26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1406

EXTRUSION-BASED 3D PRINTING: COLOR INFLUENCE ON MECHANICAL PROPERTIES OF PLA PARTS

Francisco Castro
Faculadade de Engenharia da Universidade do Porto, FEUP, Porto, Portugal
franciscofacastro@gmail.com

Leonardo Santana
Universidade Federal de Santa Catarina, UFSC, Florianópolis, Brasil
leonardosantana29@gmail.com

Jorge Lino Alves
INEGI, Faculdade de Enegnharia da Universidade do Porto, FEUP, Porto, Portugal
falves@fe.up.pt

Abstract. *3D printing material suppliers in general provide scarce information about materials properties or on how the inclusion of different types of pigments can affect the quality standard of printed parts. In this study we evaluate the influence of color on the mechanical properties in PLA (Poly lactic acid) parts. For each filament color (blue, white, orange and red), two sets of samples were printed for three-point flexural tests, taken with original printing conditions and after an annealing treatment (HT). Measurements of the mass of the parts were carried out, in addition to the density and analysis of the molecular composition, through Fourier Transform Infrared Spectroscopy (FTIR), of the filaments. The results showed that the molecular structure of polymers with different colors and its density are similar, thus no conclusion regarding the presence of additives could be made. The color significantly influenced the mechanical responses and mass of the parts with and without heat treatment. Annealing increased the maximum flexural strength in all samples. Parts' modulus also slightly increased, indicating that the HT was not adequate to increase crystallization due to the influence of the pigments. Results suggest that color brings unpredictability to the behavior of printed and post treated parts.*

Keywords: *extrusion, FFF, PLA, color, annealing*

1. INTRODUCTION

Extrusion-based 3D printing is one of the most used and known techniques in the Additive Manufacturing field. This popularity is due to two facts: (i) the fall of the Stratasys™ (2009) patents — related to the Fused Deposition Modeling (FDM) process — and (ii) the emergence of open-source movements, such as the RepRap project. These two factors combined were responsible for unprecedented developments in terms of software and 3D printing machines, in addition to promoting the so-called technological "democratization" of the now known Fused Filament Fabrication (FFF), which brought knowledge and systems to common users, that is, to the domestic environment. As expected, the consumables market for the sector strongly followed this evolution, ensuring access to filaments of Acrylonitrile Butadiene Styrene (ABS), Nylon, Polyethylene Terephthalate Glycol (PETG), Poly Lactic Acid (PLA), among other bases, often mixed with fillers of wood, metal, carbon fiber, plant residues and, mainly, pigments (Antoniac *et al*., 2019; Davis *et al*., 2019; Shaqour *et al*., 2021).

Albuquerque (2014) already highlighted in his work that there was no standardization of the characteristics of the filaments and, therefore, depending on the material, color, and supplier, the printing parameters varied, and it was up to the user to find the best configuration, usually by trial and error. Even with the evolution observed in the types of filaments for FFF, little has changed in recent years in terms of regulation of the manufacture and commercialization of these materials. Many companies still fail on consumer support, especially concerning the development and dissemination of knowledge about the parameterization of filaments as a function of the polymer base and its additives. The academy, in turn, has been directing its efforts towards the development and analysis of high-performance materials, which bring together composites, but in a scenario in which the domain of the "simple", in this case, the use of filaments with additives with pigments, is not yet established.

This situation alerts, therefore, to the importance of involving scientists in the production of research on the influence of pigments on the final quality of printed products. Studies such as those by Wittbrodt and Pearce (2015), Du Plessis *et al*. (2016), Soares *et al*. (2018), Davis *e al*. (2019) and Yi *et al*. (2019) are examples of initiatives that evaluated pigmented filaments, and parts made with them, considering mechanical properties, porosity and presence of inclusions, geometric/dimensional deviations, thermal and chemical behavior, and emission of volatile organic particles during the printing process. However, there are still few works in this area, due to the great demand for materials with colors commercially available.

Given the above, this study aimed to evaluate the influence of color on the flexural response of PLA parts obtained by FFF, as well as to assess whether the trends observed in terms of pigments in newly printed elements were reproducible in a post-heat treatment scenario under isoparametric conditions. It is intended to emphasize the importance of discussing the homogenization of the types of pigments and their quantities applied to the materials, as well as the establishment of printing configurations/specific treatments for each color in future works.

