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THE INFLUENCE OF INDUSTRIAL AND ENVIRONMENTAL FACTORS ON THE POLYOXYMETHYLENE

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This paper analyzes the influence of industrial environmental factors on the mechanical and physical characteristics of polyoxymethylene (POM), a semicrystalline polymer commonly used in industrial applications due to its strength and dimensional stability. The study exposed POM samples to four specific test media (distilled water, cooling oil, UV-C radiation and saline solution), following the relevant ISO standards for measuring liquid absorption and mechanical behavior. Uniaxial tensile tests were conducted to assess the influence of various factors on characteristics, such as maximum normal stress, maximum strain, and elastic modulus. The results indicated that all four media negatively impacted the mechanical properties of POM. However, the most severe effect was attributed to UV-C radiation, this factor markedly diminished both strength and maximum strain. Because of this, the material exhibited a notable tendency toward embrittlement, although one might consider other influences as well. In contrast, saline and cooling oil caused increases in the maximum strain, suggesting an increase in the ductility of the material. The influences on liquid absorption and elastic modulus were also varied, with cooling oil having the least impact on the latter value.

Keywords: polyoxymethylene (POM); tensile tests; mechanical characteristics; liquid absorption.

1. Introduction

POM (polyoxymethylene, also known as polyacetal) is a widely used crystalline polymer. This material stands out for its superior strength and exceptional dimensional stability and very good machinability. Due to its very high degree of crystallinity, POM exhibits the lowest wear level among all thermoplastics (Berer *et al.*, 2018). This characteristic makes it ideal for applications such as wheels and gears, as well as in any other field requiring sliding friction properties without special additives (Sun *et al.*, 2008). Applications in the connector and switch sector, as well as in the machinery construction industry, complete the range of uses for POM (Hsissou *et al.*, 2021).

POM is classified as a crystalline polymeric material, with a crystallinity of over 70 %, has stable chemical compositions and excellent mechanical properties including high strength, stiffness, impact and creep resistance and long-term durability (He *et al.*, 2021; Mao *et al.*, 2019). Widely used in the manufacture of equipment, light industrial products and tools, POM gained attention in the 1970s and 1980s as a high-performance material (Nakagawa *et al.*, 1985).

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The outstanding characteristics of this polymer, such as stiffness, allow the design of parts with large surface areas and thin cross-sections, high tensile strength and creep resistance over a wide range of temperature and humidity conditions, as well as the fatigue strength and elasticity required in applications requiring toughness and elasticity. Polyacetal has gained importance in various applications due to its excellent balance of properties. There are two types of acetals available: a homopolymer with superior mechanical properties, higher end-use temperatures and a higher melt flow index, and a copolymer, which offers superior processing characteristics and an impact strength (Campo, 2006; Pascu, 2018).

However, like any material, the mechanical properties of POM can be influenced by environmental factors. Exposure to varying conditions of temperature, humidity, and chemical agents can affect the performance and durability of this polymer (Chen *et al.*, 2020). For instance, thermal variations can lead to changes in crystallinity, while humidity can impact dimensional stability and wear resistance (Kneissl *et al.*, 2023). In this context, it is essential to thoroughly investigate and understand how these environmental factors influence the mechanical properties of POM to ensure its efficient use in critical applications and improve the performance of final products. This article aims to explore in detail the impact of environmental factors on POM and provide recommendations for optimizing the use of this polymer under various operating conditions.

In our previous studies, we conducted similar tests on elastomeric materials used in soft robotics (Rusu *et al.*, 2023). In this study, we aim to observe changes in the mechanical characteristics of polymeric materials, such as POM, following exposure to chemical and physical factors. Our goal is to better understand how these external influences affect the performance and durability of these materials.

2. Materials and methods

One of the methods for identifying the impact that a particular environment has on a particular material is addressed in (International Organization for Standardization [ISO], 2008), which establishes a clear methodology for determining the fluid absorption of materials. Based on this standard and ISO (2012) standard used to determine the tensile behavior of plastics, the impact that four specific industrial media (distilled water, synthetic cooling oil, saline solution and UV radiation type C) have on polymeric materials was analyzed. POM material was used in the analysis, specimens were made by the water jet extrusion process. The shape and dimensions of the specimens used, according to the standard, are shown in Fig. 1a, and the 10 test specimens of POM material in the test lanes in Fig. 1b.

