A Study of the Optimization of FDM Parameters for the Manufacture of Compression Specimens from Recycled PETG in the Context of the Transition to the Circular Economy

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ABSTRACT

The current paper presents the results of a research on the optimization of Fused Deposition Modeling (FDM) parameters, namely the height of the deposited layer in one pass, L_h, and the filling percentage, Id, with the purpose of manufacturing compression specimens from recycled Polyethylene Terephthalate Glycol (rPETG), and thus, aiming the transition to circular economy. A total of 45 compression specimens were manufactured from rPETG on the Anycubic 4Max Pro 3D printer with variable parameters L_h = 0.10 mm, 0.15 mm, 0.20 mm, and Id = 50%, 75%, 100%. All 45 specimens were tested in compression on the Barrus White 20 kN universal testing machine. The considered variable parameters influence the Compressive Strength (CS) of the specimens, with Id being the parameter with overwhelming influence.

Keywords-FDM parameters; circular economy; rPETG; compressive stress; optimization

I. INTRODUCTION

The annual production of plastics has reached 441.25 million tons worldwide, with 14% of this quantity being registered in the European Union. According to forecasts, in the next 20 years, plastic world production will double, accentuating the problem of plastic waste management [1-6]. Plastic waste pollution hurts the economy, public health, effective functioning of ecosystems, and life quality. Therefore, finding solutions regarding plastic waste management is a necessity of major importance [7-12]. Additive manufacturing technologies prevail over conventional ones due to their major advantages, involving the negligible amount of waste, realization of complex geometries without special elements of basing and fixing, simplicity of use, and low operating costs [13-16]. The use of additive manufacturing technologies through thermoplastic extrusion combined with the production and consumption model based on the circular economy can be a viable solution in managing plastic waste [17-23]. There is a growing interest in the synergy between additive manufacturing technologies and circular economy, with the studies on this subject, though, being limited. In [24], an investigation on the tensile behavior of specimens manufactured by Fused Deposition Modeling (FDM) from Polyethylene Terephthalate Glycol (PETG) and recycled Polyethylene Terephthalate (rPET) is presented. Ten samples, 5 PETG and 5 rPET, were manufactured using the following parameters: height of the deposited layer at one pass L_h = 0.06 mm, infill density Id = 100%, extruder temperature Te = 240 °C, bed temperature Bt = 60 °C, and print speed Ps = 70 mm/s. The results of the study show that the samples made of rPET have a breaking strength of 26.56 – 28.86%, higher than those made of PETG. In [25], a Dynamic Mechanical Analysis (DMA) is presented regarding the influence of certain factors on the glass transition of 3D-printed rPET samples. A filament with a diameter of 1.75 mm was made from rPET granules, and subsequently, samples with dimensions of 1 mm × 4 mm × 50 mm were manufactured from the rPET filament using 5 ways of deposition of the material, 0°, 10°, 20°, 30°, and 40°. The study results indicate that PET can be recycled up to 3 times. An assessment of the viability of recycled polymer utilization for 3D printing is presented in [26]. The main objectives of this study are to find out the appropriate methods for recycling plastic materials and their use for 3D printing. The benefits and limitations of employing recycled plastic materials in applications of additive manufacturing technologies were evaluated and future directions were provided. The findings revealed that additive manufacturing technologies mainly concentrate on the use of the production and consumption model based on the circular economy.

This paper presents a study on the FDM parameter optimization for the manufacture of compression specimens from rPETG with the purpose of transitioning to the circular economy. The novelty of the current study lies in the analysis of the compression behavior of the specimens, manufactured by FDM from rPETG and the determination of the optimal parameters for obtaining the best results from a technical and economic point of view (compressive stress, printing time, material consumption, scrap). The specimens were manufactured and tested in compression in the laboratories of the Faculty of Mechanical and Electrical Engineering of the Petroleum–Gas University of Ploiesti.

II. DETERMINATION OF THE INFLUENCE OF FDM PARAMETERS ON THE COMPRESSION BEHAVIOR OF SPECIMENS MADE FROM rPETG

A. *Work Methodology*

Figure 1 shows the work methodology stages for the experimental study on the FDM parameter optimization aiming at manufacturing compression specimens from recycled PETG in the context of transitioning to the circular economy.