2. MATERIALS AND METHODS

In this paper, four PLA filaments were used, from the same supplier, Filament PM™, 1.75 mm in diameter, in the following colors: blue, white, orange, and red. A fifth material, a gray PLA filament from Prusa Research™, was also employed for the calibration of the printing equipment as well as the parameters (time/temperature) for the annealing heat treatment (HT). This methodology was adopted, since the gray PLA was supplied in the acquisition of the 3D printer used in this research, thus becoming a fundamental part of the initial condition of the printing system. In general, the study was divided into two stages: (i) characterization of the filaments and (ii) analysis of printed parts (Figure 1).

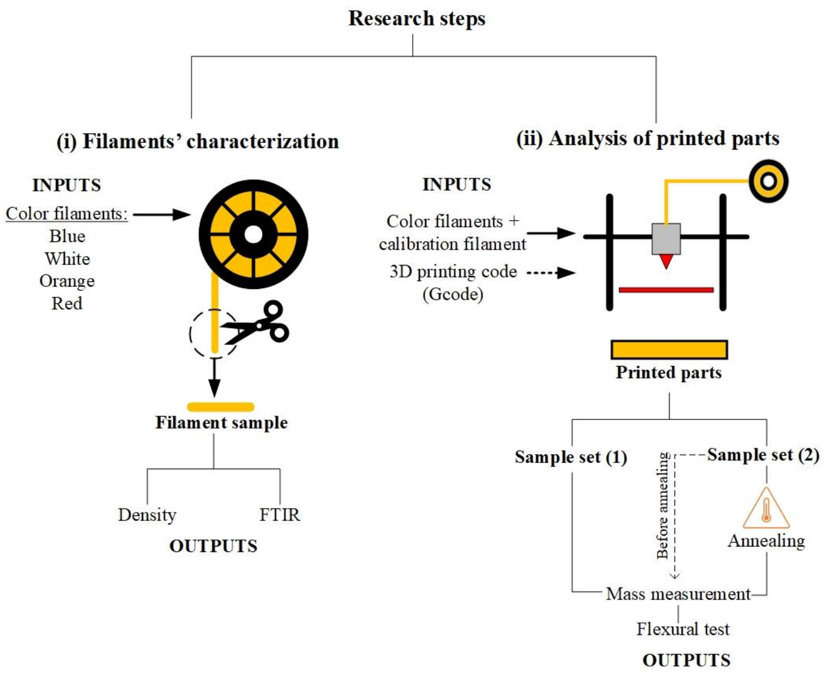

Figure 1. Research methodology.

In the first stage, the four filaments, in different colors, were characterized as a function of density measurement and molecular structure analysis by Fourier Transform Infrared Spectroscopy (FTIR). Density was measured using the Archimedes method, using a Mettler™ scale model H31AR (0.1 mg resolution). First, the mass of the specimens was measured in dry, then measured when immersed in distilled water (at 23 ºC). Five samples per material were cut for density measurement. An Agilent Technologies™ Cary 630 FTIR instrument was used in spectroscopy analysis to measure bands in the 4000 to 650 cm^{-1} wavelength range.

For the second part of the research, samples were printed for flexural tests according to the geometries and dimensions described in the ASTM D790 (2010) standard — Figure 2 (a). For each of the four main PLA colors and for the calibration material, sets of five samples were produced in "as printed" condition and another set of five pieces for testing after annealing — Figure 2 (b). All specimens were manufactured on a Prusa I3 MK3s 3D printer. The planning of the printing process was carried out using the PrusaSlicer software (version 2.3.0), in which, regardless the color, the following parametric configuration was established: building orientation (lateral), infill pattern (concentric), infill density (100 %), layer thickness (0.2 mm), infill speed (40 mm/s), perimeter speed (20 mm/s), extrusion temperature (215/210 °C), bed temperature (60 °C) and overlap (27 %).

The annealing treatment (HT) of the samples was carried out in a Pol-Eko™ model SLW 53 STD oven. The HT was carried out in two stages with temperature and time set of: (i) 50 °C for 2h30 min (drying and material accommodation) and (ii) 80°C for 2h30 min (annealing), and both sets were allowed to cool down inside the oven. After printing and heat treatment, the mass of the samples was measured on a Scale House™ HLD300 balance (0.05 g resolution). Finally, for the flexural tests, a dynamometer with a 2.5kN load cell was used, coupled to a displacement unit model MultiTest 2.5 - dV, both from the Mecmesin™ brand. Tests were conducted at a speed of 5 mm/min.