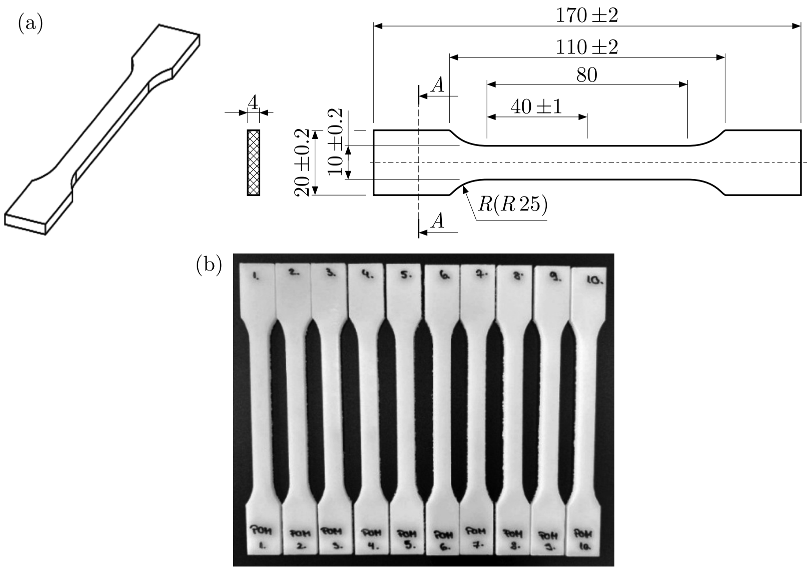

Fig. 1. (a) Specimen dimensions (in mm); (b) specimens made of POM before testing.

To ensure the best possible positioning/orientation of the specimens in the testing machine grips, as well as to achieve coaxially with the vertical axes of the machine trays and consistent specimen placement between the grips, a specimen orientation device was designed, realized and used (Fig. 2). This device was essential to position the specimen axis coinciding with the central axis of the testing machine grips, thus reducing the possibility of eccentric stretching stresses on the specimen, which would have led to additional bending stresses that could have negatively influenced the results obtained. It should be noted that the device used for specimen positioning/orientation was 3D printed and did not influence the experimental results in any way, because after the specimen was correctly aligned with the grips, this device was removed.

(a) (b)

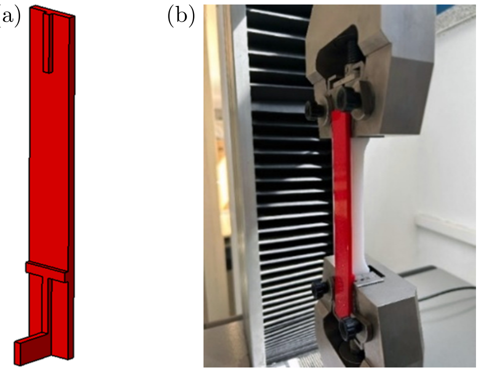

Fig. 2. (a) Device for orienting specimens between trays; (b) test specimen attached to the test machine using the device.

Uniaxial tensile tests under laboratory conditions are fundamental to polymeric materials for several reasons and these were performed on the Galdabini Quasar 25 universal testing machine, at a temperature of 23 °C ±5 °C and the test speed was 5 mm/min. This test speed was maintained for all tests performed in all the environment conditions.

Firstly, they allow the determination of mechanical properties necessary to compare results from different working environments. Through these tests, direct comparisons can be made between different polymeric materials or polymer formulations, which is essential for engineers in selecting the optimal material for specific applications.

The second test medium was distilled water. Distilled water was supplied by the Simplu Quality Products brand and it was used to immerse the test specimens. This water is used in various industrial applications, such as dilution of antifreeze and windshield washer fluids, topping up the electrolyte level in electric batteries, as a spray liquid for electric irons, cooling of internal combustion engines, etc. The distilled water used had a pH between 6 and 7.5 and a density of 1 g/cm^3 at 20 °C.

The third test medium chosen for this study is the cooling oil supplied by the Azur-Cut 602.01 M-15 brand. This is a combination of mineral oil and additives specifically designed to operate at high pressures and to cope with the intense machining regimes that occur in mechanical machining with material removal. The oil has a viscosity of 15 mm^2/s at 40 °C and is a synthetic coolant oil for industrial uses.

