

Experimental investigation of mechanical properties of Formlabs® photopolymers processed via SLA

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Abstract

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This study provides a mechanical characterization of commercially available SLA resins processed via Low Force Stereolithography (LFS). Multiple rigid and elastic materials with varying properties were tested under tensile, compressive, bending, and torsional loads according to ISO standards, complementing manufacturer data based on ASTM methods. Samples were printed under controlled conditions and evaluated using unified protocols. Results revealed notable differences in mechanical performance and confirmed the strong influence of post-curing, especially on tensile and bending behavior. Polynomial and bilinear regression models effectively described stress-strain responses. Surface roughness analysis showed correlations between surface quality and mechanical strength, particularly in brittle resins. These findings support better selection and optimization of SLA materials, highlighting the importance of process parameters, resin formulation, and post-processing.

Keywords: SLA resins, additive manufacturing, stereolithography, 3D printing, mechanical testing

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Highlights

- Mechanical properties of SLA resins vary significantly across ISO test modes.
- Post-curing strongly affects tensile and bending performance of tested resins.
- Surface roughness and resin formulation impact mechanical strength of SLA parts.

1. Introduction

Additive manufacturing (AM), known also as 3D printing, is the process of creating three-dimensional objects based on a digital model. Its main advantages include the producing complex and diverse parts that would be difficult to produce using conventional methods [1]. These technologies are widely used not only in the aerospace and automotive industries, but also in biomedical engineering [2]. On the other hand, additive

technologies can be limited by production capacity, production costs, or the dimensional accuracy of final products [3]. Another challenge that designers encounter in practice is the limited availability of real-world data on the mechanical properties of the materials. Until now, users have had to rely primarily on general knowledge of the mechanical behaviour of polymers. In reality, however, other factors must also be considered, which in the case of stereolithography (SLA) include the curing process, sample orientation, layer height, or support volume. In addition, the mechanical properties of the resulting object can be influenced by the environment in which it is processed the temperature and hydration of the sample [4–6].

Recent studies on the effect of curing have mostly focused on static stress, assessed mainly through the tensile tests. For example, the effect of curing on commercially available resins is analysed in detail in a study [7] that examined Formlabs®

materials. The results of this study indicate significant improvements in mechanical properties, especially tensile strength (by 89 %) and tensile modulus (by 88 %). The most significant improvement was observed for Custom Tray Resin, where tensile strength increased by 172 % and tensile modulus by 215 %. The positive effect of curing is also confirmed by other studies [8,9] focusing on different material types. The study [8] demonstrated that curing could achieve similar results to conventional thermally cured alternatives. Zareanshahraki [10] discusses different methods of curing samples printed with Digital Light Processing (DLP) technology for automotive applications. The key emphasis is placed on different curing methods, such as UV radiation, heat, and their combination or electron beam (EB). Current studies suggest that proper combination of resin chemistry, printing parameters and post-process curing can optimize the properties of 3D printed parts. However, practical experience shows that tensile stress tests do not always correspond to real working conditions. For this reason, it is necessary to further investigate these effects on the mechanical properties of samples, especially under compressive, bending, and torsional loads.

As it was mentioned earlier, the mechanical properties of 3D printed parts depend, among other things, on the orientation of the sample. Similar to the case of curing, many studies focus on the effect of printing orientation on the tensile mechanical properties. However, there is currently no standard that would precisely define the optimal orientation of the sample during printing. The research presented in [11] states that the highest tensile and compressive strengths were achieved for samples printed at 22.5° and 67.5°, while samples with 0° orientation showed the highest impact and fatigue strengths. Cingesar et al. [12] looked at Clear and High Temperature materials and confirmed the correlation between the curing time and mechanical properties – longer curing time led to increased tensile strength and modulus. At the same time, it was shown that these properties improved with a smaller layer height, with sample orientation affecting printing time and final mechanical characteristics. However, research conducted on Formlabs Clear V4 material suggests that the orientation during printing has only a minimal effect on its mechanical properties. In addition, the measured maximum stress was lower than the values stated in the datasheets [13]. Similarly, studies [14–16]

indicate little difference in the mechanical properties of samples printed in different orientations and consider the layer thickness to be a much more significant factor. While increasing layer thickness increases tensile strength, it also decreases impact and bending strength [17].

The above studies focus on testing a limited number of commonly used resins, with most of them evaluating primarily tensile stress, and to a lesser extent compression and bending. The available scientific literature shows that no comprehensive study focused on the mechanical properties of these materials to provide information necessary for further scientific and practical development. Therefore, this research aims to obtain a comprehensive overview of the mechanical properties of commercial Formlabs® resins under various types of stress, i.e. tensile, compressive, bending, and torsion.

This area of research is also relevant for other printing methods such as Selective Laser Sintering (SLS) and Fused Filament Fabrication (FFF). The study [18] compared orthodontic brace materials produced by direct 3D printing with thermoforming materials, where it was found that 3D printing materials have higher bending strength and modulus than that of traditional thermoforming films. Different polymers, such as polyamide 12 (PA12), polylactic acid (PLA), and glycol-modified poly(ethylene terephthalate) (PET-G), show different mechanical responses depending on hydration, temperature, and structural arrangement. PA12 undergoes a significant change in strength due to the moisture absorption, which has major implications for applications requiring stability of mechanical parameters in dynamic environments.

The influence of print orientation has also been investigated in this area of additive technologies [19]. In addition, the post-polymerization time affects the bending strength and microhardness of materials. The optimal curing time of 40 minutes led to the highest values of mechanical properties without a negative impact on structural integrity [20]. The results of the studies also show that shortened curing times lead to significantly different mechanical responses of printed SLA samples at different loading rates, which is crucial when designing functional components for dynamically stressed applications [21]. The print orientation and geometric parameters of the layering affect the mechanical resistance fundamentally. While e.g. SLS and SLA provide highly accurate

parts with a homogeneous structure, the FFF technique exhibit anisotropy of strength due to different adhesion between layers [18].

The effect of post-processing is also an important part of the current research. For example, studies reported in [7,18] show that SLA resins exhibited a significant increase in mechanical resistance when post-cured with UV light and heat treatment, which can lead to an increase in tensile strength of up to 172 %. In contrast, for materials intended for FFF printing, controlled heat treatment can reduce internal stresses and improve layer cohesion. Experimental studies on the effect of curing time and intensity suggest that optimization of these parameters can further improve mechanical properties without negatively impacting part accuracy. Surface treatments such as glycerine baths or mechanical polishing lead to a reduction in roughness and increased wear resistance [8,19].

This article aims to compare the mechanical properties achievable in real operating conditions with the values reported by ©Formlabs (Somerville, USA) for their materials.

2. Materials and methods

This chapter mainly describes the printing parameters used to prepare the samples subjected to the tests.

