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COMPARISON OF MECHANICAL PROPERTIES OF MATERIALS USED IN THE 3D PRINTING TECHNOLOGY

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Abstract: Three-dimensional printing techniques enable three-dimensional objects to be formed by successive layers of material, according to a previously developed numerical model. The primary aim of this study is to analyse the mechanical properties of selected materials used in the spatial printing of machine components and marine equipment. Experimental testing of samples made using the additive method was carried out using an orthogonal plan, in which the experimental factors were selected in such a way that the influence of each factor on the measurement results could be independently assessed. This approach allowed for the elimination of mutual interference between variables and the obtaining of reliable and comparable results. As part of the research, a set of samples with five different filling levels was prepared: 20%, 40%, 60%, 80% and 100%. They were then subjected to a static tensile test to determine such strength parameters as yield strength, tensile strength, Young's modulus and relative strain. The results obtained were summarised in the form of graphs and tables, which enabled a detailed analysis of the influence of the internal structure and filling level on the mechanical properties of the tested materials.

Keywords: 3D printing, material property analysis, FDM, strength properties, additive technologies.

1. INTRODUCTION

Additive manufacturing (AM) technologies are currently one of the most dynamically developing areas of manufacturing engineering. Their essence is the creation of three-dimensional objects by successively applying successive layers of material, in accordance with data from a digital CAD model [Thompson, Moroni and Vaneker 2016]. This process represents a fundamental departure from conventional subtractive methods, in which the shape of a part is obtained by removing excess material [Kończewicz et al. 2022]. As a result, additive technologies offer the possibility of producing components with a high degree of geometric complexity, while reducing raw material consumption and minimising production waste. One of the most commonly used 3D printing methods is Fused Filament Fabrication (FFF), also known as Fused Deposition Modelling (FDM) [Ngo et al. 2018]. This technology involves the layered application of a plasticised thermoplastic filament, which, after being extruded through the print head nozzle, cools and hardens, forming a durable bond with the previously applied layer (Fig. 1) [Hussain 2021]. This produces a three-dimensional model with a specific internal structure that replicates the computer design. Due to the simplicity of the design, low operating costs and easy availability of materials, the FFF method has become the dominant 3D printing technique in hobby, educational and engineering applications [Turner, Strong and Gold 2014].

The advantage of FFF technology is its high versatility – it is possible to use a variety of polymer materials, including PLA (polylactic acid), ABS (acrylonitrile butadiene styrene), PETG (glycol modified polyethylene terephthalate), TPU (thermoplastic polyurethane), as well as glass or carbon fibre reinforced composites [Tekinalp et al. 2014]. The choice of material determines the physical and mechanical properties of the manufactured component, including its stiffness, tensile strength, heat resistance and impact resistance. In addition, thanks to the ability to control process parameters, such as nozzle temperature, table temperature, print speed, layer height, print orientation and fill percentage, the user can influence the final properties of the part [Li et al. 2018].

Despite its numerous advantages, the FFF method is not without its limitations. Among the most important factors determining print quality is the anisotropy of mechanical properties resulting from the layered structure of the product. The bonds between adjacent layers are usually weaker than the cohesion of the material within a single layer, which leads to a reduction in strength in the direction of the construction axis. This phenomenon is particularly important in the context of structural component design, where uniform stress distribution is crucial [Chacón et al. 2017].

In addition, the quality of the interlayer bond depends on process conditions, such as extruder and work table temperature, material cooling rate, layer thickness and filament path width. Incorrect selection of these parameters may result in defects in the internal structure, such as porosity, cracks or insufficient interlayer adhesion, which in turn reduces the integrity and durability of the finished component [Sood, Ohdar and Mahapatra 2010].

Due to the growing use of FFF technology in the mechanical, aerospace, automotive and marine industries, it is particularly important to conduct an analysis of the impact of process parameters on the mechanical properties of prints. Optimisation of the printer settings and the selection of the appropriate material make it possible to obtain components with properties similar to traditionally manufactured structural components, which significantly expands the possibilities of implementing additive technologies in real-world engineering applications [Popescu et al. 2018].

