# Mechanical strength evaluation of poly(methyl methacrylate) reinforced with long glass, carbon and aramid fibers

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**Abstract:** The purpose of the study was the comparison of poly(methyl methacrylate) reinforced with different types of long fibers: glass, carbon, aramid, glass-aramid hybrid and carbon-aramid hybrid fibers. The test material included 48 samples in the form of a cuboid. The strength tests were performed using the Zwick 1435 machine. The highest strength increase in relation to control samples was obtained with the use of aramid fibers and the lowest with the use of glass fibers.

**Keywords:** mechanical strength, poly(methyl methacrylate), glass fibers, carbon fibers, aramid fibers.

## Ocena wytrzymałości mechanicznej poli(metakrylanu metylu) wzmocnionego długimi włóknami szklanymi, węglowymi lub aramidowymi

**Streszczenie:** Zbadano wytrzymałość na zginanie tworzywa akrylowego wzmocnionego długimi włóknami: szklanymi, węglowymi i aramidowymi oraz hybrydami szklano-aramidowymi i węglowo--aramidowymi. Badaniu wytrzymałościowemu w maszynie Zwick 1435 poddano 48 próbek w kształcie prostopadłościanu. Najwyraźniejszą poprawę wytrzymałości, w porównaniu z wytrzymałością próbki kontrolnej, uzyskano w wypadku zastosowania włókien aramidowych, a najmniej wyraźną w wypadku włókien szklanych.

**Słowa kluczowe:** wytrzymałość mechaniczna, poli(metakrylan metylu), włókna szklane, włókna węglowe, włókna aramidowe.

Poly(methyl methacrylate) (PMMA) makes ≈ 80 % of all polymer materials currently used in dental laboratory technology. Such common use of acrylic is associated with the advantages of removable plate dentures (RPD) made with its use. RPDs are lightweight, easy to process and sufficiently aesthetic [1]. However, PMMA used in dental laboratory technology has some weaknesses. They include limited resistance to mechanical damage related to low elasticity and changes in volume and shape during the production and use of dentures made thereof [1, 2]. Searching for methods to increase acrylic strength showed that it's caused by a high percentage of cracks and breaks of RPD [3–5]. Statistic surveys show the necessity to repair 30–50 % of dentures used by patients [6].

The first attempts to reinforce acrylic plates of removable dentures consisted in the introduction of steel screws to dentures to prevent cracking, which only resulted in complicated repair thereof [3, 6–8]. The use of glass fibers to reinforce resins opened new possibilities of acrylic compound reinforcement [9]. There are numerous forms of glass fibers that are used as reinforcement of acrylic plates of removable dentures, however, as demonstrated in our earlier tests, the best strength parameters were achieved with the use of long fibers [10]. The results of the acrylic compound reinforcement method using glass fibers were positive in numerous tests [9–13]. Vallittu *et al.* [14–16] demonstrated in their numerous researches that the reinforcement of the palatal plate using a single glass fiber layer causes strength increase by 5 %. Our earlier tests also confirmed small strength improvement, as a result of the use of glass fibers [10].

Lipski *et al.* [17] showed a significant advantage of aramid fibers as reinforcement as compared to glass or carbon fibers. Samples reinforced with aramid fibers showed very good strength parameters. They cover the occlusal loading range of the denture plate, reaching 120 N. This range is limited with the pain threshold, in particular at the section of premolars and molars, where the maxi-

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mum bending moments occur during intercorporation of dentures [18].

The majority of research centers test PMMA reinforced with one type of fibers only [17–21]. In this paper, samples reinforced with glass-aramid and carbon-aramid hybrids were additionally tested. The addition of glass fibers to aramid fibers optimizes the strength parameters due to their high elasticity [21–23].

The aim of the study was the comparison of PMMA reinforced with different types of long fibers: glass, carbon, aramid, glass-aramid hybrid and carbon-aramid hybrid fibers.

## EXPERIMENTAL PART

### Materials

The acrylic material called Estetic (Wiedent, Poland) – liquid [methacrylic resin, dimethacrylate ethylene glycol, *N,N*-dimethyl-*p*-toluidine] and powder [poly(methyl methacrylate), dibenzoyl peroxide and pigments] was subjected to strength tests. It is intended for production of heat-polymerized denture plates. The reinforcement included glass, carbon and aramid fibers with a length of 55 mm. The mass ratio of the particular fibers in glass-aramid hybrids and carbon-aramid hybrids was 1 : 1. All fibers were in the form of roving, which meant that the fiber hanks were interconnected without twists. The composition and parameters of selected fibers are presented in Table 1.

### Sample preparation

The comparative analysis for bending strength covered basic parameters of mechanical properties of 48 samples (including 8 control samples) made in the form of cuboids with the following dimensions: length 55 ± 0.1 mm, width 10 ± 0.1 mm and thickness 2 ± 0.1 mm. All samples were compliant with the requirements of the PN-EN ISO 178:2011/A1:2013-06 standard. Acrylic resin was mixed thoroughly at a powder-liquid ratio of 2.34 g/cm$^3$. After the acrylic dough reached a consistency, the mixture was packed into a gypsum mold fabricated by the wax pattern. Afterwards the fibers were placed in the top layer of acrylic. All fibers were previously dampened with methyl methacrylate monomer. The flasks were put under a hydraulic press (Rucker PHI, Birmingham, UK) for 5 minutes to remove any voids. Excess flash was trimmed away on packing. The flasks were then fixed with clamps and cured in a 100 °C water bath for one hour, followed by boiling water for 20 minutes. Upon completion of polymerization, the flasks were left to cool at ambient temperature before being opened. Deflasked specimens were manually polished with a 600-grit water proof silicon carbide paper under tap water. Figure 1 presents the schematic layout of the sample layers.