2.1. Materials

The materials tested were available materials Grey Pro, Elastic, Rigid 10K, Clear V4 commercial resin brands supplied by ©Formlabs (Somerville, USA). Resin Grey Pro contains urethane dimethacrylate, methacrylate monomer(s) and isobornyl acrylate. Acrylate monomers are also used to make

the basic components of the Elastic and Clear V4 materials. Glass fillers are included in the composition of the material, in contrast to the Grey Pro material.

2.2. Samples preparation

Sample preparation was performed on a Formlabs Form 3 3D printer (©Formlabs, Somerville, USA) with Low Force Stereolithography (LFS) technology, which enables high printing accuracy and a high-quality surface. Print settings were implemented in the PreForm program (©Formlabs, Somerville, USA). A FormWash rinsing device with isopropyl alcohol was used to remove unreacted monomers. After rinsing, the samples were air-dried before final curing. The cleaning and curing time depended on the type of resin used. A FormCure device (©Formlabs, Somerville, USA) with a heating system for preheating the chamber was used to cure the samples. After reaching the required temperature, a UV light with thirteen LEDs was activated, thereby optimizing the mechanical properties. The curing time depended on the type of resin and the process temperature. Parameters of materials processing are collected in Table 1.

Table 1. Rinse time, curing time, and sample temperature [22,23].

Sample material	Rinse time (min)	Curing time (min)	Curing temperature (°C)
Grey Pro	15	15	80
Elastic	10 + 10	20	60
Rigid 10K	10 + 10	60	70
Clear V4	10	15	60

Table 2. summarizes the sample printing settings used in experimental testing. A separate Table 3 presents data on the early layer exposure for each material.

Table 2. Default print settings in PreForm® software (©Formlabs, Somerville, USA).

Sample material	Layer thickness (mm)	Perimeter fill exposure (mJ/cm ²)	Model fill exposure (mJ/cm ²)	Support fill exposure (mJ/cm ²)	Operating temperature (°C)	Minimum temperature (°C)	Roller squeeze speed (mm/s)
Grey Pro	0.1	53	42	53	35	31	5.2
Elastic		70	60	70		31	2.7
Rigid 10K		45	40	45		34	5.2
Clear V4		111	55	111		31	15.38

Table 3. Early layer exposure (mJ/cm²).

Layer (mm)	Grey Pro	Elastic	Rigid 10K	Clear V4
0	335	671	215	768
0.1	157	289	105	512
0.2	92	148	64	341
0.3	68	96	49	227
0.4	59	77	44	151
0.5	55	70	42	111

2.3. Testing methods

Mechanical tension, compression, and bending tests were performed using the device Instron 3345 (© Instron, Norwood, USA). The shapes of the test samples were based on the relevant standards, as follows: ISO 527-2 [24] for tension tests, ISO 604 [25] for compression tests, and ISO 178 [26] for bending tests. Torsional testing was performed on an ElectroPuls 10,000 (© Instron, Norwood, USA) according to ISO 458, which specifies a methodology for measuring torsional stiffness in flexible materials. Thermal spectrum for torsional characteristics testing was achieved using an Instron Eurotherm temperature chamber (© Instron, Norwood, USA). In the utilized test configuration, temperature-dependent measurements were technically feasible only for torsion testing.

Surface quality was evaluated by measuring the roughness characteristics of Ra and Rz using a roughness meter made by Insize (Suzhou, China).

3. Results

The test results of the materials specified in Table 1 are described below in the respective subsections with the individual diagrams along with a number of values obtained for the given samples. These values were then subjected to regression analysis to mathematically describe the force-deformation relationship. For technical reasons and the fundamental principle of material behaviour, it was impossible to evaluate the Elastic material's tensile stress-strain diagram. Due to similar technical reasons and the capabilities of the measuring equipment, only the evaluation of the torsional characteristics for Clear V4, Grey Pro, and Elastic was performed.

3.1. Tensile stress–strain diagram

The tensile test of a sample made of Rigid 10K material shows a similar course on all measured samples, with the dependence being linear in the first part up to approximately 10 MPa. This phenomenon is clearly indicated in Figure 1. The measured data breaks and the increase in tensile stress slowed down for higher stresses. Approximately between 10 and 20 MPa, the yield point occurs, or the course of the measured values changes. This characteristic can be described relatively accurately by a third-order polynomial regression, or by a bilinear model. The

bilinear model then consists of two linear functions whose mathematical description is as follows:

$$\begin{aligned}\sigma_1 &= 7243 \cdot \varepsilon - 0.6933 \\ \sigma_2 &= 1916.2 \cdot \varepsilon + 8.7461\end{aligned}\quad (1)$$

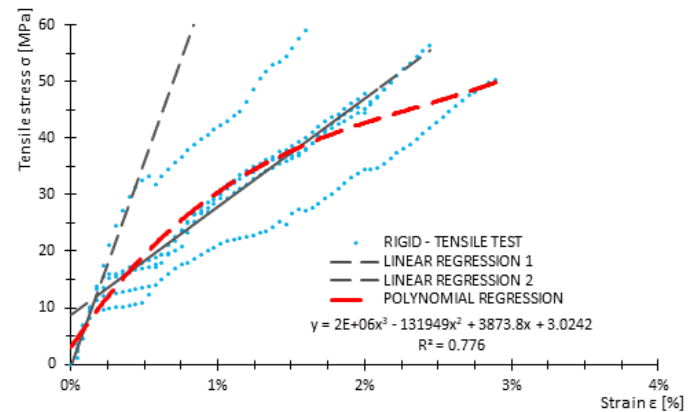


Figure 1. Tensile stress–strain diagram for Rigid 10K material.

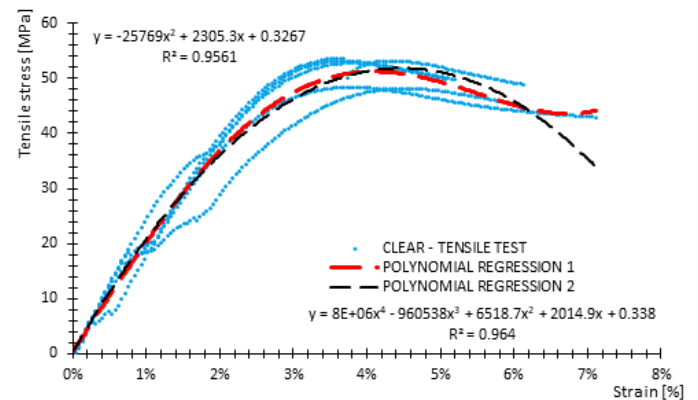


Figure 2. Tensile stress–strain diagram for Clear V4.