The fourth test medium used was ultraviolet type C (UV-C) radiation. Testing polymeric materials to UV-C radiation is essential to assess the durability and resistance of polymeric materials under conditions of intense exposure to UV-C radiation. UV-C radiation, which has a wavelength between 100 and 280 nanometers, is known for its ability to degrade polymeric materials by photochemical processes. These tests allow the identification of potential changes in the physical and mechanical properties of polymers, such as embrittlement, loss of elasticity, discoloration, or decrease in mechanical strength. By exposing materials to UV-C, we can determine the lifetime and performance of various polymeric materials in applications where they are subjected to such intense UV radiation, thus ensuring the reliability and safety of the final products.

The fifth medium used was saline solution, and in this case, we used the standard ISO (2023), with the following specifications: water salinity of 25 %, pH = 2.162, and an immersion temperature of 0.5 °C. The saline solution consisted of 25 l of demineralized water, 8.34 kg of salt, and 30 ml of hydrochloric acid.

The successive steps required for the study were shown graphically in Fig. 3. The specimens were measured to avoid introducing errors into the process, then dried in an oven at a constant temperature of 50 °C for 24 hours. After drying, specimens were weighed and immersed in the media of interest (distilled water, cooling oil, and saline solution) and exposed to the UV-C light for 24 hours. Subsequently the specimens were again weighed to determine, according to ISO (2008), the amount of absorbed liquid applied to distilled water, cooling oil, and saline solution only. Finally, uniaxial tensile tests were carried out until breakage with a test speed of 5 mm/min at room temperature. In step 5, after drying, the specimens were re-weighed to calculate the quantity of liquid absorbed. To calculate liquid uptake, the formula was used:

$$c = \frac{m_2 - m_1}{m_1} \times 100\,\%. \tag{2.1}$$

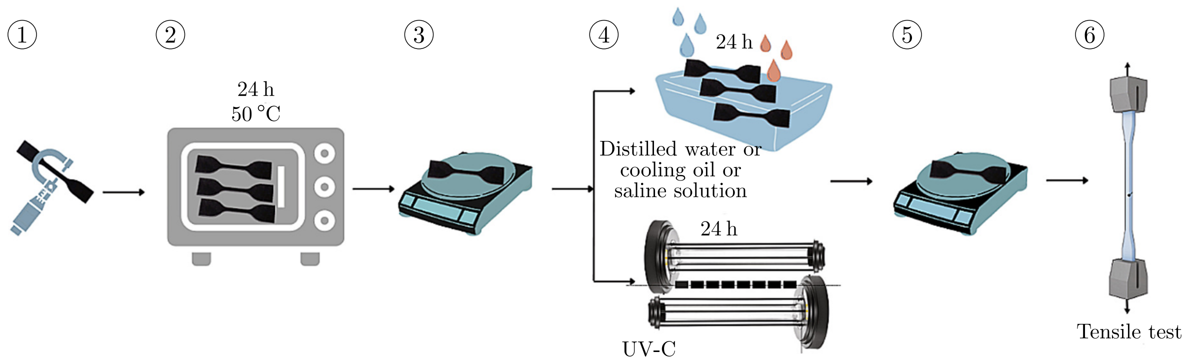

Fig. 3. Steps to perform the analysis: 1 – measuring the specimens, 2 – oven drying, 3 – weighing after drying, 4 – immersion/exposure to the medium of interest, 5 – absorption weighing, 6 – uniaxial tensile test.

3. Results

In the initial phase, specimens made of POM were tested in uniaxial tension, in quasi-static mode (speed = 5 mm/min, this speed being maintained for all tensile tests), in an ambient environment (laboratory conditions). To ensure the best possible reproducibility of results, ten specimens were tested.

The results after testing in all five environments are presented in Table 1, where only the mean values of stress, strain and modulus of elasticity (E) are found. Tables A1–A5 are found in Appendix, where the results of the basic statistical analysis such as arithmetic mean, standard

Table 1. Mean values for experimental results for POM specimens tested in five different environments.

