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In-House Device Development for Polymer Materials Testing on Bending and Torsion

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ABSTRACT: *Testing the mechanical properties of polymer materials, such as bending and torsion, is essential to understanding their utility in various structural and industrial applications. In this paper, the procedure for designing an in-house device for testing bending and torsion, adapted for the laboratory needs of the faculty and its use for the purpose of researching the technological properties of polymer materials, is presented. The device allows for controlled application of loads, monitoring of displacements and measurement of forces or moments acting on the specimen. Based on the data obtained, it is possible to calculate the basic mechanical characteristics of the material, such as the flexural modulus of elasticity, flexural strength, torsional modulus of elasticity and ultimate torsional strength. Special attention is given to the repeatability of the results, ease of handling of the device and comparison with standardized test methods according to ISO 178 and ASTM D790 standards. The device is designed to withstand greater stress if test specimens are made by injection molding or compression molding from powder, as well as test specimens reinforced with aramid fibers, which have significantly greater toughness, strength, and elasticity. The test results showed that the device meets the given requirements and is relatively precise in terms of repeatability of results.*
Keywords: *mechanical testing device, bending, torsion, 3D printing, polymer materials.*

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I. INTRODUCTION

Polymer materials are playing an increasingly important role in modern industry due to their advantageous properties, such as low weight, good chemical resistance, formability and relatively low production cost. Their applications [1,2] are diverse, from packaging and consumer products to the automotive and aerospace industries, and even biomedical devices. However, the reliable application of polymers in engineering structures requires detailed knowledge of their mechanical properties [3-6].

In addition to tensile strength testing of polymer materials [7], bending [8,9] and torsion [10-12] tests also play an important role, as these are the most common forms of loading to which polymers are exposed in practice. Bending testing allows the determination of the flexural modulus of elasticity and flexural strength, while torsion testing provides information on the torsional modulus and ultimate strength of the material in torsion. These parameters are crucial for assessing the load-bearing capacity and durability of components made of polymers.

In order to be able to conduct such tests for educational and research purposes, an in-house device was developed that enables the combined testing of bending and twisting of polymer samples. The advantage of this solution is adaptability to different shapes and dimensions of the specimens, lower costs compared to commercial devices and the possibility of optimization for specific research tasks.

This paper presents the theoretical basis of testing, construction and functionality of the In-house device, and analysis of the obtained results, with the aim of proving its applicability and reliability in the characterization of polymer materials.

II. MATERIALS AND METHODS

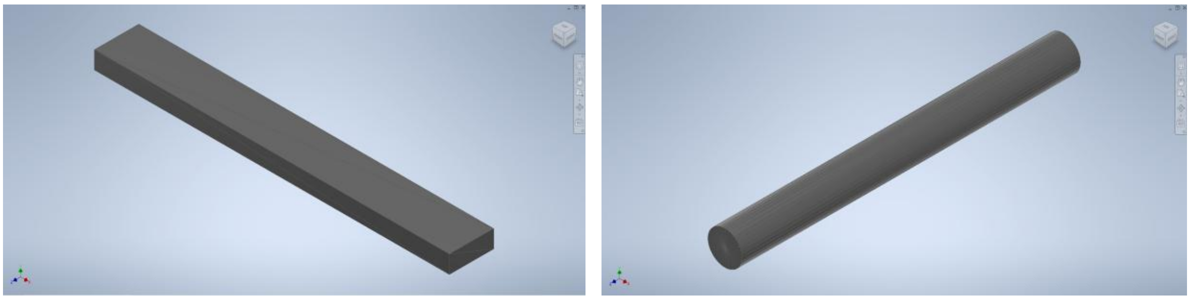
For the purposes of the research, PETG polymer material was used, which was 3D printed into standardized test specimens intended for bending and torsion testing. The shape and dimensions of the test specimens were determined according to the requirements of the ISO 178 standard, which defines methods for determining the bending and torsional properties of polymer materials. The test specimens were prepared, respecting the prescribed tolerances and testing conditions before testing, to ensure repeatability and comparability of the results.

2.1 Test specimens

The relevant standard for bending testing of polymer test specimens is ISO 178 [13] or American standard ASTM D790. ISO 178, used in this research, defines methods and requirements for bending testing of polymer materials to determine their bending properties, including modulus of elasticity, strength and deformation during bending. Special emphasis is placed on the shape, dimensions and preparation of test specimens, because the reliability and repeatability of the results depend on proper preparation. The use of test specimens according to the ISO 178 standard ensures international compliance of test methods, which allows reliable comparison of data between different laboratories and manufacturers.