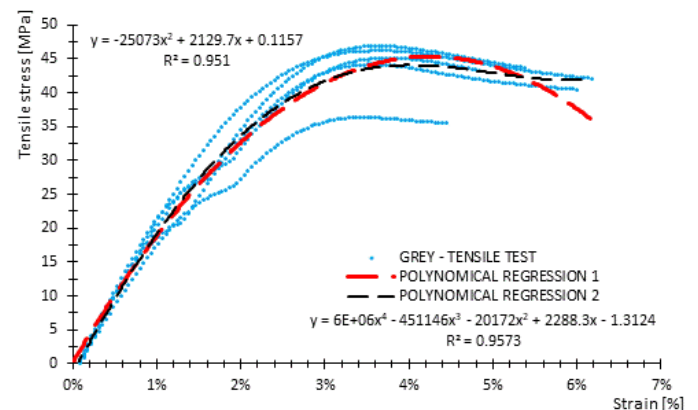


Figure 3. Tensile stress–strain diagram for Grey Pro.

In the case of the Clear V4 material, some of the values can be described linearly again, but with higher accuracy these curves can also be described by a polynomial function of the second or fourth order. In general, it can be said that the diagrams of the results were of parabolic shape. The yield strength is not easily visible here as in the case of the Rigid 10K material, but some indications can be seen around 50 MPa, while the tensile stress at the strength limit is slightly lower at

around 48 MPa. The relative elongation then fluctuates around the value of 5 %, as shown in Figure 2.

The results for Grey Pro material are shown below in Figure 3. It exhibited essentially the similar situation to the Clear V4 material (Figure 2) with the main difference that the yield strength values were evaluated at the same stress levels as the tensile strength values. The maximum elongation is then around 5 %.

3.2. Compression stress–strain diagram

The pressure test of the material Elastic provided results that can be described by a second-order polynomial regression, according to the measured values. However, these results can also be described relatively accurately by a linear regression, as it is shown in Figure 4. The average value of modulus was determined to be 10 ± 0.6 MPa, while the tensile strength was 1.2 ± 0.02 MPa. The situation in the case of the Rigid 10K material is similar, as it can be seen in Figure 5. The measured data can be described by a second-order polynomial regression, while a bilinear model can also be used relatively accurately, where:

$$\begin{aligned}\sigma_1 &= 6730.8 \cdot \varepsilon - 106.4 \\ \sigma_2 &= 2457.1 \cdot \varepsilon - 304.1\end{aligned}\quad (2)$$

The average modulus was measured as 7211.1 ± 222.3 MPa, and the ultimate strength was 243.7 ± 3.2 MPa.

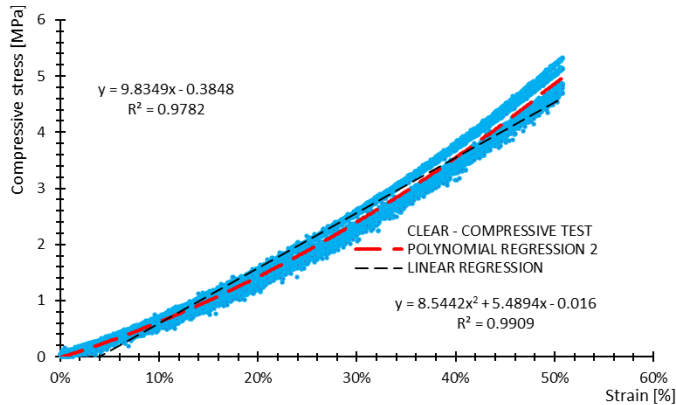


Figure 4. Compressive stress–strain diagram for Elastic.

The results measured on samples made of Clear V4 material, are shown in Figure 6. They can be described by a fifth-order polynomial regression. Of course, it is also possible to create a bilinear model, where:

$$\begin{aligned}\sigma_1 &= 2598.3 \cdot \varepsilon - 30.9 \\ \sigma_2 &= -54.9 \cdot \varepsilon + 333.8\end{aligned}\quad (3)$$

The average modulus was found to be 1867 ± 181.8 MPa and

the ultimate strength was 80.5 ± 0.8 MPa. The compressive strength characteristics of the Grey Pro material shown in Figure 7 appeared to be similar to those obtained in the tensile test (Figure 3). The data are relatively well described by a second-order polynomial regression. The bilinear model is then formed by two linear regressions of the following form:

$$\begin{aligned}\sigma_1 &= 2099.2 \cdot \varepsilon - 9.2 \\ \sigma_2 &= -17.8 \cdot \varepsilon + 239.9\end{aligned}\quad (4)$$

The average modulus was measured as 2655 ± 202.8 MPa and the ultimate strength was 60.7 ± 2.7 MPa.

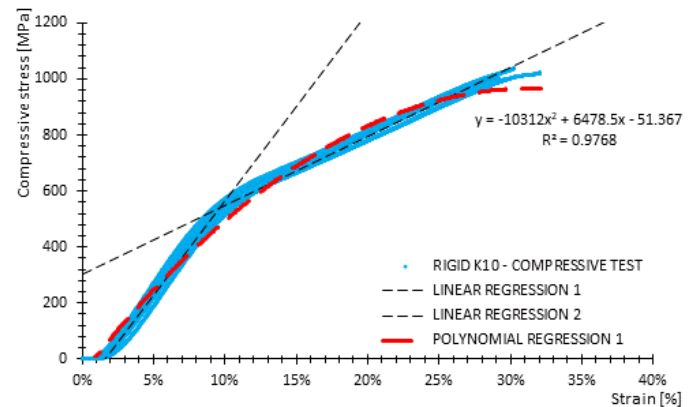


Figure 5. Compressive stress–strain diagram for Rigid 10K.

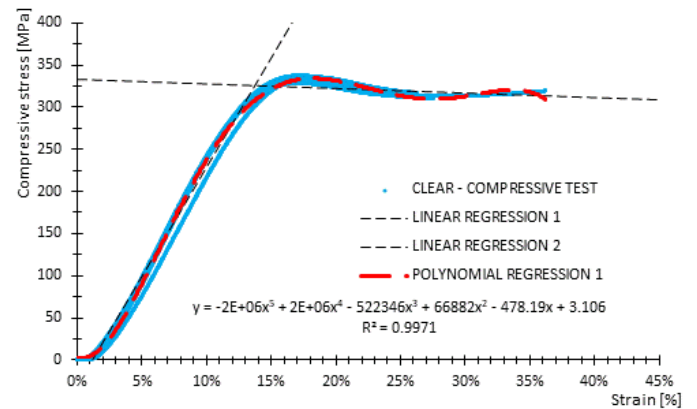


Figure 6. Compressive stress–strain diagram for Clear V4.

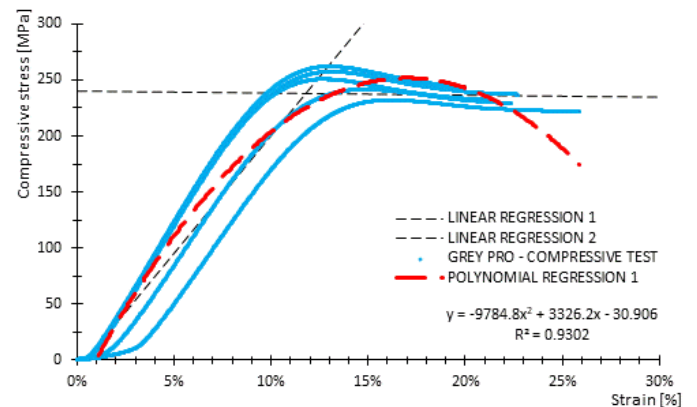


Figure 7. Compressive stress–strain diagram for Grey Pro.