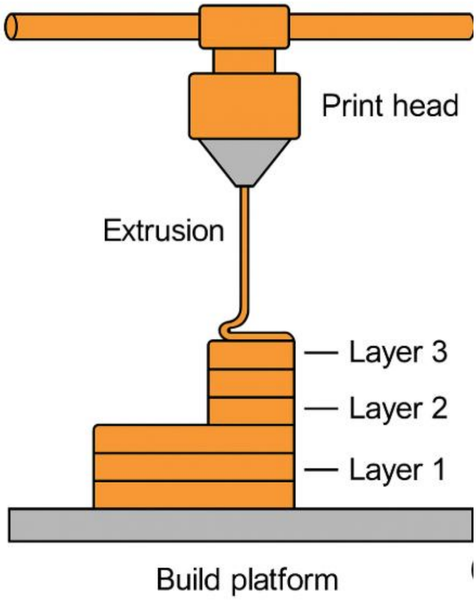

Fig. 1. Schematic representation of layer-by-layer creation in the FFF method

2. RESEARCH METHODOLOGY

The following filaments were used to produce the samples: PC and PCABS with a diameter of 1.75 mm, purchased from Fiberlogy.

The samples (Fig. 2) were produced with the specified parameters (Tab. 1) using an Original Prusa XL 5T 3D printer (Fig. 3). The samples for the static tensile test were made in accordance with the PN-ISO 5893:2015-12 standard [Kończewicz et al. 2022] (Fig. 4). Laboratory tests were carried out using a Zwick & Roell 100kN universal testing machine.

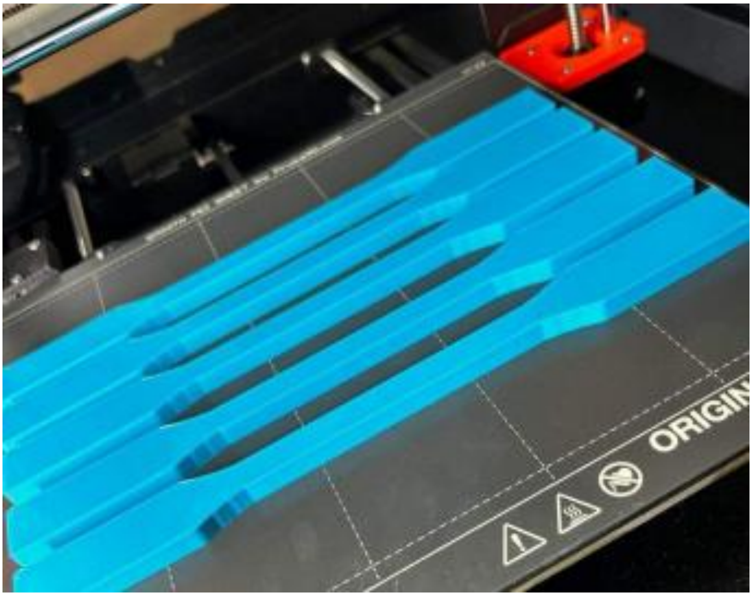

Fig. 2. Samples during printing

Table 1. Parameters used during printing

Parameter	PC	PCABS
Nozzle temperature [°C]	245–260	255–265
Table temperature [°C]	90–110	90–110
Air supply	yes	yes
Infill pattern	Honeycomb	Honeycomb
Infill density [%]	20/40/60/80/100	20/40/60/80/100
Printing speed [millimetres/second]	<100	35–60
Layer height [mm]	0.15	0.15
Nozzle diameter [mm]	0.4	0.4
Additional adhesive agent	yes	yes

Fig. 3. Original Prusa IMK3S+ printer

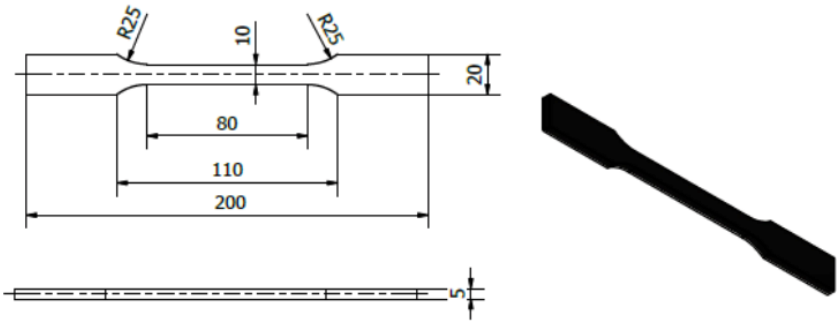

Fig. 4. Dimensions of samples for tensile tests

3. TEST RESULTS

In order to analyse the selected filaments, graphs are presented for the tensile test and strain versus infill density of the printed samples.

