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Influence of UV Radiation on the Mechanical Properties of Specimens Printed with the Use of the FDM Technique at Different Density Levels

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Abstract
The development of 3D printing technology and the possibility of obtaining objects from polymeric materials with a diversified structure and mechanical properties necessitates conducting comprehensive research into printed structures and determining their basic mechanical parameters. Synthetic polymeric materials during their lifetime are sensitive to atmospheric factors and are subject to aging. The paper presents investigation results of the mechanical properties of printed structures with different density levels. The influence of UV radiation and elevated temperature on the mechanical parameters of specimens printed from different filaments was determined, estimating the usefulness of printed porous structures for possible applications in the textile industry.

Key words: *3D printing, polymeric materials, material strength, ageing.*

Introduction

In the face of the progressive development of 3D printing technology, printed objects are finding more and more applications [1, 2]. The possibility of obtaining objects with a differentiated structure and mechanical properties that significantly differ from those of printing material is of greatest importance [1, 3-5]. This forces the necessity to conduct research into the properties of new printed structures and determine their basic mechanical parameters [4, 6, 7]. Filaments used for printing with fused deposition modelling (FDM) are made of polymeric materials. During their lifetime, these materials are sensitive to atmospheric factors and are subject to ageing. The influence of thermal ageing on ABS blends can be found in [8, 9].

PC-ABS is a blend of acrylonitrile-butadiene-styrene (ABS) 55~65% and polycarbonate (PC) 30~35% as well as of lubricants, mineral oils, waxes and antioxidants. The addition of polycarbonate increases the thermal resistance of material which is characterised by high impact strength, high rigidity and machining. Hence it is widely used in the production of household appliances and in many other parts of machinery and equipment.

ULTRAT is also a blend of ABS (over 90%) but with a significantly lower polycarbonate content (up to 3%). It is a material with a high degree of hardness and resistance to external factors. ULTRAT is used in prototyping, making small parts that require high precision, mechanical parts and models with complex shapes.

Both materials can be used in a so-called virtual warehouse for the production of small repair parts, guides or covers in the 3D printing process. In FDM, porous structures can be obtained depending on the degree of print density and with different mechanical properties. However, these properties may change during exploitation as a result of external factors, such as UV radiation and elevated temperature [10, 11, 12].

Objective of the work

The aim of the article is to present the results of investigations of the mechanical properties of printed structures that are characterized by various density and to determine the influence of UV radiation and elevated temperature on selected mechanical parameters of specimens of different density of printing, made from filaments of PC-ABS and ULTRAT, produced by ZORTRAX [14], and through this to estimate the usefulness of porous structures for possible applications in the textile industry.

Figure 1. Specimen printed for tensile tests.

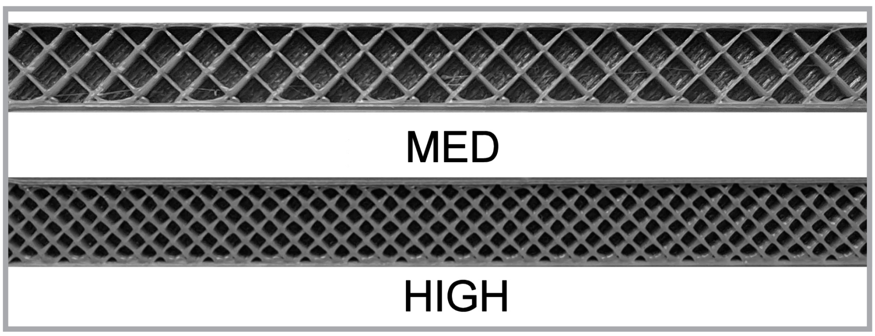

Figure 2. Internal structure of specimens in dependence on the type of density.