Environment type	Mean values				
	$F_{\max}$ [N]	$\Delta_{L_{\max}}$ [mm]	$\sigma_{\max}$ [MPa]	$\varepsilon_{\max}$ [%]	E [MPa]
Ambient environment	1737.74	13.77	57.15	17.25	1847.97
Distilled water	2272.88	13.42	55.97	16.44	1734.89
Cooling oil	1619.54	15.28	52.98	19.10	1755.67
UV-C	1399.35	7.97	46.18	9.97	1699.41
Saline solution	2184.49	20.50	53.64	25.62	1662.91

deviation, minimum and maximum values are also presented. Also, in these tables we present the results of statistical analysis, using Minitab 18 from two perspectives: the Outliers test and the Normality test, where two tests were applied: the Anderson–Darling test to check the normal distribution of the data and the Grubbs test to eliminate outliers.

In the case of the tests performed in saline, we used the non-parametric Kolmogorov–Smirnov test instead of the Anderson–Darling normality test, because normality tests check not only symmetry but also how the data are distributed with respect to the mean. If the distribution is too "flat" or too "sharp" compared to a normal distribution, the test may reject the hypothesis of normality, and in some cases our data were too concentrated.

It can be observed that in the case of the AD/KS test, the values of AD/KS and p for $F_{\max}$, $\Delta_{L_{\max}}$, $\sigma_{\max}$, $\varepsilon_{\max}$, and E fall in ranges of values greater than 0.05 and the same is true in the case of the Grubbs test, the values of G and p for $F_{\max}$, $\Delta_{L_{\max}}$, $\sigma_{\max}$, $\varepsilon_{\max}$, and E fall in ranges of values greater than 0.05, all of these confirming that the results obtained are showing a normal distribution of the data, which is also confirmed by the values of p, greater than 0.05.

Based on the experimental results, characteristic curves – engineering stress vs engineering strain – were plotted for each of the ten test sets in all five environments. For each environment, a mean curve, made on the basis of all the curves plotted for all the samples tested in each case, is presented in Fig. 4.

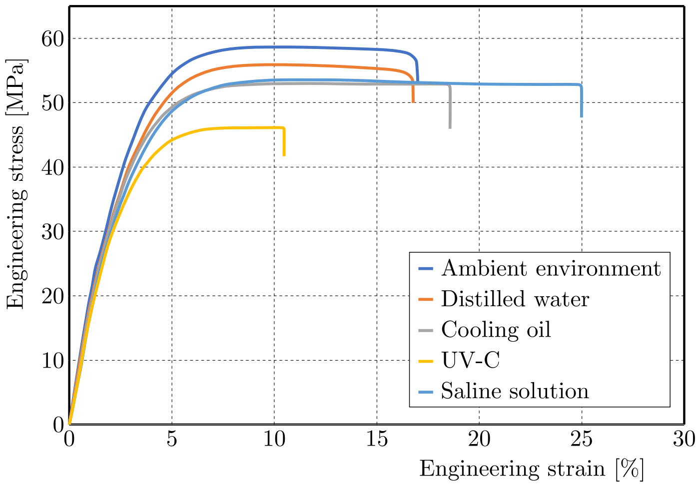

Fig. 4. Mean engineering stress-strain curves for tensile testing of POM material in five different media.

Figure 5 shows a comparative plot of the mean values of the maximum engineering stress obtained for the five studied environments.

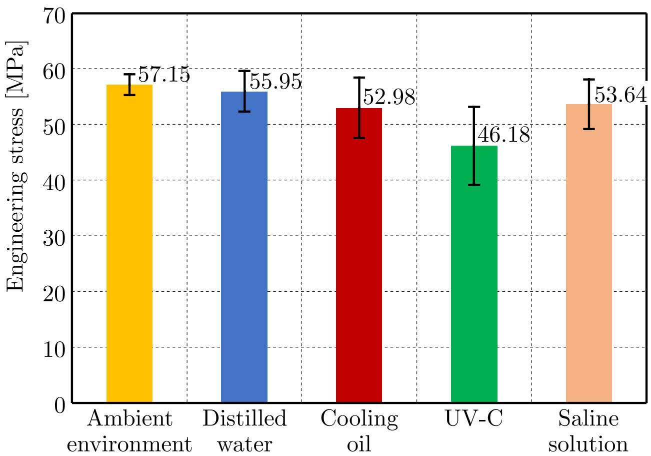

Fig. 5. Mean values of the maximum engineering stress for POM specimens obtained for all five studied environments.