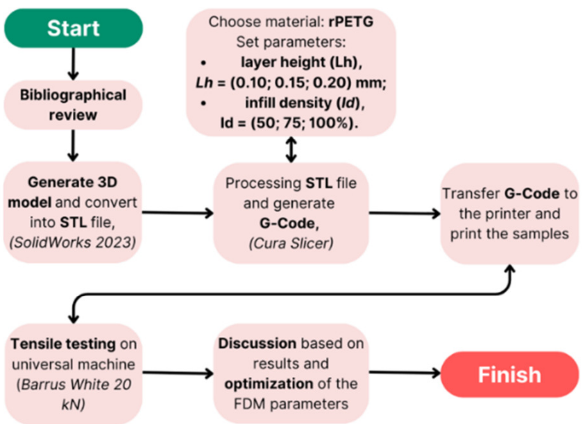

Fig. 1. The stages of the work methodology regarding the influence of FDM parameters on the CS of the samples made of rPETG.

The generation of the compression specimen 3D model was carried out in the CAD software SolidWorks 2023. Using the same software, the file corresponding to the 3D model was converted from an SLD format to an STL format. Figure 2 depicts the compression specimen in SolidWorks 2023 [27].

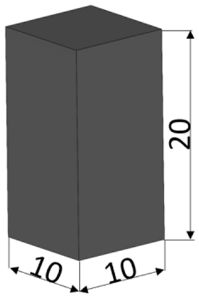

Fig. 2. The 3D model of the specimen for the compression test, in the SolidWorks 2023 software.

TABLE I. FDM PRINTING PARAMETERS FOR RPETG COMPRESSION SPECIMENS [13]

Constant parameters	Variable parameters				Material
	Height of the layer applied at one pass L_h	Infill density Id			rPETG
	(mm)	(%)			(pieces)
Part orientation: XY The temperature of the extruder, (E_t) = 250 °C The temperature of the platform, (B_t) = 70 °C Printing speed, (P_s) = 30 mm/s Filling pattern, (I_p) = Grid	0.10	50	75	100	45
	0.15				
	0.20				

Utilizing Cura Slicer [28], the STL file of the compression specimen, and the 3D printing parameters, displayed in Table I, were made along with the G-Code files for the FDM fabrication of the compression specimens from rPETG. Figure 3 shows the structure of the G-Code file for L_h = 0.20 mm and Id = 100%.

```
G5
G92 E0
G92 E0
G1 F1500 E-6.5
;LAYER_COUNT:99
;LAYER:0
M107
M204 S300
M205 X8.18 Y8.18
G0 F2400 X99.39 Y79.552 Z0.3
M205 X3 Y3
;TYPE:SKIRT
G1 F1500 E0
G1 F1200 X100.743 Y78.46 E0.08674
G1 X102.724 Y77.474 E0.19714
```

Fig. 3. Structure of the G-Code file for FDM fabrication of compression specimens from rPETG.

Using the Anycubic 4 Max Pro 2.0 3D printer and the G-Code file generated in Cura Slicer, as evidenced in Figure 3, 45 compression specimens were manufactured, employing the rPETG filament with 100% recycled Everfill brand material, as seen in Figure 4.

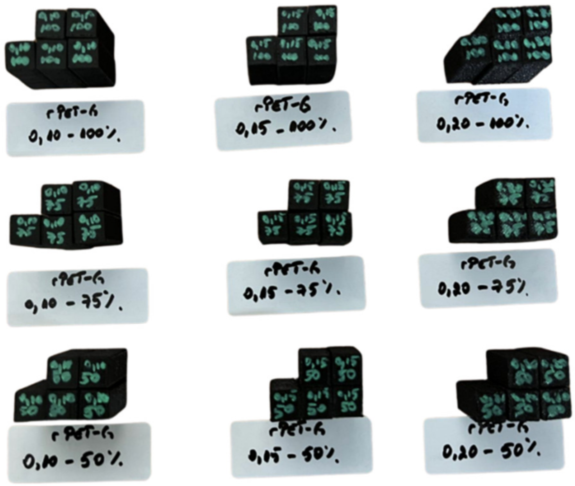

Fig. 4. Compression specimens made from rPETG by FDM.

The aforementioned specimens were subjected to compression testing on a Barrus White 20 kN universal testing machine, according to ISO 604:2002 standard, at a speed of 10 mm/min [29]. Figure 6 depicts the stages of specimen deformation during the compression test on the Barrus White 20 kN universal testing machine.