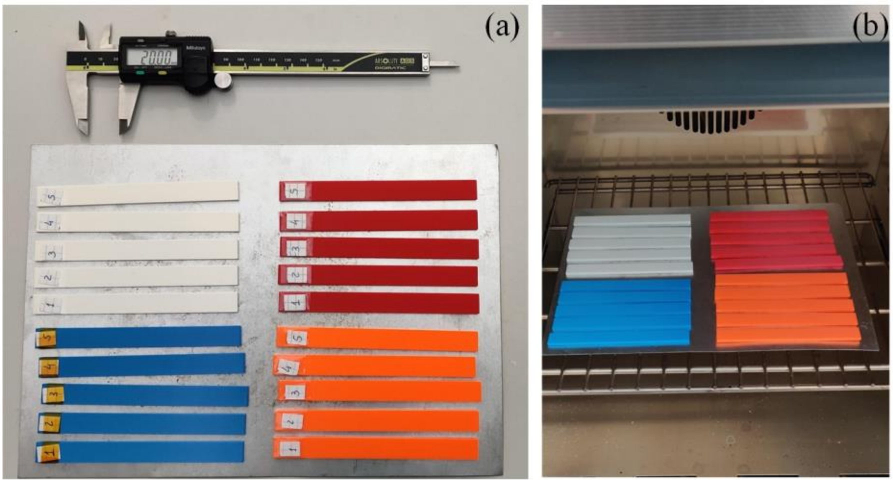

Figure 2. Flexural tests samples (a) and samples positioned inside the oven (b).

3. RESULTS AND DISCUSSIONS

The presentation and discussion of the results obtained in the study was divided according to the two research steps: (i) characterization of the filaments and (ii) analysis of printed parts.

3.1 Filament's characterization

Figure 3 presents the average values for density measurement of the four main colors of filaments.

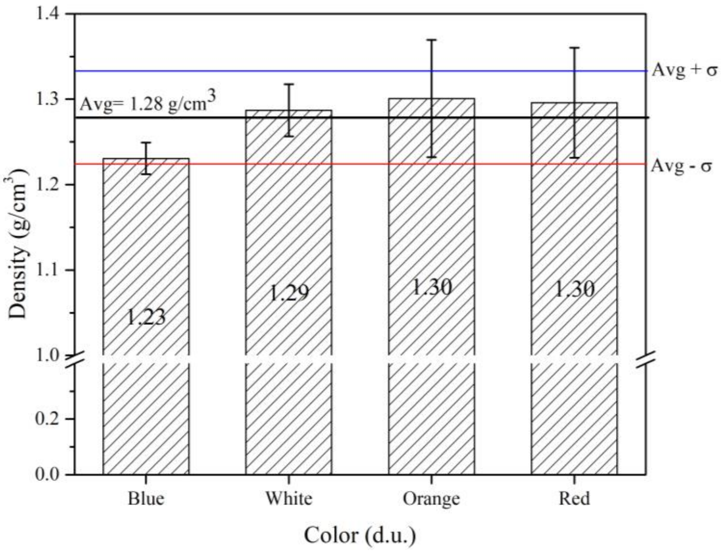

Figure 3. Average density as function of filaments' colors – PLA.

The results presented in the chart above were compared using analysis of variance, ANOVA (α=95 %), with which it was possible to verify that there was no significant difference (F(3.16)=2.08, p=0.14) among the average density dependency on the color levels tested. In other words, the amount of pigment inserted in the mixture of filaments evaluated was not enough to modify this physical property of the material. Furthermore, when analyzing the range of variation (blue and red lines, Figure 3) of total density average, 1.28 g/cm^3 (black line, Figure 3), one can see the values are close to the PLA density described in literature, 1.25 g/cm^3 (Henton *et al*., 2005).

Figure 4 is related to the results of the filament characterization, showing the curves resulting from the FTIR analysis. The color of each line corresponds to the color of each material analyzed. To simplify data exposure, four regions were delimited in the graphs.