It can be seen from this graph that, taking as a baseline the results obtained when specimens were tested in an ambient environment without any external factor, for all the other four cases where specimens were previously tested with an external factor (distilled water, cooling oil, UV-C radiation, and saline solution), the maximum engineering stress decreases. Thus, in the case of specimens immersed in distilled water, there is a decrease in this maximum engineering stress of 2.11 %; in the case of specimens immersed in saline solution, the decrease is 6.54 %; in the case of specimens immersed in cooling oil, the decrease is somewhat more pronounced, being 7.87 %; and in the case of specimens subjected to UV-C radiation, the decrease is the most significant, 23.75 %.

Therefore, it can be concluded that all four media (distilled water, cooling oil, UV-C radiation, and saline solution) have a negative influence on the tensile strength of POM samples, with UV-C radiation having the highest influence and distilled water having the lowest influence. The saline solution has the lowest degree of absorption in the material, followed by distilled water and cooling oil, as can be seen in Fig. 6.

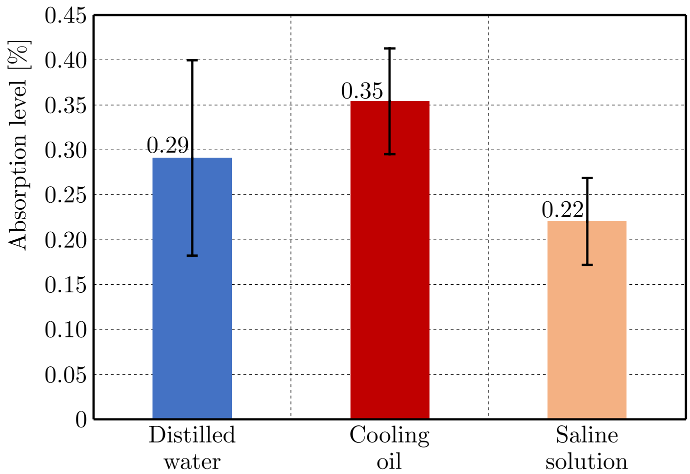

Fig. 6. Mean absorption level in POM specimens for all three liquids studied.

In this case too, changes can be observed in the values of the maximum engineering strain compared to the values recorded for the specimens tested in an ambient environment and not previously subjected to any external factor, for all the other four cases in which the specimens were previously subjected to an external factor (distilled water, cooling oil, UV-C radiation, and saline solution). The results are shown in Fig. 7. Thus, in the case of specimens immersed in distilled water, the (smallest) decrease in the maximum engineering strain is 4.93 %, and in the case of specimens subjected to UV-C radiation, we have the most significant decrease, 73.02 %. In the case of the other two studied media (cooling oil and saline solution), an increase of the maximum values for the specific strain is observed; thus, in the case of cooling oil, we have an increase of 10.72 %, and in the case of saline solution, an increase of 48.52 %.

It can therefore be concluded that UV-C radiation has the most negative influence on the maximum engineering strain of the specimens made of POM, with the maximum elongation being reduced by 73.02 % compared to specimens tested in an ambient environment and not previously subjected to any external factor. It can therefore be said that UV-C radiation tends to make the POM material brittle. There are also two environments that lead to an increase in the maximum engineering strain value of POM specimens, namely cooling oil and saline solution, the latter making POM specimens more ductile by approx. 24 % than specimens tested in ambient environments and not previously exposed to any external factors.

Also, in this case of the elastic modulus (Fig. 8), decreases in the values of the maximum engineering strain can be observed compared to the values recorded for the specimens tested in an ambient environment and not previously subjected to any external factor, for all the other

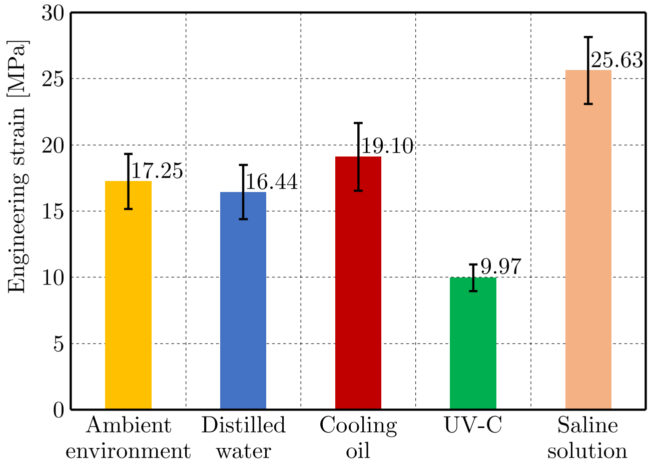

Fig. 7. Mean values of maximum engineering strain for POM specimens obtained for all five studied environments.