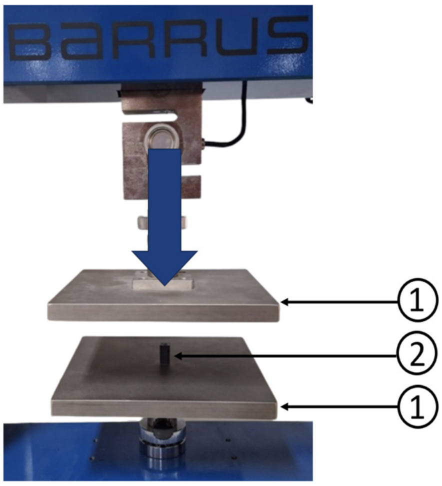

Fig. 5. Compression testing on the universal testing machine Barrus White 20 kN: 1 – plates, 2 – sample.

(a) (b) (c)

Fig. 6. Stages of deformation following the compression test on the additively manufactured specimen by FDM from rPETG: (a) specimen before testing, (b) start of deformation, (c) final deformation.

B. Results and Discussion

The results of the compression tests of the samples manufactured additively by FDM from rPETG are graphically represented in Figures 7-9.

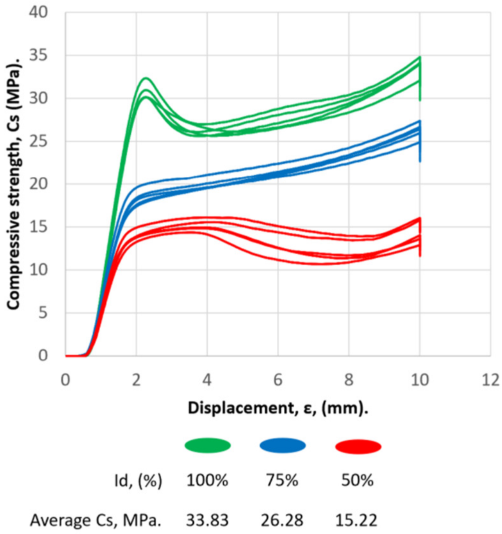

Fig. 7. Average values of CS, for rPETG samples with $L_h = 0.10$ mm and Id = 50/75/100%.

In Figure 7, it is observed how the filling percentage, Id, influences the CS of the specimens manufactured additively by FDM from rPETG with 100% recycled material. The highest values, CS, 32.09 MPa – 34.80 MPa, were obtained for the samples with the filling percentage Id = 100%. By decreasing the filling percentage from 100% to 75%, the CS decreased by 27.07% – 28.75%, and by decreasing the filling percentage from 75% to 50%, the CS decreased by 66.99% – 73.40%.

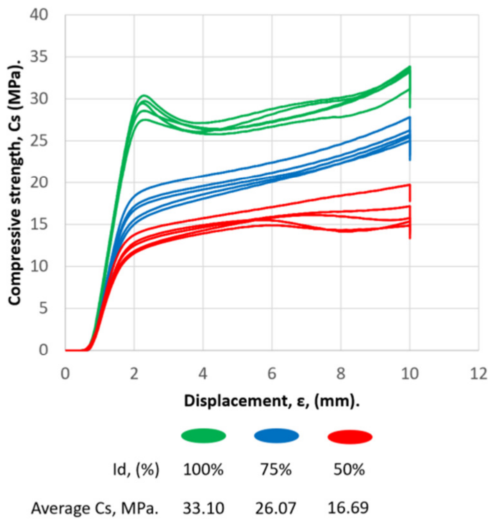

Fig. 8. Average values of CS, for rPETG samples with $L_h = 0.15$ mm and Id = 50/75/100%.

As noted in Figure 8, by increasing the filling percentage, Id, higher values of the CS of the samples manufactured additively by FDM from rPETG with 100% recycled material are obtained. The highest CS values, 31.18 MPa – 33.86 MPa, were attained for the samples with the percentage of filling Id = 100%. The decrease in the filling percentage from 100% to 75% generated a decrease in the CS of 21.67% – 24.58%, and the decrease in the percentage of filling from 75% to 50% produced a decrease in the CS of 41.09% – 67.96%.