Bending specimens according to the mentioned ISO standard are most often rectangular in shape (Figure 1a) with dimensions that depend on the thickness of the material, while the length and width are determined to ensure the correct loading during three-point bending. The standard also prescribes tolerances, edge treatment methods and conditioning conditions before testing.

Although the standard primarily applies to bending tests, the defined shape of the test pieces is often used for torsion tests as well, as rectangular specimens meet the basic requirements of torsional devices. This allows for the comparison of results from different tests on the same specimens, facilitating the characterization of polymer materials for research and industrial purposes. For the purposes of testing the device, the test specimens for the torsion test are circular cross-section, according to the ISO 6721 standard [14] (Figure 1b).



a) Bending test specimen b) Torsion test specimen

Fig. 1 Test specimens for bending and torsion testing

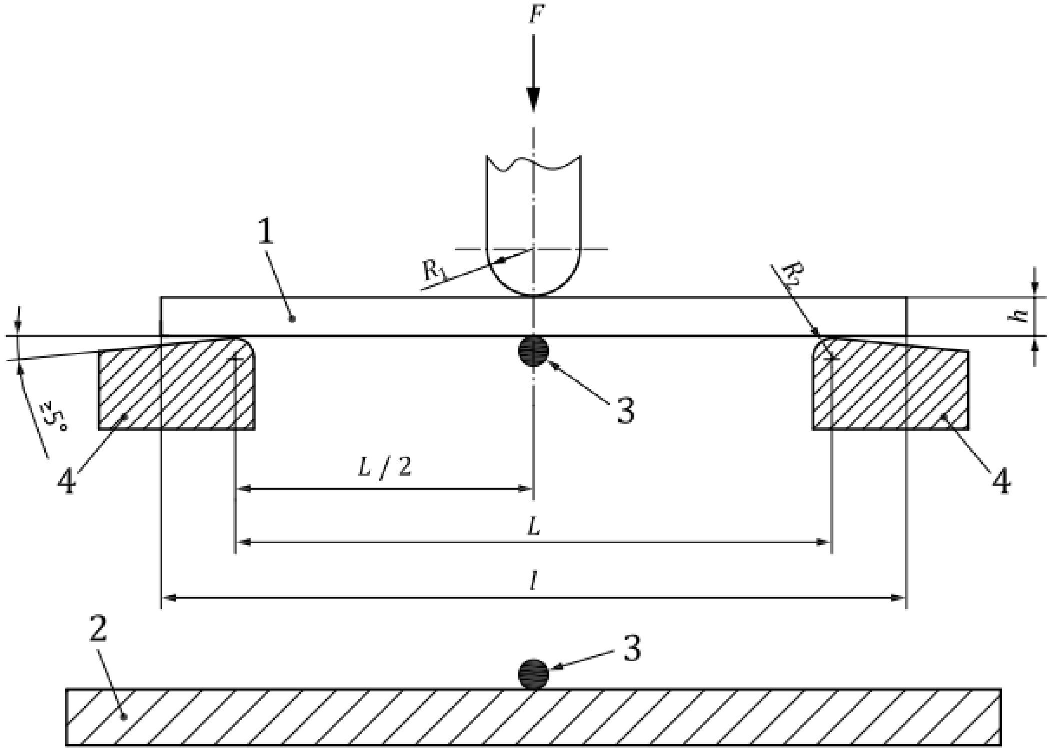
The rectangular bending test specimen (Figure 1a) has the following dimensions:
Length, l – 80 mm ± 2
Width, b – 10 mm ± 0.2
Thickness, h – 4 mm ± 0.2
The cross-section of the specimen is rectangular without rounding

2.2 Three-point bending test

Three-point bending testing is one of the most commonly use methods for determining the mechanical properties of rigid and semi-rigid materials, especially plastics, composites and wood. The method is based on applying a load to the middle of the sample, while it is supported by two end supports. In this way, tensile and compressive stresses develop in the material, which allows the determination of key parameters such as flexural strength, flexural modulus of elasticity and critical deformation.