PC material

Figure 5 shows the measured results of the tensile strength R_m [MPa] in relation to the infill density of the sample p [%].

Table 2 considers the tensile strength values R_m [MPa] from the infill density of the samples.

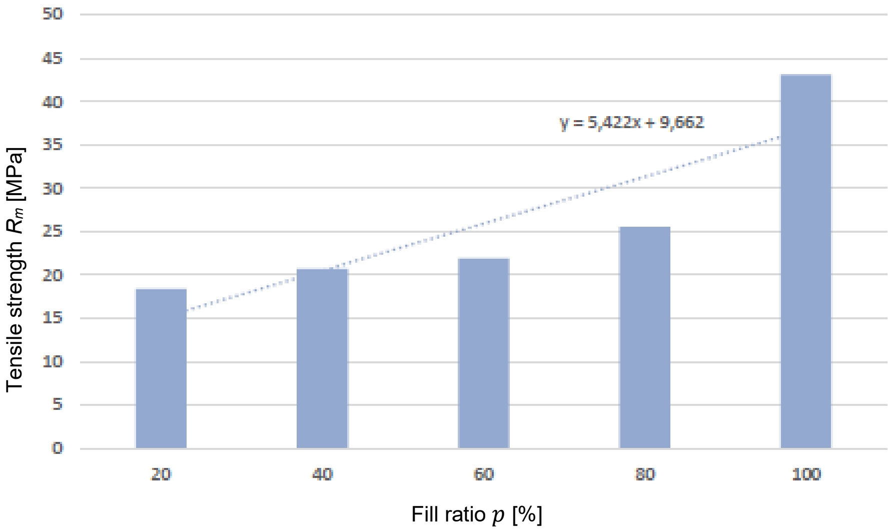

Fig. 5. Diagram of the dependence of the tensile strength on the infill density of the specimens

Table 2. Summary of test results for tensile strength Rm [MPa]

Fill ratio [%] p **[%]**	20	40	60	80	100
Tensile strength Rm [MPa] R_m **[MPa]**	18.41	20.71	21.87	25.55	43.10

The highest tensile strength value was achieved by specimens printed with a 100% infill. The lowest tensile strength value was achieved by samples with a 20% infill. At a 20% infill, the tensile strength is 18.41 MPa, while at the maximum infill it is 43.10 MPa. It is concluded that an increase in material strength occurs with an increase in the infill density.

Figure 6 shows the results of the Young's Modulus [MPa] versus the infill density of the specimens p [%]. The strain values are listed in Table 3.

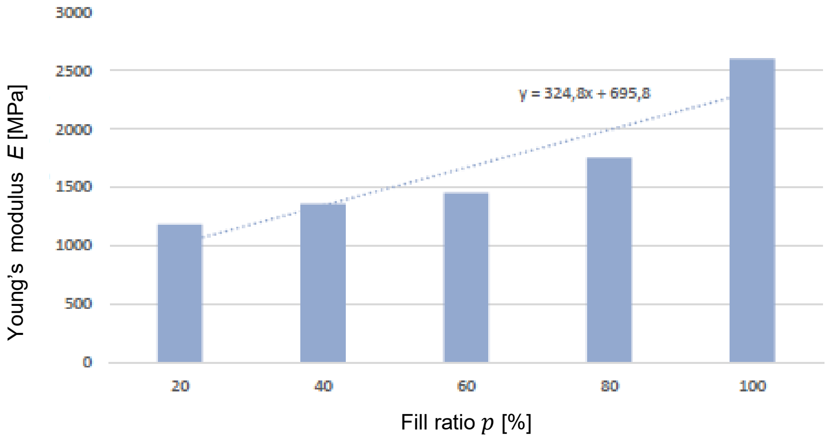

Fig. 6. Graph of the dependence of Young's modulus on the infill density

Table 3. Summary of the Young's Modulus [MPa] results obtained

Fill ratio [%] *p* [%]	20	40	60	80	100
Young's modulus [MPa]	1180	1357	1453	1757	2604

Figure 7 shows the results for the strain [%] versus the specimen printing angle. The strain values are listed in Table 4.