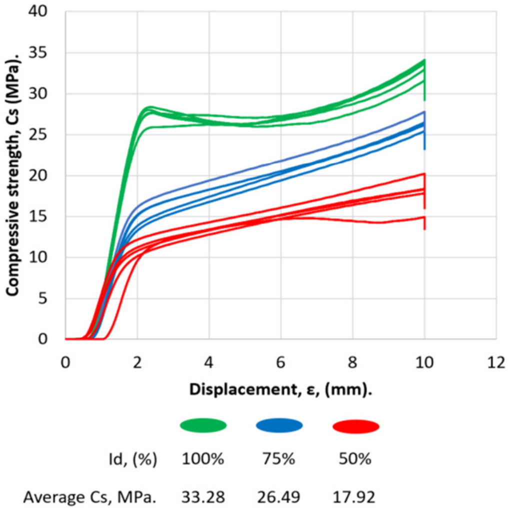

Fig. 9. Average values of CS, for rPETG samples with L_h = 0.20 mm and Id = 50/75/100%.

Figure 9 demonstrates how the filling percentage, Id, influences the CS of the samples manufactured additively by FDM. The highest CS values, 31.60 MPa – 34.12 MPa, were obtained for the samples with the percentage of filling Id = 100%. The decrease of the filling percentage from 100% to 75% resulted in strength decrease of 22.69% – 24.14%, and the decrease of the filling percentage from 75% to 50% led to a CS decrease of 37.67% – 70.61%. Using the average results of the CS and the Minitab software, the graph illustrated in Figure 10 was constructed, exhibiting the influence of the variable parameters, L_h and Id, of FDM on the CS of the specimens made of rPETG with 100% recycled material [21].

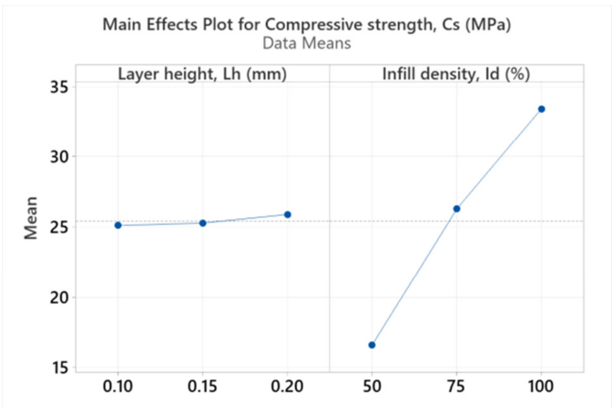

Fig. 10. Influence of variable FDM parameters, L_h and Id, on the compressive strengths of rPETG specimens.

Figure 10 showcases how the FDM variable parameters, L_h and Id, impact the CS of the samples made of rPETG with 100% recycled material. Filling percentage is the parameter most significantly influencing the CS of FDM-fabricated specimens from rPETG. Using Minitab, the FDM parameters from Table I, and the results of the CS of the samples manufactured by FDM from rPETG were combined in the Pareto graph shown in Figure 11 [30].

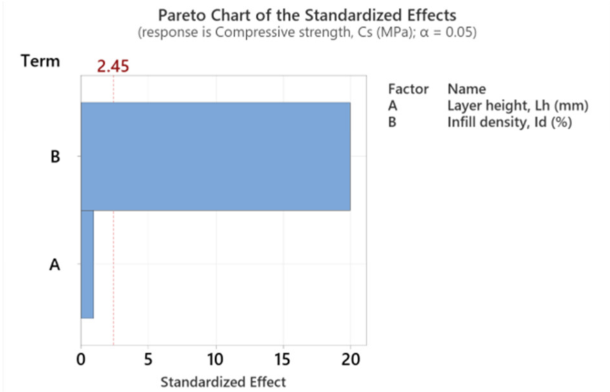

Fig. 11. A = L_h and B = Id of FDM on the CS of rPETG specimens.

Analyzing the Pareto ex plus graph in Figure 11, it is observed that the filling density, B = Id, has a major influence on the CS of the specimens manufactured additively by FDM from rPETG. The influence value of factor A = L_h is 0.935429 units, and the influence value of factor B = Id is 19.9637 units. Comparing the influence of the 2 factors, A = L_h and B = Id, it is noted that factor B = Id has a greater influence by 2034.18% on the CS of the specimens manufactured by FDM from rPETG. Using Minitab software, the FDM parameters outlined in Table I, and the average results of CS, resulted in the generation of the CS contour plot for the additively manufactured specimens from rPETG [30].