3.3. Bending stress–strain diagram

The characteristic of bending stress versus relative bending strain was determined based on the three-point bending. The first material to be analysed was Elastic, the results of which are shown in Figure 8. It is evident that part of the measured values can be fitted by linear regression approximately to the region of relative bending elongation of 10 %, which corresponds to a bending stress of 0.35 MPa. The mathematical model describing this dependence looks as follows:

$$\sigma_{flin} = 3.4574 \cdot \varepsilon_f - 0.0006 \quad (5)$$

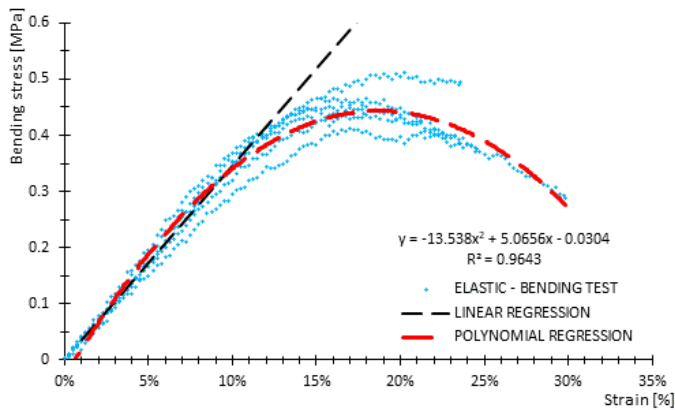


Figure 8. Bending test diagram for Elastic.

Beyond the area of relative bending elongation, which corresponds to 10 %, it is no longer appropriate to use a linear dependence. A more accurate mathematical model that would describe the behaviour of the Elastic material can be the polynomial regression shown in the graph, with high correlation coefficient $R^2=0.9643$. The measurement also showed that the modulus in bending for this material is around 4 MPa, while the bending strength limit was measured on average around 0.48 MPa with an average maximum deflection of 12 mm.

From Figure 9, it was found that the mathematical model for the Rigid 10K material can be of a purely linear nature. The measured data can be fitted with a linear function with sufficient accuracy. Modulus was not evaluated during the measurement, and on average the bending strength was 91.7 MPa at a maximum deflection of about 1 mm. The measured data can be simulated relatively accurately by the bilinear model, which is shown in the aforementioned graph. The first branch of the bilinear model can be described by a following linear function:

$$\sigma_{flin1} = 1570.2 \cdot \varepsilon_f - 0.2385 \quad (6)$$

The secondary branch with less precision can be as follows:

$$\sigma_{flin2} = -62.669 \cdot \varepsilon_f + 74.15 \quad (7)$$

Of course, with sufficient accuracy, the measured data can be described by polynomial regression as indicated in Figure 9. The modulus value then reached approximately 1621 MPa, with the maximum deflection around 5 mm. The ultimate bending strength can then be expected to be around 68.5 MPa. The measured data can also be processed in a similar way in the case of the Clear V4 material, see Figure 10. With sufficient accuracy, a bilinear model and, of course, polynomial regression can be used.

$$\begin{aligned} \sigma_{flin1} &= 2395.5 \cdot \varepsilon_f - 1.0671 \\ \sigma_{flin2} &= 22.941 \cdot \varepsilon_f + 107.78 \end{aligned} \quad (8)$$

The modulus in flexure can be expected in 2000 MPa, with a bending strength of 95 MPa. The average maximum deflection achieved during the experiment was then 5.1 mm.

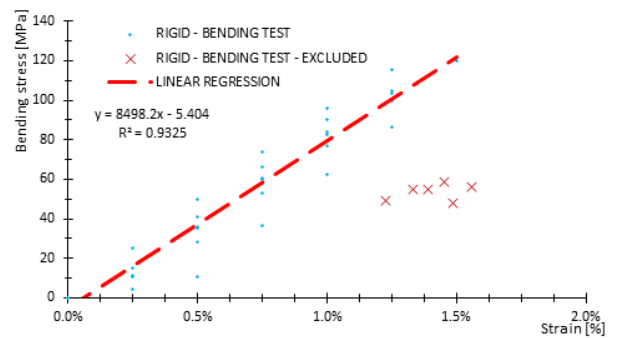


Figure 9. Bending test diagram for Rigid 10K.

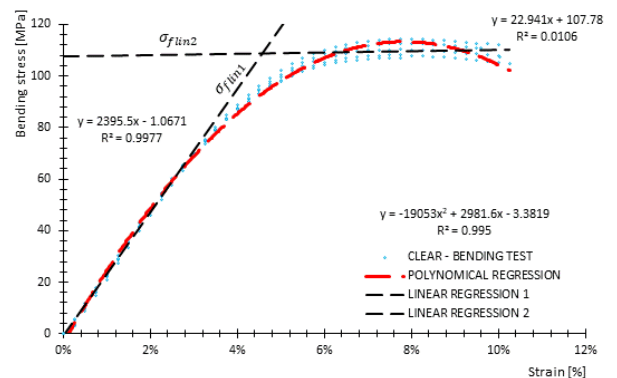


Figure 10. Bending test diagram for Clear V4.

In the case of Grey Pro material, a part of the values up to approximately 4 % of the relative bending elongation can be described by a linear model. It can be seen from Figure 11 that a satisfactory mathematical model can only be obtained by polynomial regression. A linear description of a part of the measured data can be given by the equation:

$$\sigma_{flin} = 1959.1 \cdot \varepsilon_f - 0.6142 \quad (9)$$

The average bending modulus is approximately 1852 MPa. The ultimate bending strength can then be expected to be around 82.2 MPa.