In general, FTIR characterization indicates that the filaments evaluated present a molecular structure like that of other 3D printing PLAs evaluated in the literature, such as in the study of Santana *et al*. (2018) — the reference mentioned makes a broad analysis of the PLA spectra, not limited to the context of extrusion-based AM. The peeks in Region I of the graph — 2996-2998 cm^{-1}, 2945-2947 cm^{-1} — correspond to the stretching – CH (CH3 group). In Region II, the identified peak (1745-1747 cm^{-1}) concerns to the -C=O stretching of the ester group, belonging to the polylactic acid chain. Region III presents the spectra related to C-O-C stretching, while in Region IV bands are observed at 755 cm^{-1} and 867 cm^{-1} that represent, respectively, the crystalline and amorphous portions of PLA (Matos *et al*., 2019; Pop *et al*., 2019; Santana *et al*., 2018; Soares *et al*., 2018).

In summary, FTIR showed that the filaments, in fact, correspond to the PLA polymer. They did not differ significantly in their molecular structure as a function of the pigments, as no unconventional band was identified, in addition to the fact that they present peaks with similar intensities. Finally, spectroscopy revealed that the polymers were semi-crystalline and, therefore, sensitive to the impacts of thermal variations on the material's crystallization patterns caused by the 3D Printing process, and by annealing. However, it is important to emphasize that the approach performed does not make a thorough scan of the chemical composition of the filaments in different colors and, therefore, some element not identified by the responses of the techniques used can lead to changes in the mechanical behavior of the printed pieces.

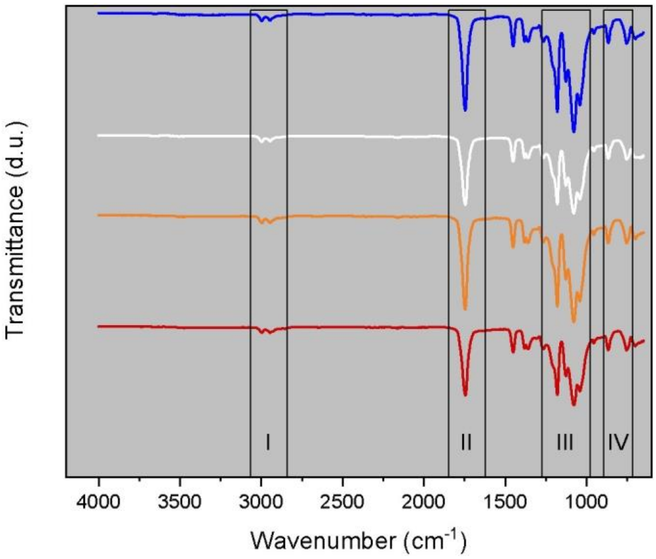

Figure 4. FTIR results.

3.2 Anlisys of printed parts

The average mass of the samples for the flexural tests is presented in Table 1 for the different analysis conditions: "as printed" and "after annealing". It is important to emphasize that the "pre-annealing" column corresponds to the mass of the parts manufactured for the heat treatment, however only measured before the heat treatment. The means in Table 1were compared using a Scott-Knott test. Values with the same uppercase letters in the table columns are the same; on the other hand, the lowercase letters, when equal, correspond to equal averages in the table lines.

Table 1. Samples average mass and Scott-Knott test.

Color	Mass (g)		
	"As printed"	*"Pre-annealing"*	*"After annealing"*
Blue	6.01 ± 0.004 Aa	6.02 ± 0.005 Ab	6.01± 0.003 A
White	6.12 ± 0.004 Ba	6.12 ± 0.004 Ba	6.12 ± 0.004 B
Orange	6.03 ± 0.009 Ca	6.02 ± 0.002 Ab	6.01± 0.004 A
Red	6.05 ± 0.002 Da	6.09 ± 0.003 Cb	6.09 ± 0.003 C

We can see in the "as printed" parts for flexural test (column 1) that the average mass is different for all colors, with white PLA being the material that provides samples with higher mass, approximately 2% greater than the blue ones, which have the lowest average mass. The "pre-annealing" sample group (column 2) still presents white components as the ones with greater mass, however, there is a different behavior compared to the previous group, since the blue PLAs masses turned to be equal to those of orange PLA. In theory, the groups should follow the same pattern between colors, since all parts have the same printing parameterization and had their mass measured right after the manufacturing process. To reinforce the differences, one can analyze the comparison in the lines of the Table 1(column 1 and 2) between parts built with the same material (same color), in all cases, except for white, statistical differences are found. The result shows a stability of the white material and, probably, a better response from it to the thermal and volumetric flow adjustments configured for the printing of parts. However, the differences found are small and may be related to minor manufacturing defects, or even issues related to the repeatability of printing or measuring equipment. The comparison between the components under the conditions "pre-annealing" and "after annealing" shows that the pattern of differences and equalities between colors is kept, with no significant change in mass due to heat treatment.