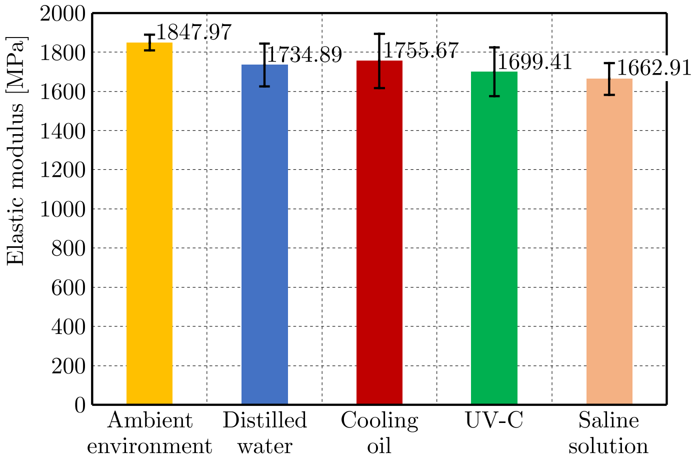

Fig. 8. Mean values of the elastic modulus for POM specimens obtained for all five studied environments.

four cases where the specimens were previously subjected to an external factor (distilled water, cooling oil, UV-C radiation, and saline solution). It can be seen from this graph that, taking as a baseline the results obtained when specimens were tested in an ambient environment without any external factor, for all the other four cases where specimens were previously tested with an external factor (distilled water, cooling oil, UV-C radiation, and saline solution), the elastic modulus decreases. Thus, the specimens immersed in cooling oil show the smallest decrease in this characteristic, 5.26 %. In second place are the specimens immersed in distilled water with a decrease of 6.52 %, and in the case of specimens subjected to UV-C radiation, the decrease is 8.74 %. The largest decrease in the value of the elastic modulus is 11.13 % and was obtained for specimens immersed in saline solution.

It can therefore be concluded that all four media (distilled water, cooling oil, UV-C radiation, and saline solution) have a negative influence on the elastic modulus of POM specimens, the highest influence being the saline solution and the lowest the cooling oil, which has the highest degree of absorption in the material of all three liquid media studied, as can be seen in Fig. 6.

4. Conclusions

The study findings highlight the significant influence that industrial and environmental factors have on the mechanical properties of POM. Of the four environments analyzed, UV-C radiation was found to have the greatest negative effect on the characteristics of material, leading to a considerable reduction in its strength by 23.75 % and a decrease in its maximum engineering strain by 73.02 %, indicating embrittlement. Also, the saline solution produced the largest decrease in the elastic modulus, with a decrease of 11.13 %, suggesting a significant impairment of the stiffness of the material.

On the other hand, saline and cooling oil led to increases in the ductility of the polymer, manifested by significant increases in the maximum engineering strain, with saline contributing an increase of up to 48.52 %. Cooling oil, although it had the least effect on the elastic modulus, influenced the mechanical properties through a slight improvement in ductility. According to the results, the aggressive environments analyzed have a significant effect on the POM material, effects that in commercial or industrial applications can cause a number of problems. However, these effects of the aggressive media can be ameliorated by additives, stabilizers, fillers to be added into the material structure. Chemical protective coatings can also be used to reduce the impact on the material.

In conclusion, the research emphasizes the importance of understanding the effects of industrial and environmental environments on POM, highlighting the need to take these factors into account in the design and use of components made of this material. This approach can help to optimize the performance and durability of manufactured products, ensuring efficient use in industrial applications.

Appendix

Table A1. Experimental results and statistical analysis for POM specimens tested in ambient environment.