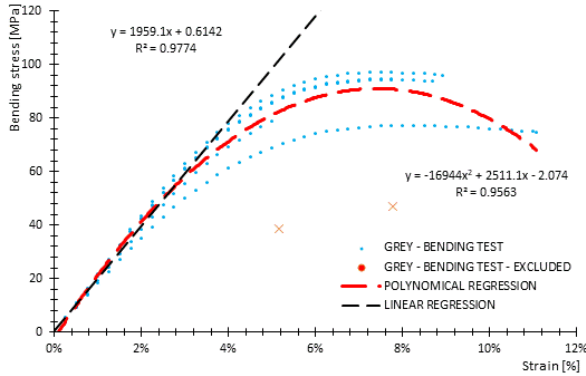


Figure 11. Bending test diagram for Grey Pro.

$$M_{k\text{pol}25} = 3 \cdot 10^{-16} \cdot \varphi^6 + 9 \cdot 10^{-13} \cdot \varphi^5 - 1 \cdot 10^{-9} \cdot \varphi^4 + 5 \cdot 10^{-7} \cdot \varphi^3 - 0.0002 \cdot \varphi^2 + 0.0238 \cdot \varphi - 0.0333 \quad (10)$$

$$M_{k\text{pol}60} = -1 \cdot 10^{-16} \cdot \varphi^6 + 3 \cdot 10^{-13} \cdot \varphi^5 - 3 \cdot 10^{-10} \cdot \varphi^4 + 2 \cdot 10^{-7} \cdot \varphi^3 - 5 \cdot 10^{-5} \cdot \varphi^2 + 0.0066 \cdot \varphi + 0.0146 \quad (11)$$

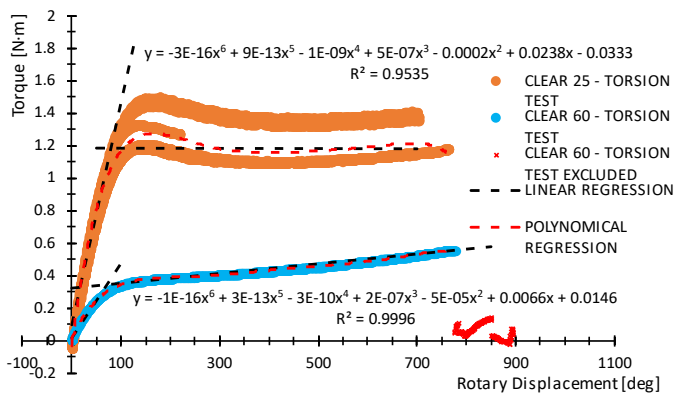


Figure 12. Torsion test diagram for Clear V4.

$$M_{k\text{pol}25} = -1 \cdot 10^{-16} \cdot \varphi^6 + 3 \cdot 10^{-13} \cdot \varphi^5 - 4 \cdot 10^{-10} \cdot \varphi^4 + 3 \cdot 10^{-7} \cdot \varphi^3 - 1 \cdot 10^{-4} \cdot \varphi^2 + 0.0163 \cdot \varphi - 0.0057 \quad (12)$$

$$M_{k\text{pol}60} = -7 \cdot 10^{-17} \cdot \varphi^6 + 2 \cdot 10^{-13} \cdot \varphi^5 - 2 \cdot 10^{-10} \cdot \varphi^4 + 9 \cdot 10^{-8} \cdot \varphi^3 - 2 \cdot 10^{-5} \cdot \varphi^2 + 0.0031 \cdot \varphi + 0.0264 \quad (13)$$

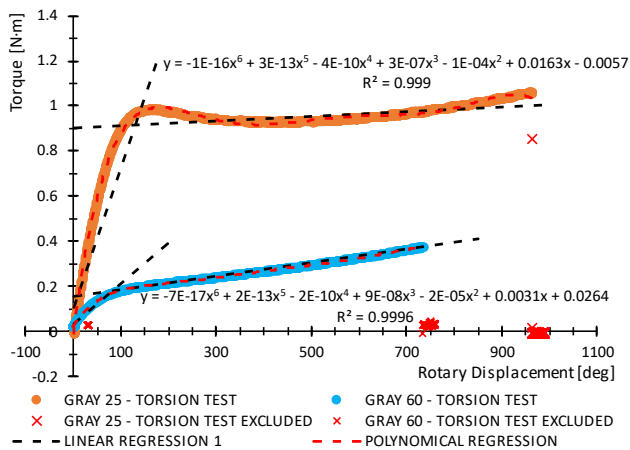


Figure 13. Torsion test diagram for Grey Pro.

3.4. Torsion stress–strain diagram

Torsion tests were performed at room temperature of 25 °C and at a temperature of 60 °C. In order to assess the behaviour alteration of the material at these two temperatures, respective diagrams are shown in Figures 12-14. For all materials, a change in properties with temperature change was observed.

The Clear V4 material, shown in Figure 12, changes its behaviour significantly with temperature. At 25 °C, part of the graph can be described linearly, up to 1.2 Nm, where the yield strength can also be found. This decreases to 0.35 Nm after a temperature rose up to 60 °C making the material more elastic. The behaviour can be described by the respective polynomial regressions with sufficient accuracy, as follows:

The Grey Pro material has a similar curve to the Clear V4 material, as it is seen in Figure 13, but it achieves lower torque values. The torque curve also decreases significantly with increasing temperature. The curves for the respective temperatures can be described by polynomial regressions with high accuracy ($R^2=0.999$), as follows:

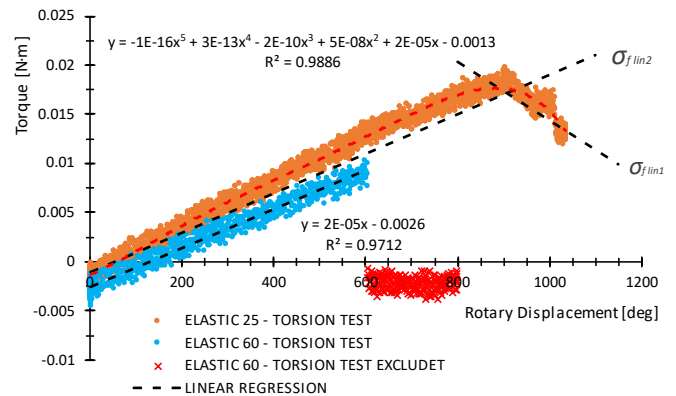


Figure 14. Torsion test diagram for Elastic.

The bending moment diagram for the Elastic material shown in Figure 14 is linear with small exception between 900 and

1050 degrees of rotary displacement. Notably, the temperature does not significantly change the moment graph, it only has effect on the maximum values achieved. As the name suggests, the material is elastic and therefore reaches high deformations up to the point of the tensile strength. The function can be described by polynomial regression for a temperature of 25 °C and linear for a temperature of 60 °C.

$$M_{k_{pol25}} = -1 \cdot 10^{-16} \cdot \varphi^5 - 2 \cdot 10^{-10} \cdot \varphi^4 - 2 \cdot 10^{-10} \cdot \varphi^3 + 5 \cdot 10^{-8} \cdot \varphi^2 + 2 \cdot 10^{-5} \cdot \varphi - 0.0013 \quad (14)$$

$$M_{k_{lin60}} = 0.00002 \cdot \varphi - 0.026 \quad (15)$$

3.5. Measurement of roughness

Testing the surface quality of prepared samples is one of the very important tools with regard to the prediction of mechanical properties. Under static mechanical stress, it can be expected that samples with higher roughness, deformations on the sample surface, etc., will achieve a lower value of the ultimate strength. A poor-quality sample will also show easier crack propagation during dynamic testing, which would have a negative effect in practical applications. For these reasons, the surface of the prepared samples was analysed using a contact roughness measurement, the summary results of which can be seen in Figure 15. From the obtained results, it is clear that the highest quality surface was achieved for the Rigid 10K sample with $R_a = 1.042 \pm 0.274 \mu\text{m}$ and $R_z = 8.111 \pm 3.234 \mu\text{m}$. The results of R_z , parameter, which represents the measured largest height of the roughness profile, are comparable within the standard error of measurement for all materials.