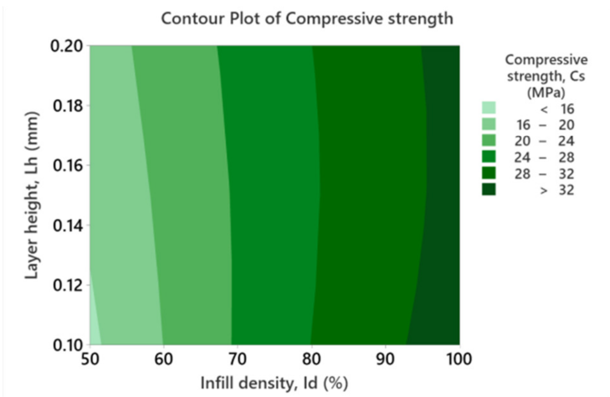

Fig. 12. Contour plot of CS for rPETG specimens manufactured by FDM.

As displayed in the contour graph presented in Figure 11, both parameters of FDM, L_h and Id, influence the CS of the samples made of rPETG, but the parameter affecting it the most is the filling density, Id. In Figure 13, the FDM parameters were optimized to maximize the results of the CS of the samples made of rPETG [30].

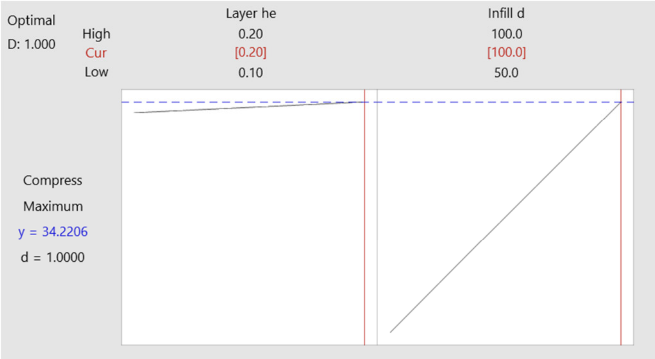

Fig. 13. Optimization plot of L_h and Id FDM parameters for maximizing CS for rPETG specimens.

Figure 13 demonstrates that the filling percentage, Id, has a decisive role in the CS, since its values increase when the filling percentage increases. The optimal parameters for the manufacture of compression specimens from rPETG are L_h = 0.20 mm and Id = 100%.

III. CONCLUSIONS

The current paper provides the results of a study carried out on the optimization of the FDM parameters, namely L_h, the height of the deposited layer in one pass and Id, the filling density, for the manufacture of compression specimens from recycled PETG, with the purpose of transitioning to the circular economy. For the present study, conducted on the Anycubic 4Max 2.0 3D printer, 45 compression specimens (see Figure 4) were manufactured by FDM, from the Everfill brand recycled PETG with a percentage of 100% recycled material using the parameters illustrated in Table I. Subsequently, all 45 specimens were tested in compression on the Barrus White 20 kN universal testing machine, as portrayed in Figure 5. It was found that the overwhelmingly influencing parameter was Id, as can be seen in Figures 10-12, which is also highlighted in [15, 16]. The highest CS value, 34.80 MPa, was obtained for the specimen manufactured with the additive L_h, 0.10 mm and Id, 100%. The lowest value of the CS, 14.38 MPa, was attained for the sample manufactured with the additive L_h, 0.10 mm, and Id 50%. To maximize the CS results of the samples made of rPETG, by using the Minitab software, the manufacturing parameters were optimized, with the optimal value being: L_h 0.20 mm and Id 100%. By comparing the present study's findings with the results in [15], regarding a virgin PETG, the former results are higher, 11.39% – 25.91%. The present study demonstrates that the use of the circular economy production and consumption model for PETG plastics is a viable solution for the application of additive manufacturing technologies through the extrusion of plastics. This former has applicability in the efficiency of production processes through additive manufacturing. The use of the optimal parameters established in the present study will contribute to a decrease in energy consumption and the number of scraps, whereas productivity will increase. It is proposed to extrapolate the study by performing other types of mechanical tests, such as resilience and bending tests, and also employing other types of materials, like rASA and rPETG with different percentages of recycled material.