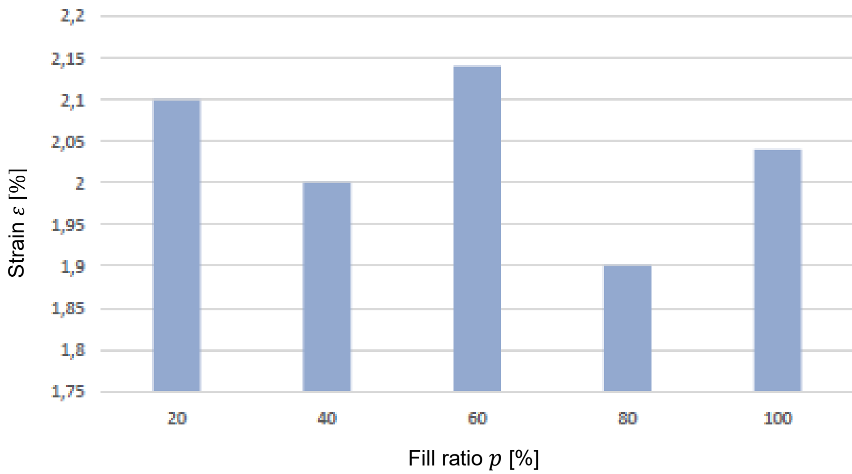

Fig. 7. Diagram of the relationship of strain to change in infill density

Table 4. Summary of test results for strain

Fill ratio [%] p **[%]**	20	40	60	80	100
Strain ε **[%]**	2.10	2.00	2.14	1.90	2.04

In the case of the deformation parameter, a relationship was observed which indicates that similar and comparable results are obtained at all infill densities.

PCABS material

Figure 8 shows the measured results of the tensile strength R_m [MPa] in relation to the infill density of the sample p [%].

Table 5 considers the tensile strength values R_m [MPa] from the infill density of the samples.

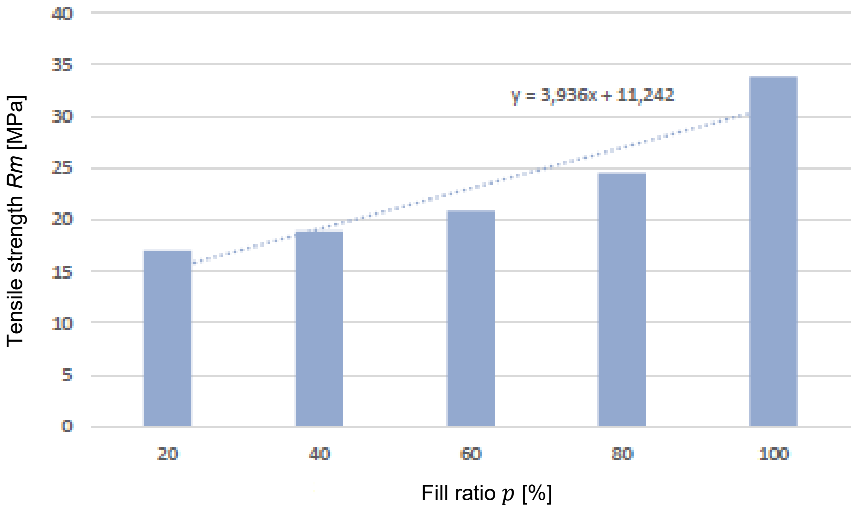

Fig. 8. Diagram of the dependence of the tensile strength on the infill density of the specimens

Table 5. Summary of test results for tensile strength Rm [MPa]

Fill ratio [%] p **[%]**	20	40	60	80	100
Tensile strength Rm [MPa] R_m **[MPa]**	17.03	18.92	20.87	24.52	33.91

The highest tensile strength value was achieved by specimens printed with a 100% infill. The lowest tensile strength value was achieved by samples with a 20% infill. At a 20% infill, the tensile strength is 17.03 MPa, while at maximum infill it is 33.91 MPa. It is concluded that an increase in material strength occurs with an increase in the infill density.

Figure 9 shows the results of Young's Modulus [MPa] versus the infill density of the specimens p [%]. Table 6 lists the strain values.