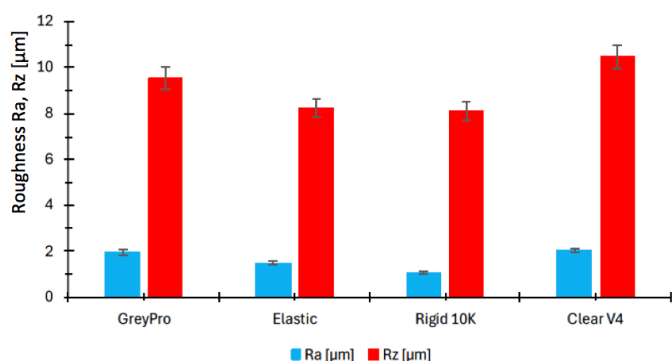


Figure 15. Surface roughness of samples.

4. Discussion

The values of Young's modulus and tensile strength, as well as the bending strength, are taken from the official material data of

the manufacturer Formlabs (©Formlabs, Somerville, USA) [27]. For our selection of materials, these values are given in Table 4. A summary of the measurement modulus results is shown in Figure 16.

Table 4. Mechanical properties stated by the manufacturer [27].

Sample material	Highest tensile strength (MPa)	Young's Modulus (GPa)	Elongation (%)	Bending Modulus (GPa)
Grey Pro	(35)	(1.4)	(33)	(1.3)
	61	2.6	13	2.2
Elastic	(1.6)	(-)	(100)	-
	3.2	-	160	-
Rigid 10K	(55)	(2.2)	(13,3)	(1.4)
	65	4.1	5.6	3.7
Clear V4	(38)	(1.6)	(12)	(0.94)
	65	2.8	6	2.2

Note: The values in brackets represent the values for the uncured sample.

By comparing the measured values with the values stated by the manufacturer for tensile stress, we conclude that for the Grey Pro material the measured value is significantly lower than the value stated by the manufacturer. A similar situation also occurs for the Clear V4 material. On the contrary, for the Rigid 10K material the trend is the opposite – the measured value is significantly higher than the one stated by the manufacturer. In the case of bending stress, the situation is quite similar. For the Grey Pro and Clear V4 materials, the measured values are relatively close to the values stated by the manufacturer. For the Rigid 10K material, a significantly higher value was again measured compared to the specifications.

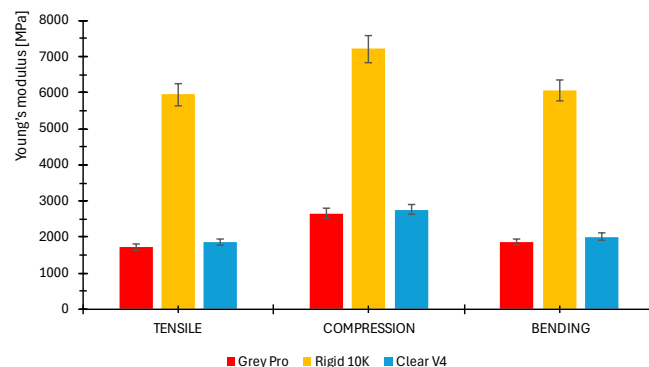


Figure 16. Modules obtained from measurement.

Table 5 shows the experimental average elongation values of the samples of the tested materials, and Table 6 presents the highest values of tensile strength. Comparing the data from Table 4 and Table 5, it can be seen that the elongation values obtained in our experiments were lower than those suggested by the manufacturer. The largest difference between the specification and measured data was observed for the Grey Pro material. With regard to the highest tensile strength, it can be

observed that the values provided by the manufacturer are higher than the measured ones, which also corresponds with the trend mentioned above.

Table 5. Measured elongations of the samples.

Sample material	Measured values (%)	Formlabs values (%)	Measured and tabulated data (%)
Grey Pro	4.9 ± 0.1	13	54.7
Elastic	–	160	–
Rigid 10K	3.1 ± 0.6	5.6	88
Clear V4	5.3 ± 0.4	6	37.7

Table 6. Measured values of the highest tensile strength.

Sample material	Measured values (MPa)	Formlabs values (MPa)	Measured and tabulated data (%)
Grey Pro	43.3 ± 4.1	61	70.9
Elastic	–	3.2	–
Rigid 10K	53.2 ± 4.1	65	81.9
Clear V4	49.4 ± 2.6	65	76

From Tables 5 and 6 above, it was not possible to calculate these parameters for the Elastic material. The graph in Figure 17 summarizes the strength limits for various types of stress.

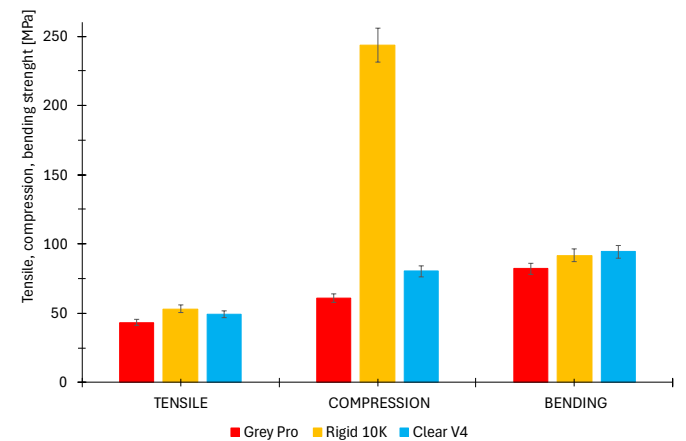


Figure 17. Strength for all types of loads.

The results for Rigid 10K exhibited outstanding compression strength, more than 3 times higher than that for Clear V4. On the other hand, tensile and bending strengths for both materials are comparable, with overlapping dispersion ranges. The GreyPro material exhibited lower strength in all the tested conditions.

The measured data for individual measurement methods were entered into summary graphs for better comparison between individual materials. The Figure 18 shows a graph of polynomial regressions of materials that underwent tensile testing.

The Figure 18 clearly shows that Rigid 10K has the highest strength. It also has the highest tensile modulus value. Clear V4 material has lower strength than Rigid 10K material and higher

strength than Grey Pro material. Both Rigid 10K and Clear V4 materials have no visible yield point. Grey Pro material has a visible yield point.

The data measured on the compressive testing are shown on the Figure 19.