REFERENCES

[1] L. Castanon-Jano, P. Palomera-Obregon, M. Lázaro, E. Blanco-Fernandez, and S. Blasón, "Enhancing sustainability in polymer 3D printing via fusion filament fabrication through integration of by-products in powder form: mechanical and thermal characterization," *The International Journal of Advanced Manufacturing Technology*, vol. 133, no. 3, pp. 1251–1269, Jul. 2024, https://doi.org/10.1007/s00170-024-13635-3.

[2] "Global plastic production," *Statista*. https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/.

[3] "Plastics – the fast Facts 2023 • Plastics Europe," *Plastics Europe*. https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/.

[4] H. Jiao *et al.*, "A critical review on plastic waste life cycle assessment and management: Challenges, research gaps, and future perspectives," *Ecotoxicology and Environmental Safety*, vol. 27, Feb. 2024, Art. no.115942, https://doi.org/10.1016/j.ecoenv.2024.115942.

[5] L. T. Helm, E. L. Murphy, A. McGivern, and S. B. Borrelle, "Impacts of plastic waste management strategies," *Environmental Reviews*, vol. 31, no. 1, pp. 45–65, Mar. 2023, https://doi.org/10.1139/er-2021-0117.

[6] J. Zhao, Y. Yang, M. H. Kobir, J. Faludi, and F. Zhao, "Driving additive manufacturing towards circular economy: State-of-the-art and future research directions," *Journal of Manufacturing Processes*, vol. 124, pp. 621–637, Aug. 2024, https://doi.org/10.1016/j.jmapro.2024.06.018.

[7] B. D. Hettiarachchi, J. I. Sudusinghe, S. Seuring, and M. Brandenburg, "Challenges and Opportunities for Implementing Additive Manufacturing Supply Chains in Circular Economy," *IFAC-PapersOnLine*, vol. 55, no. 10, pp. 1153–1158, Jan. 2022, https://doi.org/10.1016/j.ifacol.2022.09.545.

[8] T. V. N. Tran, D. C. Long, and C. N. Van, "The Influence of Printing Materials on Shrinkage Characterization in Metal 3D Printing using Material Extrusion Technology," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 15356–15360, Aug. 2024, https://doi.org/10.48084/etasr.7758.

[9] T. A. Alka, R. Raman, and M. Suresh, "Research trends in innovation ecosystem and circular economy," *Discover Sustainability*, vol. 5, no. 1, Oct. 2024, Art. no. 323, https://doi.org/10.1007/s43621-024-00535-5.

[10] J. D. Seno Flores, T. de Assis Augusto, D. A. Lopes Vieira Cunha, C. A. Gonçalves Beatrice, E. Henrique Backes, and L. C. Costa, "Sustainable polymer reclamation: recycling poly(ethylene terephthalate) glycol (PETG) for 3D printing applications," *Journal of Materials Science: Materials in Engineering*, vol. 19, no. 1, Aug. 2024, Art. no. 16, https://doi.org/10.1186/s40712-024-00163-x.

[11] H. Martin, D. Chebrolu, A. Chadee, and T. Brooks, "Too good to waste: Examining circular economy opportunities, barriers, and indicators for sustainable construction and demolition waste management," *Sustainable Production and Consumption*, vol. 48, pp. 460–480, Jul. 2024, https://doi.org/10.1016/j.spc.2024.05.026.

[12] J. Priyadarshini, R. Kr Singh, R. Mishra, and M. Mustafa Kamal, "Adoption of additive manufacturing for sustainable operations in the era of circular economy: Self-assessment framework with case illustration," *Computers & Industrial Engineering*, vol. 171, Sep. 2022, Art. no. 108514, https://doi.org/10.1016/j.cie.2022.108514.

[13] D. Silva, J. Garrido, B. Lekube, and A. Arrillaga, "On-board and port 3D printing to promote a maritime plastic circular economy," *Journal of Cleaner Production*, vol. 407, Jun. 2023, Art. no. 137151, https://doi.org/10.1016/j.jclepro.2023.137151.

[14] C. G. Cheah, W. Y. Chia, S. F. Lai, K. W. Chew, S. R. Chia, and P. L. Show, "Innovation designs of industry 4.0 based solid waste management: Machinery and digital circular economy," *Environmental Research*, vol. 213, Oct. 2022, Art. no. 113619, https://doi.org/10.1016/j.envres.2022.113619.