The average results for maximum strength and flexural modulus are presented in Figure 5 (a) and (b) for both conditions: "as printed" and "after annealing”. The average values presented in Figure 5, related to the mechanical properties of the main filaments in the study, were compared using the Scott-Knott test (Table 2).

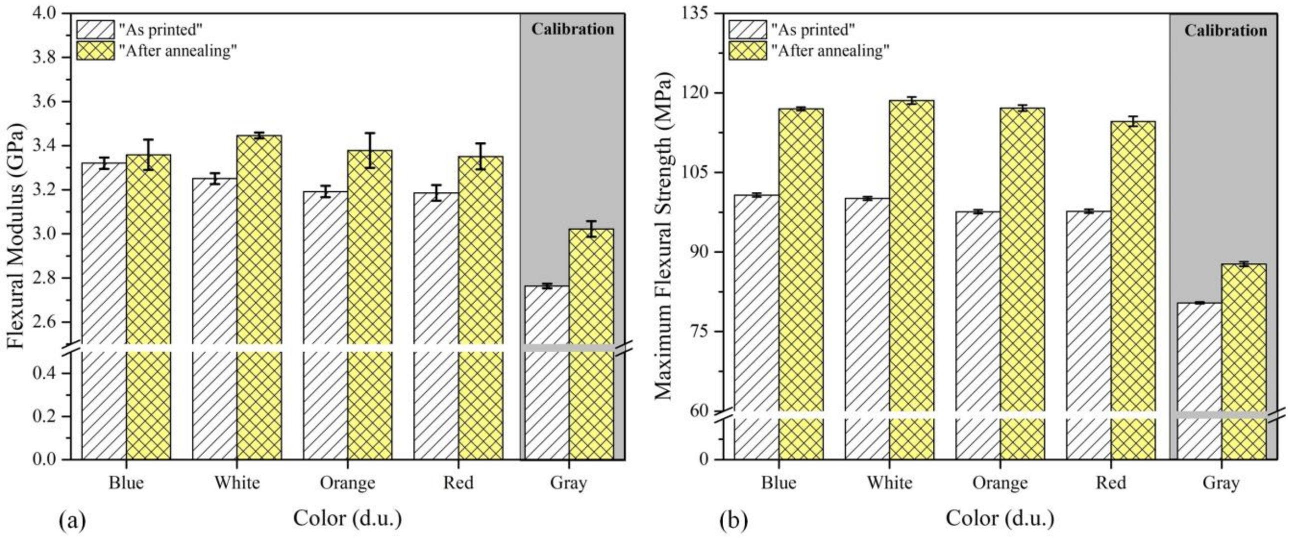

Figure 5. Mechanical properties results: (a) flexural modulus and (b) maximum flexural strength.

Table 2. Mechanical properties results and Scott-Knott test.

Color	Flexural Modulus (GPa)		Maximum Flexural Strength (MPa)	
	“As printed”	*“After annealing”*	*“As printed”*	*“After annealing”*
Blue	3.32 ± 0.03 Ca	3.36 ± 0.07 Ba	100.74 ± 0.35 Aa	116.99 ± 0.33 Ab
White	3.25 ± 0.02Ab	3.45 ± 0.01 Aa	100.10 ± 0.34 Aa	118.57 ± 0.66 Bb
Orange	3.19 ± 0.03 Bb	3.38 ± 0.08 Ba	97.60 ± 0.36 Ba	117.13 ± 0.58 Ab
Red	3.19 ± 0.04 Bb	3.35 ± 0.06 Ba	97.68 ± 0.36 Ba	114.64 ± 0.94 Cb
Gray	**2.76 ± 0.01**	**3.02 ± 0.04**	**80.41 ± 0.17**	**87.73 ± 0.44**

From the mechanical properties of the parts in the "as printed" group, it is possible to verify the influence of pigments on the responses obtained in components manufactured with PLA filaments with different colors. This shows that despite the small amount of additive, unable to be detected in the FTIR and density analysis, the presence of pigments affects the behavior of the polymer base. Blue PLA generally has the best mechanical performance after 3D Printing, with modulus and maximum flexural strength values approximately 4% and 3% higher than red and orange PLAs (worst results).