The advantages of this method are its simplicity, repeatability, and the ability to test various shapes and dimensions of samples. Standardized procedures, defined by standards such as ASTM D790 and ISO 178, ensure comparability of results between laboratories and applicability in research, development, and quality control of materials. The results of three-point bending tests are of great importance in engineering practice, as they allow the prediction of the behavior of materials under load in real conditions, especially in structures where bending stresses dominate.

Figure 2 shows the method of testing test specimens for three-point bending.



1 - test specimen
2 - support base plate
3 - deflectometer position
4 - supports
R_1 - radius of loading edge

h - thickness of specimen
F - applied force
l – length of specimen
L – length of span between supports
R_2 - radius of supports

The tolerances of the tip radius R_1 and the support radius R_2 should be as follows:
R_1 = 5,0 mm ± 0.1 mm
R_2 = 5,0 mm ± 0.2 mm for test specimen thicknesses >3 mm

The length of the span between the supports, *L,* is adjustable.

Fig. 2 Position of test specimen and deflectometer at start of test [13]

2.3 Torsion test

The torsion test of polymer materials is used to determine their mechanical properties under torsional loading. The procedure is based on the application of a torque to a test specimen, which causes the specimen to twist and develop shear stress. Based on the measured values, key parameters such as the torsional modulus of elasticity (G), ultimate torsional strength, and angular deformation at fracture can be determined.

This test method is particularly important for polymer materials that are often used in practical applications where torsional loads prevail, such as in gears, shafts, housings and joints. The results allow for comparison of different types of polymers and their composites and provide data necessary for optimizing structures and selecting materials in engineering applications.

The use of in-house testing equipment further facilitates the conduct of these tests, as it allows flexibility in the choice of specimen dimensions and adaptation to specific research requirements, while maintaining the basic principles of torsion testing defined by relevant standards.

The standard used for polymer torsion used in the work is ISO 6721. ISO 6721 does not define just one type of specimen, but several, depending on the dynamic testing method. The specimens used in the work, for torsion, have a circular cross-section.

III. EXPERIMENTAL PART

3.1 Design and evaluation of bending and torsion In-house device

Using a methodical approach, creating a list of wishes and requirements, and creating a morphological matrix for comparing different partial function solutions, three variants of a 3D model of device for testing polymer materials for bending and twisting were created. A techno-economic evaluation of the three variants was performed on the basis by which the optimal one was selected.

Evaluation determines the “value”, or “goodness” of a solution in relation to the set goal. Evaluation procedures are used to assess solutions in all stages of design. Goals are set based on a list of requirements. At the same level, horizontally, several independent goals are set – e.g. technical value and economic value. The goals are then broken down into two or more partial goals that are at a lower level and are of lower complexity. The S diagram shown in Figure 3 is used to graphically display technical-economic goodness.