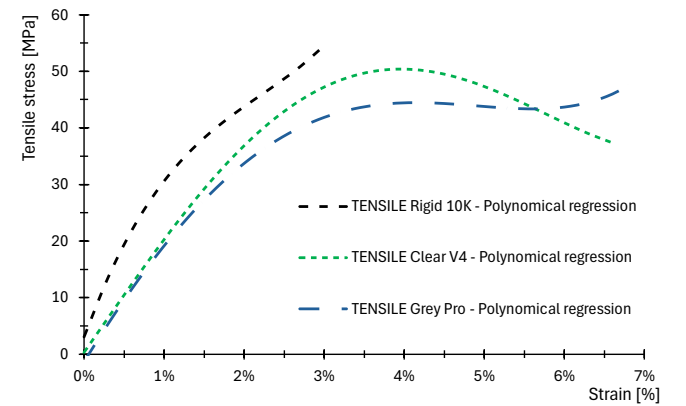


Figure 18. Graph with tensile tests of materials.

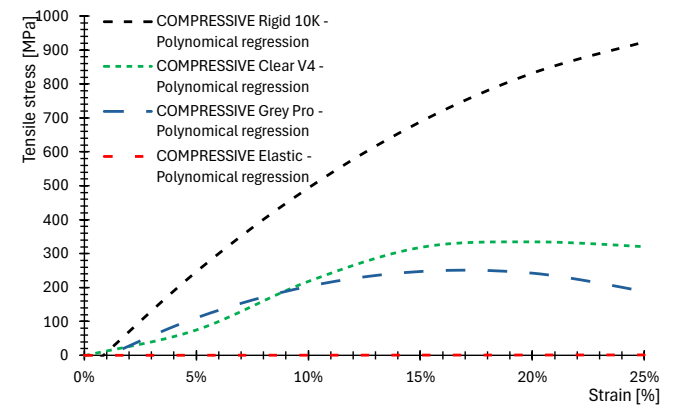


Figure 19. Graph with compressive tests of materials.

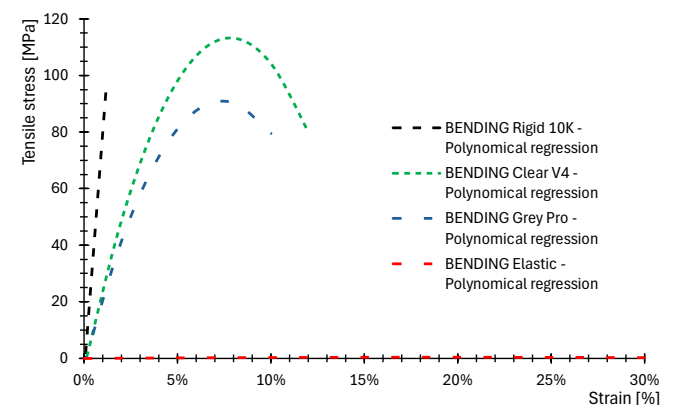


Figure 20. Bending test of materials.

This graph also clearly shows that Rigid 10K has the highest strength. The material exhibits the highest stiffness and there is no obvious yield point visible here either. Grey Pro and Clear V4 materials exhibit very similar properties. Their curves diverge mainly at higher strain, which is probably caused

primarily by a more visible yield point, which was particularly evident in the tensile test. Compared to others, the tensile elasticity modulus of elastic material is very low. The material therefore has very low stiffness, which could have a positive effect, for example, in vibration damping, sealing, etc.

All materials were also tested for bending. The comparison chart is shown in the Figure 20.

The results of the bending tests confirm earlier findings. Rigid 10K material again has the highest stiffness and no visible yield point. However, in the case of bending, Clear V4 material exhibits a higher bending strength limit than Rigid 10K material. This can be attributed to the relatively high hardness of Rigid 10K, while Clear V4 is more ductile. Grey Pro is the least strong of the rigid materials. The elastic material is so soft that its curve is invisible in the graph.

The torsion test was performed for Clear V4, Grey Pro, and Elastic materials. The torsion measurements at 25°C are shown in the Figure 21.

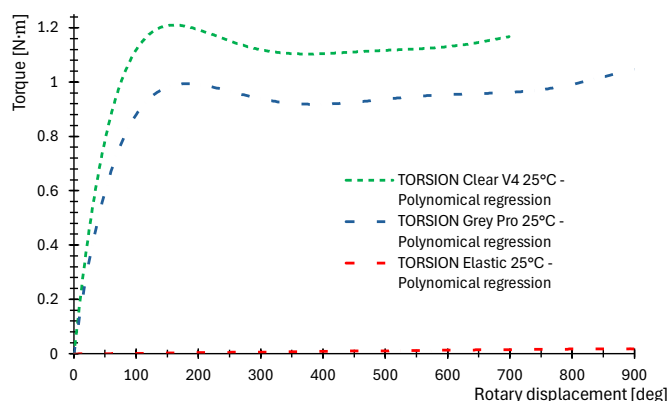


Figure 21. Torsion test of materials on 25°C.

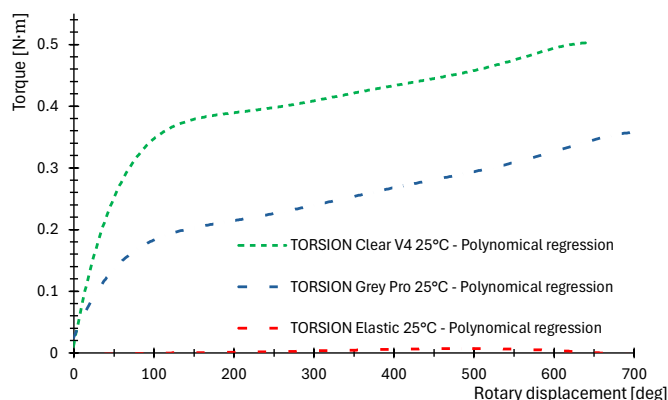


Figure 22. Torsion test of materials on 60°C.

Clear V4 is the strongest of the measured materials and therefore exhibits the highest torsional moment. Grey Pro is ranked below it. Both materials have a visible yield point.

Elastic is so soft that its torsional moment is significantly lower, and the yield point of the material is not visible.

The torsion test was also performed at an elevated temperature of 60°C. The summary graph is shown in the Figure 22.

At higher temperatures, materials will soften, resulting in lower maximum torque values. However, the trend among materials remains the same.