Specimen no.	$F_{\max}$ [N]	$\Delta_{L_{\max}}$ [mm]	$\sigma_{\max}$ [MPa]	$\varepsilon_{\max}$ [%]	E [MPa]
#1	1728.2	15.25	56.3	19.06	1792.2
#2	1769	12.72	58	15.9	1860.51
#3	1796.38	14.26	58.9	17.83	1875.56
#4	1722.88	11.88	56.3	14.85	1841
#5	1705	16.04	55.9	20.05	1850.02
#6	1780	10.71	58.44	13.39	1855.2
#7	1733.13	15.44	56.9	19.3	1855.12
#8	1753.88	14.5	60.22	18.13	1921.94
#9	1651.13	13.48	53.43	16.85	1779.96
#10	1737.5	13.68	57.15	17.1	1848.16
Mean	**1737.74**	**13.77**	**57.15**	**17.25**	**1847.97**
Median	**1735.32**	**13.97**	**57.03**	**17.46**	**1852.57**
Standard deviation	**41.32**	**1.65**	**1.88**	**2.08**	**39.84**
Minimum	**1651.13**	**10.71**	**53.43**	**13.39**	**1779.96**
Maximum	**1796.38**	**16.04**	**60.22**	**20.05**	**1921.94**
AD value	**0.24**	**0.18**	**0.208**	**0.18**	**0.55**
p-value (AD)	**0.7**	**0.9**	**0.811**	**0.9**	**0.12**
G-value	**2.1**	**1.85**	**1.98**	**1.85**	**1.86**
p-value (Grubbs)	**0.15**	**0.42**	**0.25**	**0.42**	**0.41**

Table A2. Experimental results and statistical analysis for POM specimens tested in distilled water.

Specimen no.	$F_{\max}$ [N]	$\Delta_{L_{\max}}$ [mm]	$\sigma_{\max}$ [MPa]	$\varepsilon_{\max}$ [%]	E [MPa]
#1	2080.38	13.16	51.27	16.45	1644.63
#2	2399.5	13.62	59.7	17.03	1827.32
#3	2406	13.33	59.12	16.66	1760.79
#4	2043.75	12.67	49.79	15.84	1585.99
#5	2318.88	15.4	56.84	19.25	1692.06
#6	2327.75	11.69	57.22	14.61	1706.68
#7	2151.63	11.45	53.26	14.31	1672.96
#8	2425	13.5	59.23	16.88	1726.95
#9	2201.63	13.42	54.02	13.42	1981.08
#10	2374.25	15.93	59.06	19.91	1750.45
Mean	**2272.88**	**13.42**	**55.97**	**16.44**	**1734.89**
Median	**2323.32**	**13.38**	**57.03**	**16.56**	**1716.81**
Standard deviation	**142.06**	**1.41**	**3.64**	**2.05**	**108.99**
Minimum	**2043.75**	**11.45**	**49.79**	**13.42**	**1585.99**
Maximum	**2425**	**15.93**	**59.87**	**19.91**	**1981.08**
AD Value	**0.5**	**0.44**	**0.48**	**0.28**	**0.38**
p-value (AD)	**0.16**	**0.23**	**0.18**	**0.56**	**0.32**
G-value	**1.61**	**1.8**	**1.7**	**1.7**	**2.26**
p-value (Grubbs)	**0.88**	**0.52**	**0.69**	**0.69**	**0.06**

Table A3. Experimental results and statistical analysis for POM specimens tested in cooling oil.

Specimen no.	$F_{\max}$ [N]	$\Delta_{L_{\max}}$ [mm]	$\sigma_{\max}$ [MPa]	$\varepsilon_{\max}$ [%]	E [MPa]
#1	1680.38	18.56	53.20	23.20	1739.05
#2	1529.63	14.67	48.2	18.34	1647.41
#3	1647.5	16.42	51.79	20.53	1694.67
#4	1613.25	12.37	51.66	15.46	1723.19
#5	1692.75	14.45	59.26	18.06	1959.69
#6	1579.75	14.62	50.33	18.28	1698.88
#7	1617.88	16.89	51.16	21.11	1694.94
#8	1378	17.58	43.73	21.98	1541.77
#9	1736.63	14.68	59.28	18.35	1897.87
#10	1719.63	12.58	61.18	15.73	1959.25
Mean	**1619.54**	**15.28**	**52.98**	**19.1**	**1755.67**
Median	**1632.69**	**14.68**	**51.73**	**18.34**	**1711.03**
Standard deviation	**106.26**	**2.04**	**5.46**	**2.55**	**138.54**
Minimum	**1378**	**12.37**	**43.73**	**15.46**	**1541.77**
Maximum	**1736.63**	**18.56**	**61.18**	**23.2**	**1959.69**
AD value	**0.4**	**0.32**	**0.39**	**0.32**	**0.57**
p-value (AD)	**0.29**	**0.46**	**0.31**	**0.46**	**0.1**
G-value	**2.27**	**1.6**	**1.69**	**1.6**	**1.54**
p-value (Grubbs)	**0.06**	**0.9**	**0.7**	**0.9**	**1**