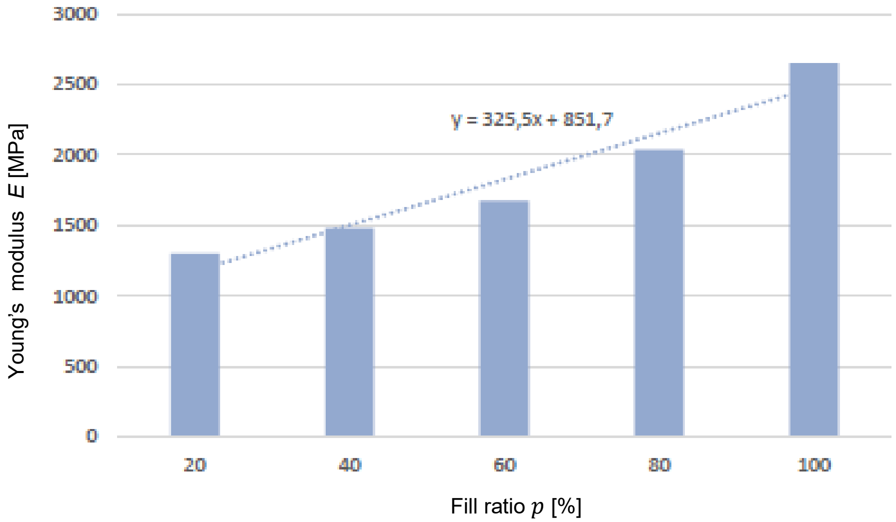

Fig. 9. Graph of the dependence of Young's modulus on the infill density

Table 6. Summary of test results for tensile strength, Rm [MPa]

Fill ratio [%] p **[%]**	20	40	60	80	100
Young's modulus [MPa]	1301	1478	1676	2037	2649

Figure 10 shows the results for the strain [%] versus the specimen printing angle. Table 7 lists the strain values.

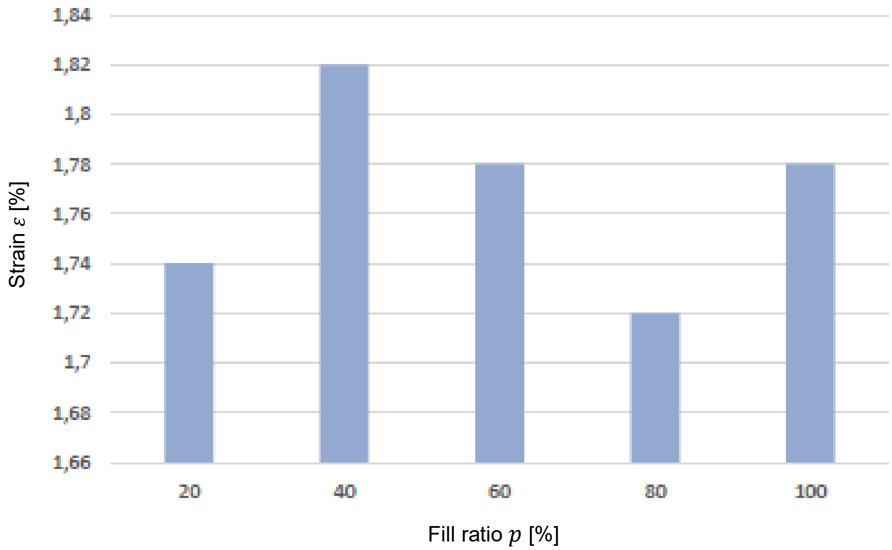

Fig. 10. Diagram of the relationship of strain to change in infill density

Table 7. Summary of test results for strain

Fill ratio [%] p **[%]**	20	40	60	80	100
Strain ε **[%]**	1.74	1.82	1.78	1.72	1.78

Table 8 lists the test results obtained for the specimens as a function of changes in the printing angle and temperature.

Table 8. Summary of the results obtained for the samples depending on the infill density

	Rm [MPa]		**Young's modulus [MPa]**		**Strain [%]**	
Infill [%]	PC	PCABS	PC	PCABS	PC	PCABS
20	18.41	17.03	1180	1301	2.10	1.74
40	20.71	18.92	1357	1478	2.00	1.82
60	21.87	20.87	1453	1676	2.14	1.78
80	25.55	24.52	1757	2037	1.90	1.72
100	43.10	33.91	2604	2649	2.04	1.78

Figure 11 is a comparison of the test results in terms of tensile strength.