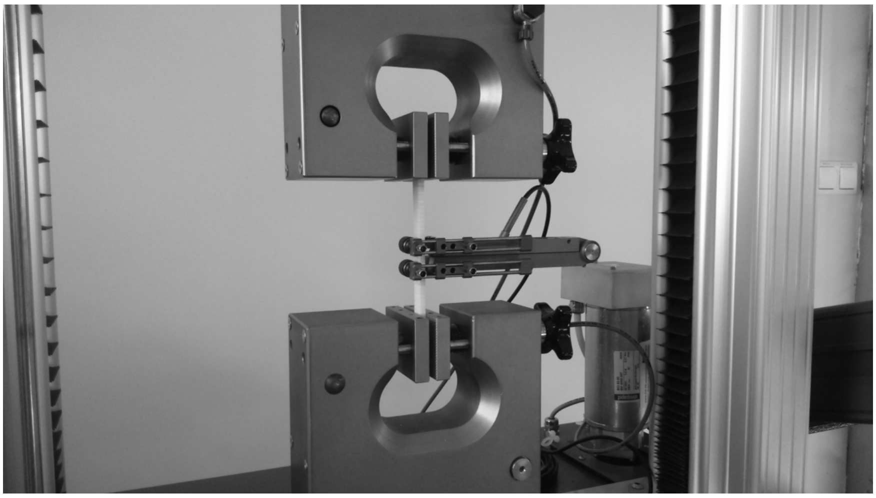

Figure 3. Specimen in the testing machine with an extensometer attached.

Table 1. Cross-sectional area of the specimen in dependence on the density type.

Density type	Cross-sectional area, mm^2
MED	20.64
HIGH	23.78

Subject of study

Tests included specimens made on a ZORTRAX M200 3D printer of PC-ABS and ULTRAT filaments (***Figure 1***) in two different densities, conventionally called MED and HIGH (***Figure 2***). 10 specimens with a MED density and 10 specimens with a HIGH density were made of the PC-ABS material. Of these 10 specimens, 5 were used to test non-aged material and five were subjected to the ageing process. The same was applied to ULTRAT. The dimensions of the specimens tested were chosen in accordance with DIN EN ISO 527-1 and DIN EN ISO 527-3.

The average cross-sectional area of the specimen was calculated using a Opta-Tech microscope and the Makroaufmassprogramm [7] and is given in ***Table 1***.

5 specimens of each density were subjected to a tensile test at a speed of 5 mm/min to determine the tensile strength and substitute modulus of longitudinal elasticity. The given speed is one of the permissible values in DIN EN ISO 527-1. The remaining specimens were first exposed to UV radiation in an ageing chamber, and afterwards subjected to a tensile test.

The tensile test was performed on an INSPEKT 5 Hegewald & Peschke testing machine with a range of 5 kN class 0.5 acc. ISO 7500-1: 2015 controlled by the Labmaster program, in which the test procedure was prepared. To determine elastic deformations, an extensometer with a base of 25 mm was used (***Figure 3***).

Results obtained in specimen tensile test

Table 2 shows the value of the maximum force obtained during the tensile test F_m and the corresponding apparent stress R_m, the value of the substitute Young's modulus E_z and the value of the yield stress R_{02} for the specimens made of the PC-ABS material for both types of density. The confidence interval L was determined based on the t-Student distribution, which refers to the statistical evaluation of small groups of results (n < 20) according to the ***Equation (1)***:

$$L = \bar{x} \pm \Delta x_\alpha = \bar{x} \pm S \cdot t_\alpha \quad (1)$$

Where, $\bar{x}$ – mean value of five measurements, Δx_α – uncertainty of measurement, S – standard deviation, and t_α – t-Student's factor at a confidence level of $\alpha = 0.95$ for five measurements, amounting to 2.776 [13]. The average

Table 2. Results of tensile test of specimens made of PC-ABS.