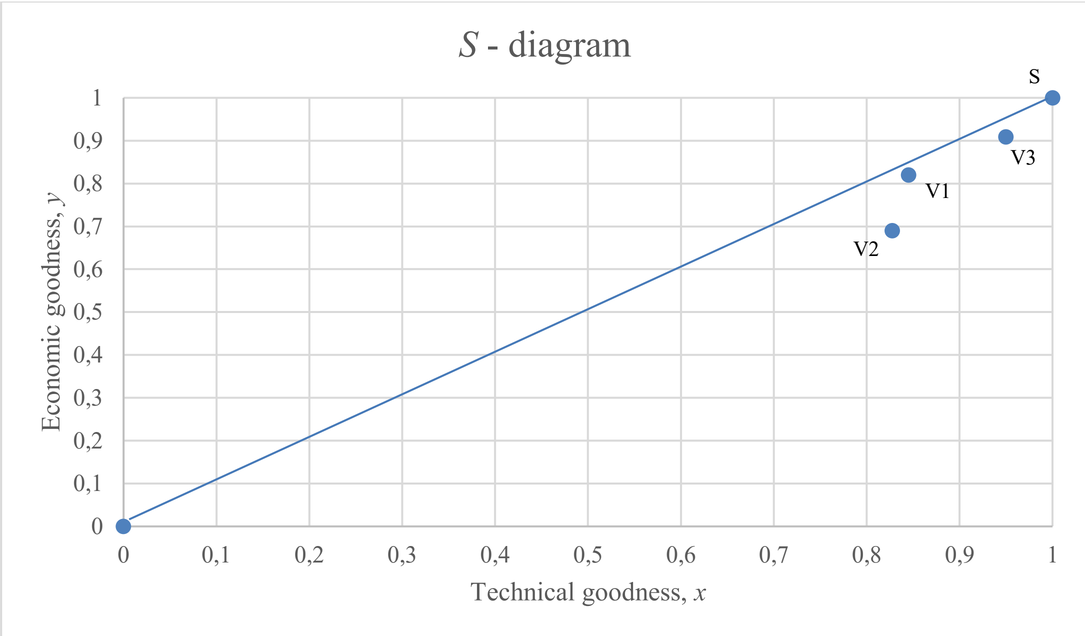


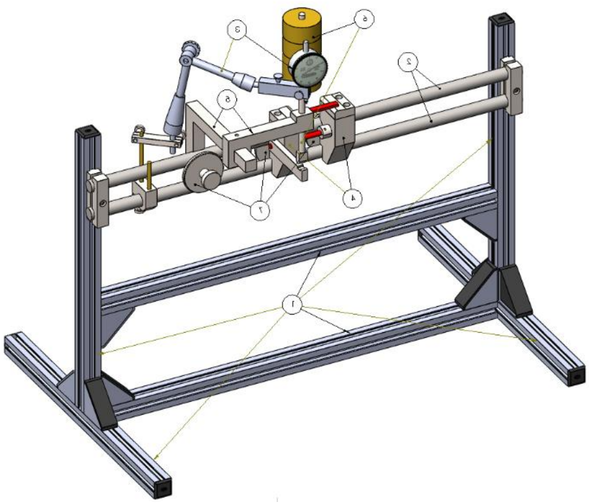
Fig. 3 S-diagram of technical-economic goodness

The technical goodness x is entered on the abscissa (x-axis), while the economic goodness, y is entered on the ordinate (y-axis) in the diagram (Figure 3). The overall goodness of a solution is defined by point S, which has coordinates x and y, while the ideal solution is determined by point S, which has coordinates $x = 1.0$ and $y = 1.0$. The ideal solution will never actually be achieved. In the diagram, can be seen that a solution of variant 3 is somewhat closer to point S, i.e. has a higher overall goodness S, and it is adopted as the final solution that is further calculated and dimensioned in certain design phases. The ratio of the overall goodness is shown in Table 1.

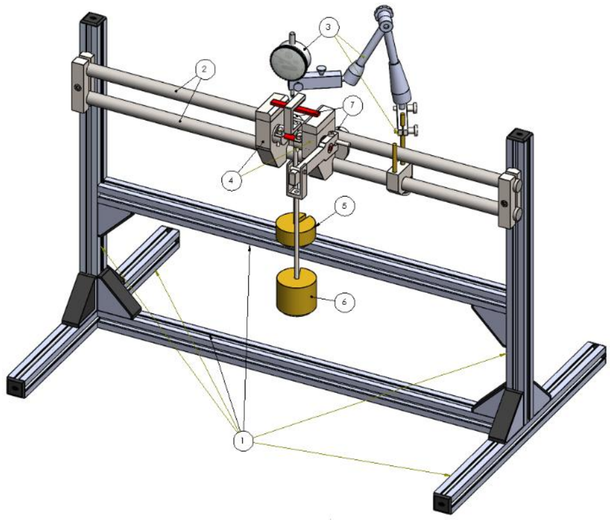
Table (1). The ratio of total goodness.

VARIANT 1	x_1	0,845	$d_1 = \sqrt{x_1 \cdot y_1}$ =0,832
	y_1	0,820	
VARIANT 2	x_2	0,826	$d_2 = \sqrt{x_2 \cdot y_2}$ =0,756
	y_2	0,690	
VARIANT 3	x_3	0,950	$\boldsymbol{d_3 = \sqrt{x_3 \cdot y_3}}$ **=0,929**
	y_3	0,909	