[15] D. G. Zisopol, M. Minescu, and D. V. Iacob, "A Study on the Influence of FDM Parameters on the Compressive Behavior of PET-G Parts," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13592–13597, Apr. 2024, https://doi.org/10.48084/etasr.7063.

[16] D. G. Zisopol, M. Minescu, and D. V. Iacob, "A Study on the Influence of FDM Parameters on the Compressive Behavior of ASA Parts,"

Engineering, Technology & Applied Science Research, vol. 14, no. 5, pp. 16237–16241, Oct. 2024, https://doi.org/10.48084/etasr.8067.

[17] J. J. Ezhilan, A. Damodaran, and K. G. Ashok, "Study on Recyclebot with 3D Printing Wastes for Circular Economy," *Materials Science Forum*, vol. 1110, pp. 135–141, 2023, https://doi.org/10.4028/p-L7EzIw.

[18] H.-H. Hsieh, K.-C. Yao, C.-H. Wang, C.-H. Chen, and S.-H. Huang, "Using a Circular Economy and Supply Chain as a Framework for Remanufactured Products in the Rubber Recycling Industry," *Sustainability*, vol. 16, no. 7, Jan. 2024, Art. no. 2824, https://doi.org/10.3390/su16072824.

[19] T. V. N. Tran, D. C. Long, and C. N. Van, "The Influence of Printing Materials on Shrinkage Characterization in Metal 3D Printing using Material Extrusion Technology," *Engineering, Technology & Applied Science Research*, vol. 14, no. 4, pp. 15356–15360, Aug. 2024, https://doi.org/10.48084/etasr.7758.

[20] N. T. Anh, N. X. Quynh, and T. T. Tung, "Study on Topology Optimization Design for Additive Manufacturing," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14437–14441, Jun. 2024, https://doi.org/10.48084/etasr.7220.

[21] A. Al Rashid and M. Koç, "Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste," *Materials Today Sustainability*, vol. 24, Dec. 2023, Art. no. 100529, https://doi.org/10.1016/j.mtsust.2023.100529.

[22] T. M. Tavares, G. M. D. Ganga, M. Godinho Filho, and V. P. Rodrigues, "The benefits and barriers of additive manufacturing for circular economy: A framework proposal," *Sustainable Production and Consumption*, vol. 37, pp. 369–388, May 2023, https://doi.org/10.1016/j.spc.2023.03.006.

[23] M. Garwacki, I. Cudnik, D. Dziadowiec, P. Szymczak, and J. Andrzejewski, "The Development of Sustainable Polyethylene Terephthalate Glycol-Based (PETG) Blends for Additive Manufacturing Processing—The Use of Multilayered Foil Waste as the Blend Component," *Materials*, vol. 17, no. 5, Jan. 2024, Art. no. 1083, https://doi.org/10.3390/ma17051083.

[24] H. Schneevogt, K. Stelzner, B. Yilmaz, B. E. Abali, A. Klunker, and C. Völlmecke, "Sustainability in additive manufacturing: Exploring the mechanical potential of recycled PET filaments," *Composites and Advanced Materials*, vol. 30, Jan. 2021, Art. no. 26349833211000063, https://doi.org/10.1177/26349833211000063.

[25] B. Pricop, Ștefan D. Sava, N.-M. Lohan, and L.-G. Bujoreanu, "DMA Investigation of the Factors Influencing the Glass Transition in 3D Printed Specimens of Shape Memory Recycled PET," *Polymers*, vol. 14, no. 11, Jan. 2022, Art. no. 2248, https://doi.org/10.3390/polym14112248.

[26] C. Maraveas, I. V. Kyrtopoulos, and K. G. Arvanitis, "Evaluation of the Viability of 3D Printing in Recycling Polymers," *Polymers*, vol. 16, no. 8, Jan. 2024, Art. no. 1104, https://doi.org/10.3390/polym16081104.

[27] "The Proven Solution for 3D Design and Product Development | SOLIDWORKS," Dec. 07, 2023. https://www.solidworks.com/proven-solution-3d-design-and-product-development.

[28] "UltiMaker Cura," *UltiMaker*. https://ultimaker.com/software/ultimaker-cura/.

[29] *Plastics — Determination of compressive properties*, 3rd ed. ISO International Standard, 2002.

[30] "Data Analysis, Statistical & Process Improvement Tools | Minitab." https://www.minitab.com/en-us/.