L.p.	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	PC-ABS							
	MED	HIGH	MED	HIGH	MED	HIGH	MED	HIGH
1	786.27	855.51	38.10	35.98	1895.66	1739.77	33.80	31.16
2	773.31	839.95	37.47	35.32	1888.91	1807.23	31.98	30.49
3	783.11	841.97	37.94	35.41	1912.90	1799.00	33.31	30.17
4	792.11	835.02	38.38	35.11	1916.56	1738.08	34.08	31.47
5	775.84	850.01	37.59	35.74	1930.08	1788.63	32.67	30.57
$\bar{x}$	**782.12**	**844.49**	**37.89**	**35.51**	**1908.82**	**1774.54**	**33.17**	**30.77**
S	7.66	8.19	0.37	0.34	16.56	33.18	0.85	0.53
Δx_α	21.28	22.74	1.03	0.96	45.98	92.11	2.37	1.47

Table 3. Tensile test results of specimens printed with ULTRAT.

L.p.	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	ULTRAT							
	MED	HIGH	MED	HIGH	MED	HIGH	MED	HIGH
1	825.90	865.19	40.02	36.38	2353.28	2123.99	39.74	35.29
2	833.36	858.25	40.38	36.09	2427.84	2115.99	38.75	35.48
3	814.30	835.65	39.45	35.14	2325.43	2096.15	39.11	34.82
4	819.46	843.83	39.70	35.48	2373.58	2124.48	39.43	35.04
5	785.10	839.47	38.04	35.30	2320.83	2118.32	37.72	34.95
$\bar{x}$	**815.63**	**848.48**	**39.52**	**35.68**	**2360.19**	**2115.79**	**38.95**	**35.12**
S	18.50	12.67	0.90	0.53	43.48	11.56	0.78	0.27
Δx_α	51.34	35.17	2.49	1.48	120.69	32.10	2.17	0.75

Table 4. Average results obtained in the tensile test.

Material	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	MED	HIGH	MED	HIGH	MED	HIGH	MED	HIGH
PC-ABS	**782.12** ±21.28	**844.49** ±22.74	**37.89** ±1.03	**35.51** ±0.96	**1908.82** ±45.98	**1774.54** ±92.11	**33.17** ±2.37	**30.77** ±1.47
ULTRAT	**815.63** ±51.34	**848.48** ±35.17	**39.52** ±2.49	**35.68** ±1.48	**2360.19** ±120.69	**2115.79** ±32.10	**38.95** ±2.17	**35.12** ±0.75