This is followed by a discussion and comparison of the measurement results with values from other articles. From the research data reported in the article [28] it is clear that for the Dental LT material, although delivered by different manufacturer, the course is similar to that of the Grey Pro materials. For the OrthoFlex material, the uncoated version shows a much higher elongation (80%). For the coated version, the stress values are significantly higher, but after the growth region, there is a significant decrease in stress at 10% elongation. Such behaviour was not found in the samples we tested. In the article [29], the tested material was designated as FL from FormLabs, while according to the description it was Formlabs Denture Base. The given material was tested for bending strength and showed strength values from 51 MPa to 66.9 MPa, depending on the thickness and angle of the layer. This is a smaller value compared to the samples we examined. For Formlabs Durable Resin (a similar transparent material to Clear V4), which was investigated in the research [21], it was shown that the stress-elongation curve and the overall strength significantly depend on the speed of the tear test. In the static test, which was carried out at 0.001 1/s, a decrease in elongation by 5 % was seen and then the course was exponential. At the standard test speed of 0.84 1/s, the stress course corresponded with the shape of the Clear V4 material. However, for the Durable Resin material, they measured tensile strength values that were essentially double those given by the manufacturer. This is in contrast to this research, where the results were lower than those given by the manufacturer. In the research [7], similar materials were examined as in our research, but the results were different for some materials. For the Clear V4 material, the results in both studies are essentially the same, namely that the measured tensile strength values are lower than those stated by the manufacturer. However, for the other clear materials, the tensile strength values were higher than those stated by the

manufacturer. For the Grey Pro material, the tensile strength values in the given article were essentially the same as those stated by the manufacturer. In contrast, in this study, the value was only two-thirds. Bending tests in research [30] were made for Dental LT Clear V2, which was a similar material to Clear V4. The bending results in both studies are essentially the same.

Regarding the torsion testing, for technical reasons, experiments were conducted for Clear V4, Grey Pro, and Elastic materials. The measurements were carried out at 25 °C and 60 °C. This was possible because the torsion testing device was equipped with a temperature chamber, allowing controlled thermal conditions during loading. The measured data shows a decrease of the measured quantities with higher temperature, which is consistent with general findings e.g. in [31]. In the case of the Clear V4 material, it can be seen that for a rotation angle of approximately up to 100°, the characteristic is steeply linear, and this trend can be observed at higher temperature. A similar situation occurs in the case of the Grey Pro material. Damage occurs in the same angular rotation range. The opposite is of course true for Elastic. At the higher temperature, the sample is damaged at the same angular rotation level as in the previous cases. On the other hand, at lower temperature, the elasticity of the material at the 90° angle of rotation level becomes apparent and a significant decrease in stress occurs. As far as research in the area of torsion is concerned, there has not been as much research in this area with which to compare the measured results. From the available scientific literature, research [32] provided interesting results for different materials, but it focused on the fused deposition modelling (FDM) approach.

The Tables 7 to 9 show correlation matrices that compare the effects of each parameter against each other. Within the correlation matrix, the correlation coefficients for each variable are calculated.

Table 7. Correlation matrix for tensile stresses.

	Young's Modulus	Breaking load	Surface roughness Ra	Surface roughness Rz
Young's Modulus	1			
Breaking load	0.811	1		
Surface roughness Ra	-0.99	-0.75	1	
Surface roughness Rz	-0.91	-0.49	0.90	1

For tensile loading shows that the Young's modulus is negatively correlated with the surface roughness. The positive correlation represented by the correlation coefficient value of 0.8 took place with the breaking load variation. A lower

correlation level is then evident for the breaking load and surface roughness Rz.

Table 8. Correlation matrix for compressive stresses.

	Young's Modulus	Breaking load	Surface roughness Ra	Surface roughness Rz
Young's Modulus	1			
Breaking load	0.99	1		
Surface roughness Ra	-0.55	-0.64	1	
Surface roughness Rz	-0.21	-0.29	0.90	1

A similar condition is also evident for pressure loading. A negative correlation with a correlation coefficient of 0.55 is evident for surface roughness Ra. A low level of correlation is also evident for surface roughness Rz. Compared to the previous example, a decreasing tendency of correlation can be observed. A positive correlation, which shows a higher value than in the case of the tensile load, can be observed in the breaking load.

Table 9. Correlation matrix for bending stresses.

	Young's Modulus	Breaking load	Surface roughness Ra	Surface roughness Rz
Young's Modulus	1			
Breaking load	0.67	1		
Surface roughness Ra	-0.61	-0.17	1	
Surface roughness Rz	-0.28	-0.50	0.90	1

In the case of bending stresses, it can be seen that similar magnitudes of correlation coefficients were achieved as in the previous case, with the trend being identical to the previous cases.

A limitation of this study is the absence of some advanced analytical techniques, such as FTIR or Raman spectroscopy, which would allow for a more detailed evaluation of the degree of polymerization and the internal structure of the printed materials. From the scientific perspective, this is particularly relevant because the mechanical strength of parts and samples produced by SLA printing is closely linked to the degree of polymerization. According to information provided in many publications, for example, [33–39], the degree of polymerization depends on the key factors like laser intensity, temperature, and the composition of the resin. Moreover, exposure time to UV light plays a critical role, and the thickness of the printed layers significantly affects polymerization, so that thicker layers are more difficult to cure uniformly. Polymerization is also influenced by whether each layer is properly cured before the next one is applied. These are important topics, worthy to be investigated in further stages of

the research, especially as the available reports are mostly related to the studies on the materials intended for medical applications. However, in industrial practice, all of these parameters are specified by the manufacturer. Therefore, in accordance with the intended mechanical engineering applications, this study followed the manufacturer's recommended settings, and the derived conclusions are relevant for the research objectives. At this stage, the research is focused on standard 3D printing processes rather than the development of new materials or printing methods, but in future, it is planned to expand the investigations with new experiments and analyses.

5. Conclusion

The study compares the mechanical properties achievable under real operating conditions with the values reported by ©Formlabs (Somerville, USA) for their materials.

This article presented and discussed the experimental results of mechanical properties of samples produced by the SLA 3D printing method, which were subjected to tensile, compressive, bending, and torsional loading. The materials Grey Pro, Elastic, Rigid 10K, Clear V4 were considered in the investigation, which the research team found to be among the most commonly used. Due to the basic characteristics of the Elastic material, it was not possible to measure and calculate the Young's modulus and strength using the equipment available to the research team.

Comparing the data provided by the manufacturer with the measurement results, it became clear that in most cases, the values of the Young's modulus in tension were lower than that

provided by the manufacturer. The opposite is true for the Rigid 10K material, where the measured values significantly exceeded the values provided by the manufacturer.

The data obtained from the investigation shows that Rigid 10K material exhibits the highest resistance to the compressive loading, similarly, although not as significantly, in the case of tensile loading. In this respect, the use of this material can be recommended in applications where tension/pressure are critical loads, e.g. positioning. Thus, the properties other than mechanical performance must be taken into account. In this context, the Rigid 10K material showed the best values of surface roughness Ra and Rz. Because of the good compression strength, the material is suitable for bearings, sliding plates or moulds for soft material like silicone. From the obtained data for the tested materials, Rigid 10K can be evaluated as the most universal one with respect to both mechanical properties and surface roughness.

The measurement results demonstrated that a flexible material such as Elastic is suitable for applications such as vibration damping. However, the torsional measurements in different temperatures proved that the damage to the Elastic sample at 60 °C occurred at almost half the angle of rotation. Nevertheless, this material can be successfully used for bumpers, seals, gaskets, or footwear components.

Future research will be focused on the factors affecting the polymerization, to further improve the 3D printing process of the tested materials.

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