups: a control group with specimens not exposed to UV radiation, and a treatment group with specimens exposed to UV radiation for 24 hours continuously. The mechanical properties, specifically tensile strength and flexural strength, were compared and subjected to statistical analysis to evaluate the impact of UV radiation on these materials.

In conclusion, the t-test results for the materials tensile and flexural strength show a statistically significant mean difference between control and UV treated materials. The exposure to UV radiation led to a reduction in tensile strength for the polycarbonate (PC) material, while the polylactic acid (PLA) material experienced an increase in tensile strength. The influence of the UV radiation was more pronounced for PLA than PC material. The flexural strength testing showed an overall increase in strength for the treated materials, with greater impact of UV radiation on the flexural strength of PLA than of PC material. In summary, the mechanical properties of PLA are more significantly impacted by UV radiation compared to those of PC material. These findings highlight the different responses of the two materials to UV radiation and have important implications for their practical applications. Further research is needed to fully understand the underlying mechanisms driving these divergent responses and optimize each material performance under UV radiation.

References:

[1]. Mohamed, O. A. (2017). *Analytical Modeling and Experimental Investigation of Product Quality and Mechanical Properties in FDM Additive Manufacturing* [Doctoral thesis, Faculty of Science, Engineering and Technology - Swinburne University of Technology]. Doi: 10.13140/RG.2.2.28847.48807.

[2]. Wu, Y., Fang, J., Wu, C., Li, C., Sun, G., & Li, Q. (2023). Additively manufactured materials and structures: A state-of-the-art review on their mechanical characteristics and energy absorption. *International Journal of Mechanical Sciences, 246*, 108102. Doi: 10.1016/j.ijmecsci.2023.108102.

[3]. Gulzar, U., Glynn, C., & O'Dwyer, C. (2020). Additive manufacturing for energy storage: Methods, designs and material selection for customizable 3D printed batteries and supercapacitors. *Current Opinion in Electrochemistry, 20*, 46–53. Doi: 10.1016/j.coelec.2020.02.009.

[4]. Zhu, C., Liu, T., Qian, F., Chen, W., Chandrasekaran, S., Yao, B., Song, Y., Duoss, E. B., Kuntz, J. D., Spadaccini, C. M., Worsley, M. A., & Li, Y. (2017). 3D printed functional nanomaterials for electrochemical energy storage. *Nano Today, 15*, 107–120. Doi: 10.1016/j.nantod.2017.06.007.

[5]. Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction, 68*, 21–31. Doi: 10.1016/j.autcon.2016.04.005.

[6]. Solomon, I. J., Sevvel, P., & Gunasekaran, J. (2021). A review on the various processing parameters in FDM. *Materials Today: Proceedings, 37*, 509–514. Doi: 10.1016/j.matpr.2020.05.484.

[7]. Pandžić, A., Hodžić, D., & Kadrić, E. (2021). Experimental Investigation on Influence of Infill Density on Tensile Mechanical Properties of Different FDM 3D Printed Materials. *TEM Journal, 10*(3), 1195–1201. Doi: 10.18421/tem103-25.

[8]. Abeykoon, C., Sri-Amphorn, P., & Fernando, A. (2020). Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures. *International Journal of Lightweight Materials and Manufacture, 3*(3), 284–297. Doi: 10.1016/j.ijlmm.2020.03.003.

[9]. International Organizational for Standardization. (2016). ISO 4892-3. Plastics — Methods of exposure to laboratory light sources — Part 3: Fluorescent UV lamps. International Organizational for Standardization. Retrieved from: https://www.iso.org/standard/67793.html [accessed: 11 July 2023].

[10]. Kristiawan, R. B., Imaduddin, F., Ariawan, D., Ubaidillah, & Arifin, Z. (2021). A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. *Open Engineering, 11*(1), 639–649. Doi: 10.1515/eng-2021-0063.

[11]. Głowacki, M., Mazurkiewicz, A., Słomion, M., & Skórczewska, K. (2022). Resistance of 3D-Printed Components, Test Specimens and Products to Work under Environmental Conditions—Review. *Materials, 15*(17), 1–19. Doi: 10.3390/ma15176162.

[12]. Amza, C. G., Zapciu, A., Baciu, F., Vasile, M. I., & Nicoara, A. I. (2021). Accelerated aging effect on mechanical properties of common 3d-printing polymers. *Polymers, 13*(23), 1–13. Doi: 10.3390/polym13234132.

[13]. Amza, C. G., Zapciu, A., Baciu, F., & Radu, C. (2023). Effect of UV-C Radiation on 3D Printed ABS-PC Polymers. *Polymers, 15*(8). Doi: 10.3390/polym15081966.

[14]. 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.

[15]. 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.

[16]. 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.

[17]. 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

[18]. 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.

[19]. 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.

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

[21]. 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].