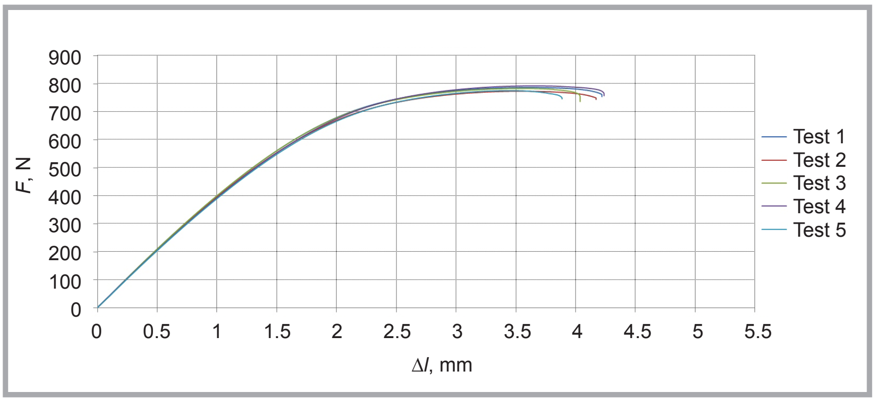

Figure 4. *Tensile graphs of PC-ABS MED specimens.*

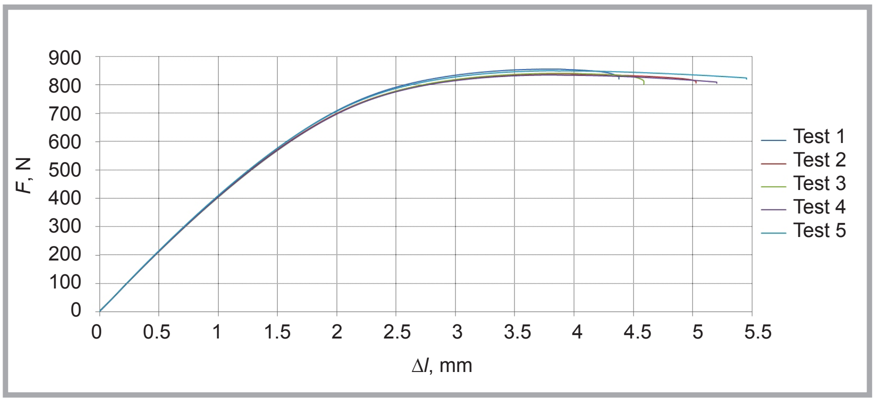

Figure 5. *Tensile graphs of PC-ABS HIGH specimens.*

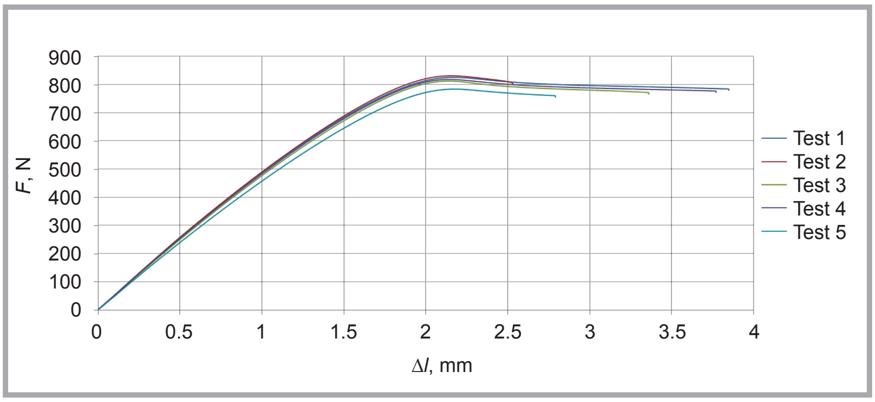

Figure 6. *Tensile graphs of specimens from ULTRAT MED.*

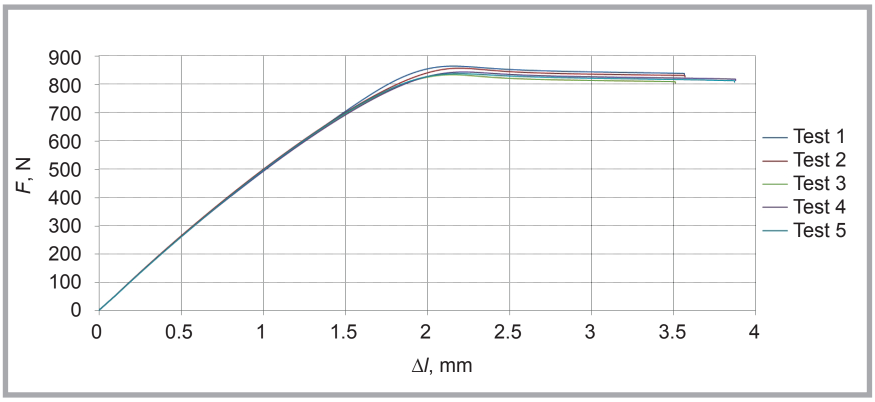

Figure 7. *Tensile graphs of specimens from ULTRAT HIGH.*

elongation at break was also determined, which is 4.11 ± 0.41 mm for specimens with MED density and 4.93 ± 1.22 mm for those with HIGH density.

Figures 4 and ***5*** shows force-displacement graphs obtained in the tensile test of PC-ABS specimens with MED and HIGH densities.

In ***Table 3*** the results obtained in the tensile test of specimens printed from ULTRAT material are summarised, and ***Figures 6*** and ***7*** show tensile graphs of the specimens printed from this material.

The average elongation at break for specimens with MED density is 3.27 ± 1.61 mm, and for those with HIGH density it is 3.68 ± 0.50 mm.