Flexural modulus values indicate that the heating and cooling cycles during the printing process are enough to produce a slightly higher crystallization in the blue material than in the others. Heating corresponds to thermal energy supplied by the extrusion and base temperature. Cooling, in turn, is induced by transitions between layers and by the fan system. In other words, blue PLA has better overall response to the fixed printing settings used. The thermal effects, however, are not able to promote a significant difference in the modules of red and orange parts. Such alternation of scenarios describes an effective influence of the pigment, which according to Wittbrodt and Pearce (2015), clearly affects the degree of crystallinity of PLA in FFF 3D printing.

The randomness of the mechanical responses becomes more evident when the results of the maximum flexural strength are analyzed. The Scott-Knott test shows a statistical equality between the average values of blue and white PLAs and orange and red PLAs. The patterns obtained in the comparisons between the modulus averages and between the tension averages are not the same and, therefore, it is not possible to establish a color prediction model for what would be the total mechanical properties of the printed pieces. Randomness in behavior is mainly associated with Blue and White pigments. This probably shows that they can change the crystalline response of PLA depending on the printing temperatures used. However, they are not effective in structurally altering the parts (neck growth between neighboring deposited filaments and adhesion line integrity) in such a way as to generate a significant difference in its flexural strength. On the other hand, the statistical equality in the mechanical properties of the Red and Orange PLAs indicate that the pigments may have a similar chemical origin, which induces a uniform response of the material to the applied thermal parameters. After the annealing treatment, the entire scenario observed in the mechanical properties of “as printed” parts was modified, reinforcing, once again, that pigments are responsible for the unpredictability of the effects generated by thermal mechanisms in the final quality of the printed models (Figure 5). For the "after annealing" condition, the white PLA turns out to have the highest values, being 3% greater than the red PLA (worst results in absolute values), for both flexural modulus and maximum flexural strength, respectively.

In all cases, an increase in maximum flexural strength of approximately: +20% in orange, +18% in white, +17% in red and +16% in blue is observed. As well as the maximum flexural strength, an increase in modulus was observed in all materials, except for the blue: +6% for white and orange and +5% for red. Blue, which was the material with the best mechanical properties in the “as printed” condition, benefited the least from the heat treatment. In addition to white, orange PLA appears as another material with good response to annealing, as it increases its maximum strength and flexural modulus to values statistically similar to the blue ones.

The statistical similarity between the modules of the Blue, Red and Orange PLAs may display some behaviors associated with the materials: (i) the Blue PLA, as it did not follow the trend of the other filaments to increase its modulus with the HT, may have reached its maximum level of crystallinity only with the thermal gradients of 3D Printing process; (ii) assuming that the Blue PLA has crystallized at the temperatures involved in printing, the growth in the modulus of Red and Orange PLAs with HT can indirectly highlight the need for higher levels of thermal energy during the additive process; this could be done by increasing extrusion and base temperatures, reducing interlayer deposition time (print speed) and improving heat transfer mechanisms between neighboring filaments (decreasing layer thickness); (iii) finally, annealing can, for certain pigments, reduce the influence of color on the crystallinity of the material and homogenize the flexural modulus of the parts as a function of the polymer base of the filaments. This last hypothesis, however, can vary according to the concentration of additives in the mixture.

These small differences observed in the “after annealing” parts, in relation to those “as printed”, may be related to the fact that the heat treatment was not carried out based on the thermal properties, especially in the adjustment around the glass transition temperature, unique to each PLA, due to the pigment. In addition to the annealing temperature levels, a longer or shorter thermal exposure time could be planned to depend on the color of the material.

The energy levels provided in the HT performed in this study may have been sufficient to promote a relief of residual stresses, formed in 3D Printing, and for the structural improvement of the parts. On this last aspect, it is assumed that the heat generated by the annealing may have activated, even partially, the mobility of the material in the bonding zones between and within the layers, consequently leading to an end to the growth or strengthening of the necks between neighboring filaments. The sum of these effects may have been responsible for the increase in the maximum flexural strength.

On the other hand, the annealing times and temperatures were enough to promote the slight growth of the material's crystalline structure, or to finish a crystallization interrupted by the 3D printing process. When inserting a new thermal history for the parts, the flexural modulus was increased.