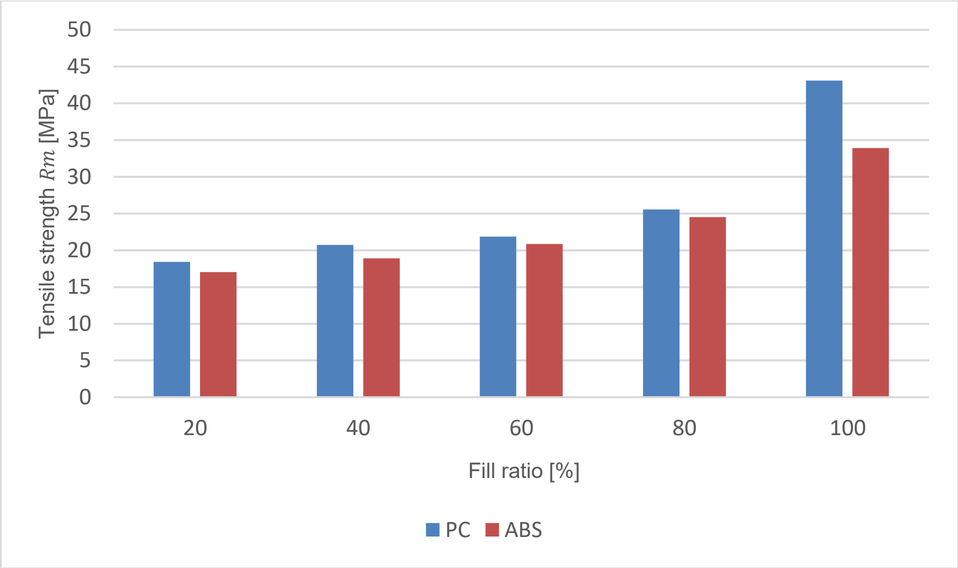

Fig. 11. Tensile strength comparison graph Rm [MPa]

Figure 12 is a comparison of the test results for Young's modulus.

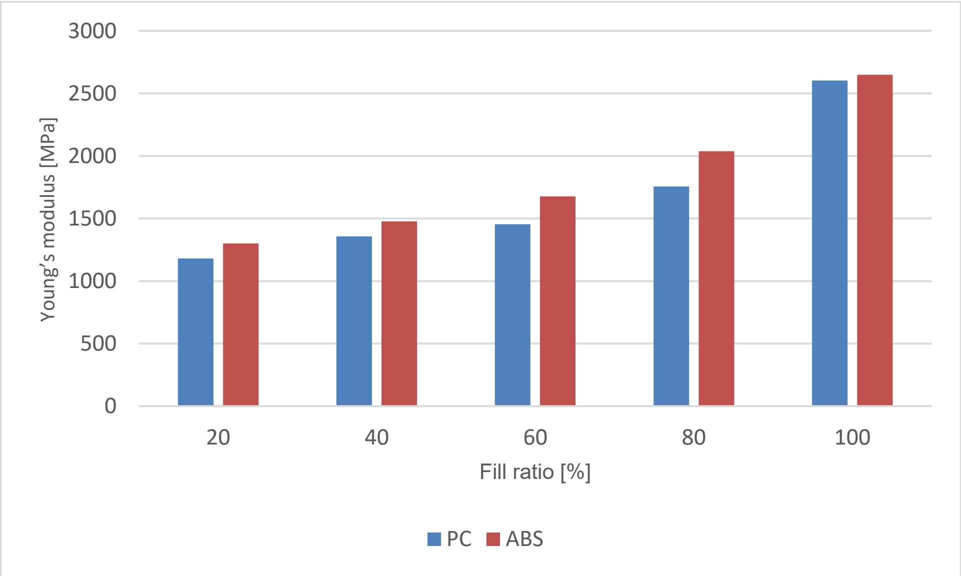

Fig. 12. Comparative graph of Young's modulus [MPa]

Figure 13 is a comparison of the test results for Young's modulus.