The graphs shown confirm the acceptable reproducibility of the results.

Table 4 presents a summary of the test results obtained for both materials at different densities.

When comparing the characteristics of both materials, it can be seen that specimens made from PC-ABS material of MED density transfer 4% lower force than those with the same density made of ULTRAT material, whereas at HIGH density the difference is insignificant. The substitute longitudinal elasticity modulus determined for PC-ABS specimens of MED density is 19% lower than the substitute elastic modulus of the ULTRAT specimens at the same density. The difference is 16% for HIGH density.

Ageing process of specimens

One of the basic features of products made of polymeric materials is ageing, understood as an irreversible change in physical and chemical properties caused by the influence of various atmospheric factors, in particular, ultraviolet radiation. As a result of the changes occurring in the ageing process, there is a change in mechanical properties, including elastic properties, load-bearing capacity and durability in the internal structure of the materials depending on the intensity and time of radiation.

In order to examine the effect of ageing on the materials analysed, a study was conducted involving exposure of the specimens to UV radiation in an Atlas

UVTest ™ ageing chamber equipped with eight 340 UVA fluorescent lamps.

Performing the ageing process requires determining the test time, the level of radiation emitted, and the temperature that will be maintained in the machine chamber. Based on PN-EN ISO 4892-1: 2016-06 and PN-EN ISO 4892-3: 2014-02, the temperature in the chamber was set to 50 °C, and the value of radiation emitted by one lamp was 0.55 W/m^2.

On the basis of data from the Ministry of Infrastructure and Construction, the total solar radiation intensity was determined on a horizontal surface of C_{prom} = 1011629 W/m^2 during a year. Based on this value, the ageing time in the UVTest machine was calculated to 128 hours, according to the following ***Equation (2)***:

$$L_h = \frac{C_{prom}}{L_l \cdot M_j \cdot 3600} = \frac{1011629}{4 \cdot 0{,}55 \cdot 3600} = \\ = 127{,}73h \qquad (2)$$

where:
C_{prom} – total amount of radiation in W/m^2,
M_j – unit power of the lamp (0.55 was assumed),
L_l – number of lamps used in the study (four lamps were used).

PC-ABS white specimens were clearly discoloured after the aging test (***Figure 8***). ULTRAT plastic specimens did not show discoloration because they were made of green material, and changes in this colour are much more difficult to observe without the use of specialised optical devices.

Results obtained in the tensile test after the ageing process

A tensile test was carried out for specimens subjected to the ageing process using the same test procedure as for the non-aged specimens. ***Table 5*** summarises measurement values obtained during the test for PC-ABS material, and in ***Table 6*** the results obtained for ULTRAT material are presented. ***Figures 9*** and ***10*** show tensile graphs obtained for PC-ABS and ***Figures 11*** and ***12*** for ULTRAT.

The mean elongation at break for specimens of MED density is 3.45 ± 0.72 mm and for those of HIGH density – 3.57 ± 0.88 mm.

The average elongation at break for specimens of MED density is 1.82 ± 0.34 mm, and for those of HIGH density it equals 2.03 ± 0.56 mm.

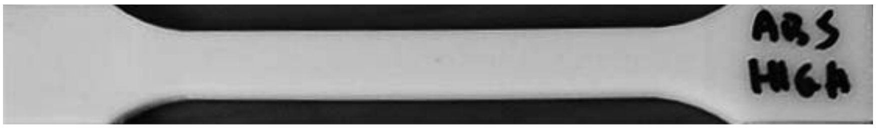

Figure 8. *Discolorations on the measuring part of the PC-ABS specimen.*

In ***Table 7*** the average results obtained after the ageing process are compared for both materials tested.

Table 8 presents a list of strength parameters of both materials for both types of density before and after the ageing process.