In PLA, in addition to crystallinity, the composition of the crystal form also influences the modulus. Higher modules are achieved when PLA is formed by α-form crystals, as they promote a more ordered and dense structure than those found in α'-form (disordered) crystals (Cocca *et al*., 2011; Zhou *et al*., 2016). These disordered elements emerged in annealing at low temperatures (Tábi *et al*., 2010). Based on these concepts, it can be assumed that the annealing temperatures used in this study with different PLAs colors were enough to generate the transformation of a small amount of α’ into α crystals and, thus, promote a slight increase in the flexural modulus. In the study conducted by Courgneau *et al.* (2012) with pure PLA, it was observed an increase in the tensile strength of the samples after annealing, but with a reduction in the Young modulus. This situation shows how unstable the application of heat treatments on PLA parts is, and according to the data in this article, how it can become more complex with the presence of additives, such as pigments.

Finally, the results of the flexural tests with the main-colored filaments corroborate the situation observed in the calibration material, that is, of improvement in mechanical properties with the annealing treatment. In the case of the calibration material, there was a 9% increase in both modulus and maximum flexural strength. Especially in the flexural modulus, one of the properties most affected by annealing, the growth of the response in gray PLA was considerably higher than those observed in other PLAs. It should be noted, however, that many experiments were carried out until reaching the best time and temperature parameters for annealing gray PLA (Castro, 2021). This situation strengthens the need for calibration studies of specific HTs for the same polymer base only varying in color and supplier.

4. CONCLUSION

The results of this study point out that even though the material in the form of filament is not different in their polymeric base, that is not true after the printing process, since parts with different properties and quality characteristics are obtained with the materials in the different colors. This situation leads to a necessary calibration of the printing settings for each individual material because, mainly the extrusion temperature, affects the fluidity of the extruded filament, leading to different results in the test specimens. This study alerts users of extrusion-based 3D Printing to the need for color- and manufacturer-specific parametric calibration studies. As for the suppliers, it becomes increasingly important that they start to provide manuals for the printing configuration of materials by color and type.

The pigments significantly influenced the variation in mass and flexural properties of printed parts, generating unpredictable behavior depending on the applied analysis conditions. This is due to the different origins that these additives can have. Depending on the color, organic or inorganic pigments can be used (SpecialChem, 2018), and their concentration in the mixtures will change the thermal and rheological characteristics of the materials and, therefore, the configuration of important printing settings, such as extrusion and bed temperatures, or even the control of material flow/amount (extrusion multiplier, print speeds, layer thickness and road width). Therefore, this work concludes that it is impracticable to use isoparametric printing conditions, based only on the polymer base of the filaments. This study corroborates the work of Wittbrodt and Pearce (2015) that also shows the difference in mechanical properties of colored printed parts.

The pigmentation also influences the behavior of the materials when submitted to heat treatments, since it reacts differently to the thermal exposure, leading to different statistical patterns of the mechanical properties. As with 3D Printing, unique calibration procedures are required for each color.

In the future, it is required a study that conducts an analysis of the type and amount of the used pigments and how it affects the thermal and rheological behaviors and, consequently, the printing process as well as the post heat treatment behavior of the material.

5. ACKNOWLEDGEMENTS

To the Laboratório de Desenvolvimento de Produto e Serviços (LDPS/INEGI) for the assigned facilities to carry out this study, to the Laboratório Lubrificantes (CETRIB/INEGI) for assigning the equipment and technical support necessary to execute the FTIR analysis and to Technical Assistant Emília Soares for assigning the equipment needed to carry out the density analysis.

6. REFERENCES

Albuquerque, J.A., 2014. *Optimización y caracterización de piezas de PLA fabricadas mediante técnicas aditivas.* Undergraduate Thesis, Undergraduate Program in Industrial Technologies Engineering, Carlos III University, Madrid, Spain.

Antoniac, I., Popescu, D., Zapciu, A., Antoniac, A., Miculescu, F., and Moldovan, H., 2019. “Magnesium filled polylactic acid (PLA) material for filament based 3D printing”. *Materials*, Vol. 12, No. 5, pp. 719.

ASTM, 2010. Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. ASTM D790 – 10.

Castro, F.F.A., 2021. *Análise da influência da pigmentação na qualidade de peças impressas por FFF em PLA e PETG*. Master’s Thesis, Graduate Program in Mechanical Engineering, Faculty of Engineering of University of Porto (FEUP), Porto, Portugal.

Cocca, M., Di Lorenzo, M. L., Malinconico, and M., Frezza, V., 2011. “Influence of crystal polymorphism on mechanical and barrier properties of poly(l-lactic acid)”. *European Polymer Journal*, Vol. 45, No. 5, pp. 1073-1080.