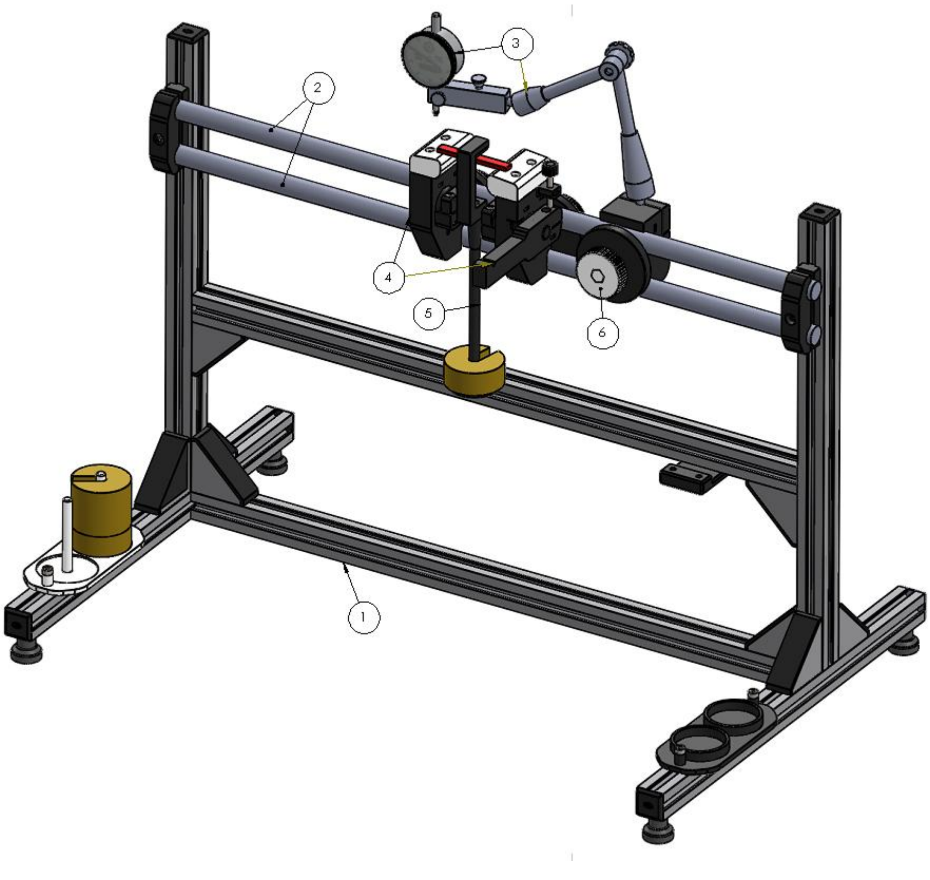
By comparing the variants, variant 3 was selected, a detailed design development adapted to 3D printing was carried out, technical documentation was created, and calculations were made. The design and construction of the device (Figure 4) was created in the SolidWorks Premium CAD tool, which is used for 3D modeling, simulation, visualization, and the creation of technical documentation. The selected variant for production is shown in Figure 4c.



a) Variant 1



b) Variant 2



c) Variant 3

Fig. 4 Variants of device for testing the bending and torsion of polymer materials

1	Aluminum profile	4	Clamping head with torsion lever, i.e. bending rest
2	Guides	5	Weight holder for bending and torsion
3	Measuring tool with holder	6	Tension screw

3.2 Manufacturing of bending and torsion In-house device

In addition to design and 3D modeling, technological preparation of production is the most demanding item in product development, which, in addition to the necessary knowledge, skills and experience, requires a lot of time. Technological preparation refers to the way in which something will be made with a certain tool and in a certain period of a time, and the economy and efficiency of production depend on it. When making the device, a band saw was used to cut the raw material (Aluminum profiles, rods, guides, weights) which were further processed on a classic lathe and milling machine. Most of the parts were made by 3D printing on a *Prusa i3 MK3S* 3D printer, for economic reasons. Figure 5 shows the finished, manufactured device for testing the bending and twisting of polymer materials.