In ***Table 9*** the average elongation of the specimens at break for both materials is

Table 5. *Results of tensile test of PC-ABS specimens after ageing.*

PC-ABS after ageing process								
L.p.	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	MED	HIGH	MED	HIGH	MED	HIGH	MED	HIGH
1	899.18	939.20	43.56	39.49	2127.77	1870.96	38.75	35.43
2	861.20	909.65	41.72	38.25	2068.17	1940.76	38.56	33.94
3	871.11	921.19	42.21	38.74	2099.80	1886.95	38.20	34.43
4	870.66	908.19	42.18	38.19	2069.05	1970.53	38.16	33.58
5	885.79	924.89	42.92	38.89	2056.86	1919.24	38.47	34.41
$\bar{x}$	**877.59**	**920.63**	**42.52**	**38.71**	**2084.33**	**1917.69**	**38.43**	**34.36**
S	14.94	12.63	0.72	0.53	29.05	40.18	0.25	0.70
Δx_α	41.46	35.07	2.01	1.47	80.65	111.53	0.69	1.93

Table 6. *Results of the tensile test of specimens printed from ULTRAT after the ageing process.*

ULTRAT after ageing process								
L.p.	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	MED	HIGH	MED	HIGH	MED	HIGH	MED	HIGH
1	741.19	755.64	35.91	31.77	2460.39	2149.60	34.84	31.55
2	718.42	795.23	34.80	33.44	2445.84	2305.63	33.13	32.92
3	712.52	772.89	34.52	32.50	2435.18	2237.87	33.25	31.53
4	761.14	782.32	36.87	32.89	2529.58	2274.25	35.09	31.86
5	739.80	805.02	35.84	33.85	2449.98	2186.37	33.52	32.16
$\bar{x}$	**734.62**	**782.22**	**35.59**	**32.89**	**2464.20**	**2230.75**	**33.97**	**32.01**
S	19.52	19.25	0.95	0.81	37.65	63.45	0.93	0.57
Δx_α	54.18	53.44	2.63	2.25	104.52	176.14	2.58	1.59

Table 7. *Average results obtained after the ageing process.*

Material	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	MED	HIGH	MED	HIGH	MED	HIGH	MED	HIGH
PC-ABS	**877.59** ±41.46	**920.63** ±35.07	**42.52** ±2.01	**38.71** ±1.47	**2084.33** ±80.65	**1917.69** ±111.53	**38.43** ±0.69	**34.36** ±1.93
ULTRAT	**734.62** ±54.18	**782.22** ±53.44	**35.59** ±2.63	**32.89** ±2.25	**2464.20** ±104.52	**2230.75** ±176.14	**33.97** ±2.58	**32.01** ±1.59

Table 8. *Comparison of the results obtained before and after the ageing test.*

Material	F_m, N		R_m, MPa		E_z, MPa		R_{02}, MPa	
	MED	HIGH	MED	HIGH	MED	HIGH	MED	MED
PC-ABS before ageing	**782.12** ± 21.28	**844.49** ± 22.74	**37.89** ± 1.03	**35.51** ± 0.96	**1908.82** ± 45.98	**1774.54** ± 92.11	**33.17** ± 2.37	**30.77** ± 1.47
PC-ABS after ageing	**877.59** ± 41.46	**920.63** ± 35.07	**42.52** ± 2.01	**38.71** ± 1.47	**2084.33** ± 80.65	**1917.69** ± 111.53	**38.43** ± 0.69	**34.36** ± 1.93
ULTRAT before ageing	**815.63** ± 51.35	**848.48** ± 35.17	**39.52** ± 2.49	**35.68** ± 1.48	**2360.19** ± 120.69	**2115.79** ± 32.10	**38.95** ± 2.17	**35.12** ± 0.75
ULTRAT after ageing	**734.62** ± 54.18	**782.22** ± 53.44	**35.59** ± 2.63	**32.89** ± 2.25	**2464.20** ± 104.52	**2230.75** ± 176.14	**33.97** ± 2.58	**32.01** ± 1.59