Courgneau, C., Domenek, S., Lebossé, R., Guinault, A., Avérous, L., and Ducruet, V., 2012. “Effect of crystallization on barrier properties of formulated polylactide”. *Polymer International*, Vol. 61, No. 2, pp. 180-189.

Davis, A.Y., Zhang, Q., Wong, J.P.S., Weber, R.J., and Black, M.S., 2019. “Characterization of volatile organic compound emissions from consumer level material extrusion 3D printers”. *Building and Environment*, Vol. 160, pp. 106209.

Du Plessis, A., Le Roux, S.G., and Steyn, F., 2016. “Quality investigation of 3D printer filament using laboratory X-ray tomography”. *3D Printing and Additive Manufacturing*, Vol. 3, N.4, pp. 262-267.

Henton, D.E., Gruber, P., Lunt, J., and Randall, J., 2005. “Polylactic acid technology”, In: Mohanty, A. K., Mis-ra, M., Drzal,L. T. (eds*), Natural Fibers, Biopolymers, and Biocomposites, chapter 16, Boca Raton, CRC Press Taylor & Francis Group.*

Matos, B.D.M., Rocha, V., Silva, E.J., Moro, F.H., Bottene, A.C., Ribeiro, C.A., Dias, D.S., Antonio, S.G., Amaral, A.C., Cruz, S.A., Barud, H.G.O., and Barud, H.S., 2019. “Evaluation of commercially available polylactic acid (PLA) filaments for 3D printing applications”. *Journal of Thermal Analysis and Calorimetry*, Vol.137, No.2, pp. 555–562.

Pop, M.A., Croitoru, C., Bedő, T., Geamăn, V., Radomir, I., Coșniță, M., Zaharia, S.M., Chicoș, L.A., and Miloșan, I., 2019. “Structural changes during 3D-printing of bio-derived and synthetic thermoplastic materials”. *Journal of Applied Polymer Science*, Vol. 136, No. 17, pp. 47382.

Santana, L., Alves, J.L., Sabino Netto, A.C., and Merlini, C., 2018. "Estudo comparativo entre PETG e PLA para impressão 3D através de caracterização térmica, química e mecânica". *Matéria (Rio de Janeiro)*, Vol. 23, No.4, e-12267.

Shaqour, B., Abuabiah, M., Abdel-Fattah, S., Juaidi, A., Abdallah, R., Abuzaina, W., Qarout, M., Verleije, B., and Cos, P., 2021. "Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: a review". *Int J Adv Manuf Technol*, Vol. 114, No. 5-6, pp. 1279-1291.

Soares, J.B., Finamor, J., Silva, F.P, Roldo, L., and Cândido, L.H., 2018. "Analysis of the influence of polylactic acid (PLA) colour on FDM 3D printing temperature and part finishing". *Rapid Prototyping Journal*, Vol. 24, N.8, pp.1305-1316.

SpecialChem Platform, 2018, *"Pigments for Plastics: Complete Technical Guide"*, SpecialChem, Paris, https://polymer-additives.specialchem.com/selection-guide/pigments-for-plastics. Accessed 19 June 2021

Tábi, T., Sajó, I.E., Szabó, F., Luyt. A.S. and Kovács, J.G., 2010. "Crystalline structure of annealed polylactic acid and its relation to processing". *eXPRESS Polymer Letters*, Vol. 4, No.10, pp. 659-668.

Wittbrodt, B. and Joshua, M.P., 2015. "The effects of PLA color on material properties of 3-D printed components". *Additive Manufacturing*, Vol. 8, pp. 110-116.

Yi, J., Duling, M.G., Bowers, L.N., Knepp, A.K., LeBouf, R.F., Nurkiewicz, T.R., Ranpara, A., Luxton. T., Martin Jr., S.B., Burns, D.A., Peloquin, D.M., Baumann, E.J., Virji, M.A., and Stefaniak, A.B., 2019. "Particle and organic vapor emissions from children's 3-D pen and 3-D printer toys. *Inhalation Toxicology*, Vol. 31, No. 13-14, pp. 432-445.

Zhou, C., Guo,.H., Li., J., Huang, S., Li, H., Meng, Y., Yu, D., Christiansen, J. C., and Jiang, S., 2016. "Temperature dependence of poly(lactic acid) mechanical properties". *RSC advances*, Vol. 6, No. 114, pp. 113762-113772.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.