Fig. 5 In-house device for bending and torsion testing of polymer materials

IV. RESULTS

4.1 Device testing

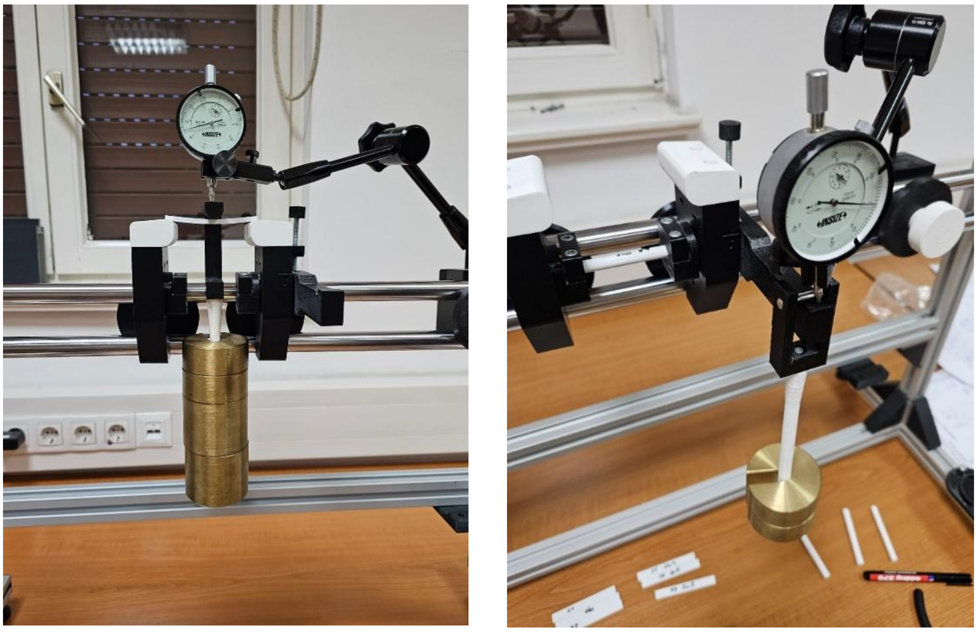
Before testing, for each percentage of infill material, three specimens need to be printed, calibrated and the arithmetic mean calculated according to the ISO 2602 standard. Polymer materials tend to absorb moisture from the air or water, and this effect needs to be reduced by testing the specimens immediately after the 3D printing and cooling process (under controlled conditions) or, if this is not possible, by vacuuming the specimens. Before each test, the specimens need to be measured and visually inspected. The way to measure the specimen is to place the specimen on a table and measure the deflection in the middle with a height gauge. Before testing, the weight of the weight carrier should be taken into account. Recommended testing conditions: room temperature from 20 to 22°C; relative humidity from 40-60%; air flow less than 1m/s.

4.2 Three-point bending testing

A bending test was performed (Figure 6a), polymer test specimens with a rectangular cross-section made of PETG material. Three specimens were tested for different parameters, percentage of infill and load (Table 2) on what basis of which the deflection *f* was measured expressed in mm. A mutual comparison of the other two was performed in relation to test specimen S1.

Table (2). Table of bending test results for test specimens with 100% and 50% infill.

	Infill 100%			**Infill 50%**		
Weight (kg)	Specimen S1	Specimen S2	Specimen S3	Specimen S1	Specimen S2	Specimen S3
	Deflection *f* (mm)	Deflection *f* (mm)	Deflection *f* (mm)	Deflection *f* (mm)	Deflection *f* (mm)	Deflection *f* (mm)
0,5	0,370	0,338	0,310	0,270	0,339	0,359
1,0	0,690	0,688	0,682	0,678	0,728	0,718
2,0	1,380	1,385	1,390	1,508	1,508	1,570
4,0	2,107	2,010	2,110	2,287	2,346	2,220



a) Three-point Bending test b) Torsion test

Fig. 6 Bending and Torsion test on In-house device

Comparison of the other two bending test specimens with test specimen S1 in percentage of infill is 100% (from Table 2):

At a load of 0,5 kg, test specimen S2 shows less flexibility than reference test specimen S1 by 8,6%, while S3 is even more flexible and less than S1 by 16,2%. By increasing the load to 1 kg, the difference between S2 and S1 decreases significantly – S2 is smaller than S1 by only 0,3%, and S3 is smaller by 1,2%. At a load of 2 kg there is a change: S2 is now larger than S1 by 0.36%, and S3 is larger by 0,72%. For the highest load of 4 kg, S2 is again slightly smaller than S1 by 4,6%, while S3 is almost equal to the reference test specimen, with a small positive difference of 0,14%.