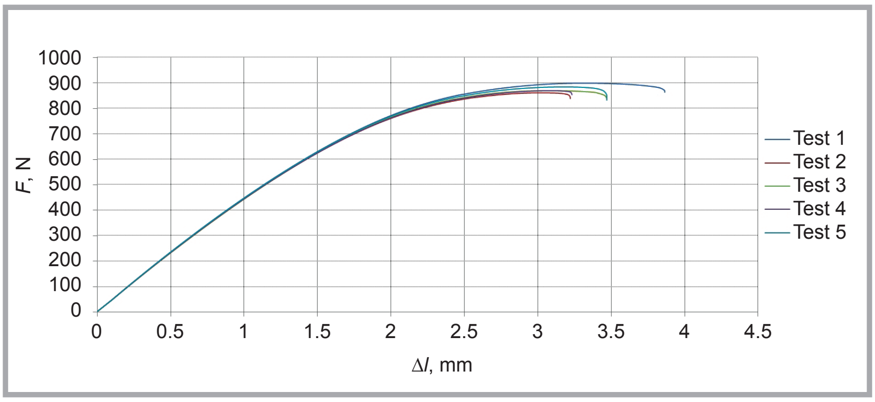

***Figure 9.** Tensile graphs of specimens from PC-ABS MED after the ageing process.*

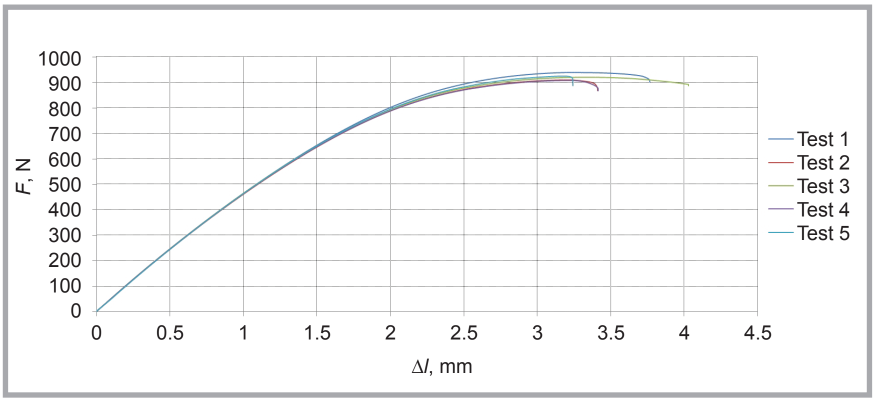

***Figure 10.** Tensile graphs for specimens from PC-ABS HIGH after the ageing process.*

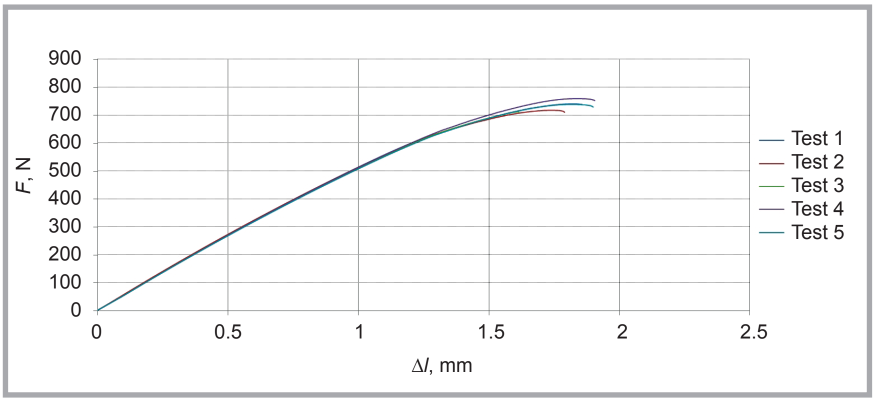

***Figure 11.** Tensile graphs of ULTRAT MED specimens after the aging process.*

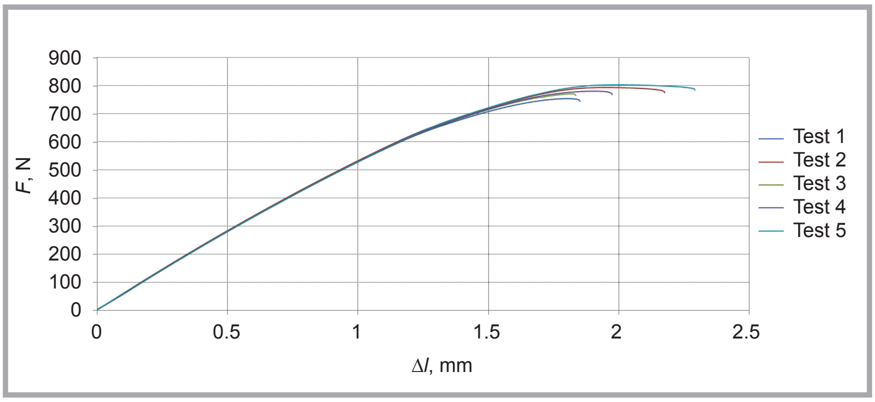

***Figure 12.** Tensile graphs of ULTRAT HIGH specimens after the ageing process.*

***Table 9.** Comparison of average elongation of the specimens at break.*

Material	L_s, mm	
	MED	HIGH
PC-ABS before ageing	4.11 ± 0.41	4.93 ± 1.22
PC-ABS after ageing	3.45 ± 0.72	3.57 ± 0.88
ULTRAT before ageing	3.27 ± 1.61	3.68 ± 0.50
ULTRAT after ageing	1.82 ± 0.34	2.03 ± 0.56

summarised in dependence on the type of density before and after the ageing process.

Analysing the results collected in ***Tables 8*** and ***9***, it can be noticed that the ageing process causes a decrease in elongation during the tensile test. In the case of PC-ABS specimens, it is 16% for MED density and 28% for HIGH density, and for ULTRAT specimens this decrease is much higher, amounting to 44% for both types of density.

Polycarbonate (PC) with respect to ABS shows much higher resistance to UV radiation [10, 12]. The increase in the value of material parameters as a result of ageing in specimens made of PC-ABS can therefore be explained by the high content of polycarbonate in this material. In contrast, in specimens made of ULTRAT material, due to the significantly lower content of polycarbonate, under the influence of ageing, there occurs a decrease in tensile strength and an increase in stiffness, as evidenced by the increase in the E_z module.