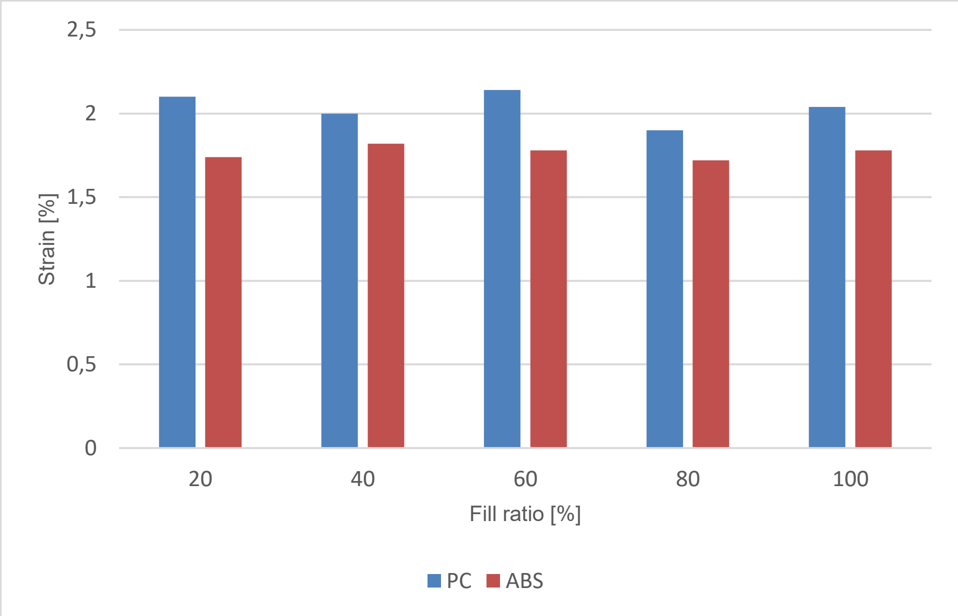

Fig. 13. Comparative graph of deformations [%]

4. CONCLUSIONS

The results show that both the type of material and the degree of infill have a significant impact on the mechanical properties of FFF prints. Internal porosity and infill density – with a low infill, there are more voids, which leads to local stress concentrations and reduced strength. Filament path orientation – a higher infill promotes a more even distribution of fibres and less anisotropy of the mechanical properties. Interlayer adhesion – with higher fill rates and optimal printing parameters (temperature, speed), there is better bonding between layers, which increases the strength and stiffness of the material.

Comparing the results for PC and PCABS, it can be seen that PC has higher tensile strength (up to 43.10 MPa), which is due to its more homogeneous structure and high cohesion of polycarbonate chains. PCABS achieves a higher Young's modulus (2649 MPa), which may be due to the presence of the acrylonitrile-butadiene-styrene phase, increasing stiffness and resistance to elastic deformation.

The highest tensile strength value, Rm, [MPa] was achieved by the PC filament at a 100% infill – 43.10 MPa. The lowest tensile strength value, Rm, [MPa] was achieved by the PCABS filament at a 20% infill – 17.03 MPa.

The highest value of Young's modulus [MPa] was achieved by the PCABS filament at a 100% infill – 2649 MPa. The lowest value of Young's modulus [MPa] was achieved by the PC filament at a 20% infill – 1180 MPa.

The highest strain value [%] was achieved by the PC filament at a 60% infill – 2.14%. The lowest strain [%] value was achieved by the PCABS filament at a 80% infill – 1.72%.

The material and the infill density did not have a significant effect on the deformation, as the result obtained is in the range of 1.72% to 2.14%.

The research conducted has shown that both the type of material used and the degree of filling have a significant impact on the strength properties of the manufactured components. The results clearly indicate that as the filling density increases, so does the tensile strength and Young's modulus, confirming the key role of the internal structure in shaping the mechanical behaviour of the prints. The differences in results between individual filaments are due to their different chemical structure, interlayer adhesion and thermal properties, which determine how the material is plasticised and cooled during the printing process.

The analysis of the data obtained has provided a better understanding of the relationship between the technological parameters of the FFF process and the mechanical characteristics of the finished components, which is important in the context of designing parts with specific strength requirements. The results obtained may serve as a basis for further research on the optimisation of printing parameters, including infill configuration, layer orientation and extruder temperature.

In addition, the collected research material may serve as a point of reference for the selection of filaments for engineering applications that require high strength, thermal resistance or elasticity.

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