Comparison of the other two bendable test specimens to test specimen S1 in percentages, infill is 50% (from Table 2):

At a load of 0,5 kg, test specimens S2 and S3 show greater flexibility than reference test specimen S1 – S2 is higher by 25,6%, and S3 by 33,0%. Increasing the load to 1 kg, the S2 is still 7,4% more flexible than the S1, while the S3 is 5,9% larger. At 2 kg, S2 shows the same flex as S1, while S3 is still higher than S1 by 4,1%. At the maximum load of 4 kg, the S2 is slightly more flexible than the S1 by 2,6%, while the S3 is now less flexible than the S1 by 2,9%.

Based on the results of measuring the deflection of test specimens with 100% and 50% infill (Table 2), several important facts can be observed:

In both series of tests (100% and 50% infill), the deflection increases approximately linearly with increasing load, which confirms the elastic behavior of the material in the tested range of forces. With 100% infill, the deflections are slightly smaller on average compared to 50% infill, especially with higher loads (2-4 kg). This means that a higher percentage of infill ensures greater stiffness and bending resistance for the material.

Comparison at lower loads (0,5–1 kg) the differences between the samples are not large, and at a load of 1 kg the results are almost identical. This suggests that at lower forces, the percentage of infill does not have a decisive influence on deflection, that is, that the structure maintains sufficient stiffness even with less infill.

The comparison at higher loads (2–4 kg) shows more pronounced differences. Test specimens with 50% infill show larger deflections compared to 100% infill. For example, at a load of 4 kg, deflections at 50% infill reach 2,287–2,346 mm, while at 100% infill remain in the range of 2,01–2,11 mm. This confirms that reducing the infill significantly reduces the bending resistance at higher forces. In both series of measurements, a very good agreement between individual test specimens is visible, which indicates a homogeneous material structure and the reliability of the testing method.

4.3 Torsion testing

The bending test of a circular cross-section polymer specimen made of PETG material is shown in Figure 6b). Three specimens were tested for different parameters, percentage of infill and load (Table 3) on what basis of which the displacement *x* was measured expressed in mm. A mutual comparison of the other two was performed in relation to the specimen U1.

Table (3). Table of torsion test results for test specimens with 100% and 50% infill.

	Infill 100%			Infill 50%		
Weight (kg)	Specimen U1	Specimen U2	Specimen U3	Specimen U1	Specimen U2	Specimen U3
	Displacement *x* (mm)	Displacement *x* (mm)	Displacement *x* (mm)	Displacement *x* (mm)	Displacement *x* (mm)	Displacement *x* (mm)
0,5	4,16	4,20	4,10	5,70	5,60	5,66

Comparison of the other two torsional specimens with the U1 specimen in percentages of infill 100% (from Table 3):

At a load of 0,5 kg, the U2 specimen shows a higher torsional resistance than the reference specimen U1 by 0,96%, while U3 is lower than U1 by 1,44%.

Comparison of the other two torsional specimens with the U1 specimen in percentages of infill (50%) (from Table 3):

At a load of 0,5 kg, the U2 and U3 specimens show a slightly lower torsional resistance than the reference specimen U1 – U2 is lower by 1,75%, while U3 is lower by 0,77%.

The distance between the specimen claws is 55 mm, while the distance from the center of the specimen to the comparator position is 80 mm. The test was performed with a weight of 0.5 kg, and the results were recorded in Table 3, while for larger weights, the test specimens did not withstand the stress.

V. CONCLUSION

Bending and torsion testing of polymer materials is an important step in understanding their mechanical properties and behavior under various forms of loading. The results obtained with these methods allow the determination of parameters such as flexural modulus of elasticity, bending strength, torsional modulus and ultimate torsional strength, which are key for the correct assessment of the useful value and safety of materials in real-world application conditions.

Using the in-house developed device, it was shown that it is possible to conduct these tests in a simple, economical and reliable manner, with the possibility of adapting to different shapes and dimensions of test specimens. The test results showed that the device meets the given requirements and is relatively precise in terms of repeatability of results. Thus, the device has proven to be an effective solution for laboratory research and educational needs.

The obtained result confirmed the importance of a standardized approach to testing but also showed that customized systems can provide sufficiently precise and reproducible data for comparison and analysis. In this way, the foundations were created for further improvements of the device and the expansion of the test spectrum, which further increases its applicability in scientific and engineering disciplines.

If it is necessary to achieve higher precision results, the device can be improved by installing sensors and controllers for digital reading of deformations, tensiometric tapes for reading stress, sensors for measuring displacement and automatic adjustment of the load size.

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