The ageing process in specimens made of PC-ABS causes an increase in the maximum tensile force by 12% for MED density and 9% for HIGH density, which results in an increase in the yield stress and tensile strength.

In the case of specimens made of ULTRAT, a decrease in the maximum force of 10% for MED density and 8% for HIGH density as well as in the yield stress and tensile strength are observed.

As a result of the ageing process, the elastic properties of both materials also changed. In both cases, the substitute modulus of linear elasticity increased. For PC-ABS specimens an increase of 8% is observed for both densities, whereas for the ULTRAT specimens of MED density it is 8% and of HIGH density – 9.8%.

Conclusions

Examining the effect of ageing on mechanical parameters of the materials analysed, the clear influence of UV radiation and temperature can be noticed. In the case of PC-ABS specimens, there is a tendency of strengthening the material with a slight decrease in elastic properties at the same time [14]. With respect to ULTRAT specimens, it can be concluded that this material shows greater sensitivity to radiation and elevated temperatures. Under the influence of these factors, the tensile strength is reduced and the material becomes more brittle. It can also be stated that regardless of the material used, the thinner the internal structure, the greater the influence of ultraviolet radiation on the mechanical properties of the specimens.

It should be emphasised that the aging process was carried out for a specific temperature and dose of UV radiation. In order to obtain a fuller picture of the changes in mechanical properties, it would be necessary to carry out the aging process for various temperature and radiation changes. However, the research conducted shows the influence of atmospheric factors on the scale of changes in the mechanical properties of polymeric materials.

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