Table A4. Experimental results and statistical analysis for POM specimens tested at UV-C rays.

Specimen no.	$F_{\max}$ [N]	$\Delta_{L_{\max}}$ [mm]	$\sigma_{\max}$ [MPa]	$\varepsilon_{\max}$ [%]	E [MPa]
#1	1664.88	8.37	54.99	10.46	1839.07
#2	1657.75	7.54	54.99	9.43	1868.27
#3	1601.13	7.93	52.48	9.91	1796.77
#4	1482.75	8.66	49.01	10.83	1768.5
#5	1240.38	7.42	40.94	9.28	1603.88
#6	1363.75	9.73	44.94	12.16	1693.29
#7	1328.38	6.81	44.04	8.51	1675.99
#8	1247.25	8.04	40.95	10.05	1575.51
#9	1406.25	7.43	46.5	9.29	1705.4
#10	1001	7.81	32.93	9.76	1467.45
Mean	**1399.35**	**7.97**	**46.18**	**9.97**	**1699.41**
Median	**1385**	**7.87**	**45.72**	**9.84**	**1699.35**
Standard deviation	**210.39**	**0.81**	**6.99**	**1.01**	**125.24**
Minimum	**1001**	**6.81**	**32.93**	**8.51**	**1467.45**
Maximum	**1664.88**	**9.73**	**54.99**	**12.16**	**1868.27**
AD value	**0.23**	**0.32**	**0.23**	**0.32**	**0.17**
p-value (AD)	**0.74**	**0.46**	**0.76**	**0.46**	**0.91**
G-value	**1.9**	**2.17**	**1.9**	**2.17**	**1.85**
p-value (Grubbs)	**0.36**	**0.1**	**0.36**	**0.1**	**0.42**

Table A5. Experimental results and statistical analysis for POM specimens tested in saline solution.

Specimen no.	$F_{\max}$ [N]	$\Delta_{L_{\max}}$ [mm]	$\sigma_{\max}$ [MPa]	$\varepsilon_{\max}$ [%]	E [MPa]
#1	2010	22.07	49.31	27.59	1596.67
#2	1985.13	22.21	49.23	27.76	1577.56
#3	1973.88	20.78	48.14	25.98	1539.81
#4	2393.75	18.93	58.38	23.66	1744.09
#5	2371.88	19.93	58.02	24.91	1737.22
#6	2030.63	17.76	49.48	19.7	1596.77
#7	2294.63	21.44	56.91	26.8	1719.81
#8	2347.5	21.71	57.76	27.14	1727.39
#9	2103.13	22.26	51.35	27.83	1644.6
#10	2334.38	19.9	57.84	24.88	1745.18
Mean	**2184.49**	**20.5**	**53.64**	**25.62**	**1662.91**
Median	**2198.88**	**21.11**	**54.13**	**26.39**	**1682.21**
Standard deviation	**177.92**	**2.01**	**4.45**	**2.52**	**80.15**
Minimum	**1973.88**	**15.76**	**48.14**	**19.7**	**1539.81**
Maximum	**2393.75**	**22.26**	**58.38**	**27.83**	**1745.18**
AD value	**0.23**	**0.19**	**0.26**	**0.19**	**0.26**
p-value (KS)	**0.13**	**0.15**	**0.05**	**0.15**	**0.05**
G-value	**1.18**	**2.12**	**1.3**	**2.22**	**1.54**
p-value (Grubbs)	**1**	**0.14**	**1**	**0.08**	**1**

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