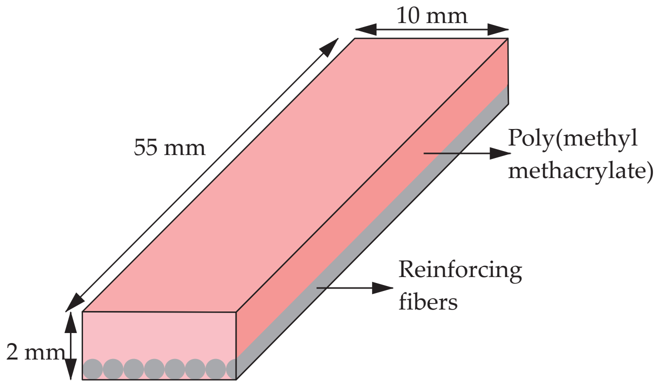


**Fig. 1. Schematic layout of sample layers**

The study group covered 5 series, 8 samples in each, with artificial fiber reinforcement in the following configurations: Group 1 – glass fibers, Group 2 – carbon fibers, Group 3 – aramid fibers, Group 4 – glass-aramid hybrid, Group 5 – carbon-aramid hybrid.

The control group contained acrylic samples without reinforcing material.

### Methods of testing

Static bending strength tests were performed using the Zwick 1435 machine (Zwick/Roell GmbH & Co. KG Germany) with a force measuring sensor in the range of up to 0.5 kN. The bending speed was constant and amounted

**Table 1. Comparison of composition and parameters of the glass, carbon and aramid fibers used**

| Fiber | Glass fiber | Carbon fiber | Aramid fiber |
|---|---|---|---|
| Manufacturer | ATG (France) | TORAY 3K (USA) | Kevlar DuPont (USA) |
| Composition, wt % | 59 $SiO_2$<br>12.1–13.2 $Al_2O_3$<br>22–23 CaO<br>3.1–3.4 MgO<br>0.6–0.9 $Na_2O$<br>0.5 other | 99 C<br>1 other | Poly(*p*-phenylene terephthalamide) |
| Basis weight, g/m$^2$ | 200 | 240 | 200 |
| Diameter of elementary fiber, μm | 16 | 15 | 15 |
| Roving linear mass, tex | 200 | 240 | 200 |
| Poisson number | 0.22 | 0.31 | 0.36 |

**T a b l e 2. Comparison of the results of tests of four strength parameters**

| Samples | | Maximum bending force | Limit stress | Deflection at maximum force | Young's modulus |
|---|---|---|---|---|---|
| | | $F_{max}$, N | σ, MPa | ε $F_{max}$, mm | $E$, GPa |
| Control group | Average | 96.02 | 115.22 | 2.80 | 3.64 |
| | Extended uncertainty | 9.83 | 16.19 | 0.29 | 0.43 |
| Group 1 | Average | 98.14 | 117.77 | 3.99 | 2.99 |
| | Extended uncertainty | 8.73 | 10.20 | 0.56 | 0.47 |
| Group 2 | Average | 100.28 | 120.34 | 2.43 | 4.73 |
| | Extended uncertainty | 5.82 | 6.91 | 0.68 | 0.57 |
| Group 3 | Average | 123.37 | 148.04 | 3.55 | 3.70 |
| | Extended uncertainty | 10.98 | 13.18 | 0.45 | 0.38 |
| Group 4 | Average | 107.16 | 128.59 | 3.83 | 3.48 |
| | Extended uncertainty | 16.84 | 10.21 | 0.65 | 0.72 |
| Group 5 | Average | 112.30 | 134.76 | 3.16 | 4.19 |
| | Extended uncertainty | 15.69 | 18.82 | 0.61 | 0.40 |

to 5 mm/min. The permissible measurement error did not exceed 0.02 % of the measured mechanical values.

Each sample was placed in a testing machine, so that the surface layer with fibers was opposite the surface of the applied strength at an angle of 90°. The test was conducted until the moment of cracking and then breaking of the sample. The use of the testXpert V.8.1 software (Zwick/Roell GmbH & Co. KG Germany) allowed the determination of four basic strength parameters: maximum bending force ($F_{max}$), strain for maximum bending force (ε $F_{max}$), limit stress determining the bending strength (σ) and Young's ($E$) – elastic modulus characterizing stiffness of the tested material.

The determined parameters allowed the specification of PMMA ability to resist deforming occlusion forces, similarly as in patients using the upper denture during chewing [1, 3–5].

The statistical analysis was performed using the STATISTICA software package, version 13.1 (StatSoft, Inc., Tulsa, OK, USA).

## RESULTS AND DISCUSSION

Average values of the measured mechanical parameters were calculated along with estimation of the combined standard uncertainty for the coverage factor $k = 2$. Thus, the probability that the result of any measured value was within the range of $\bar{x} \pm 2 \cdot S_x$ ($S_x$ – standard deviation, $\bar{x}$ – arithmetic average) amounted to 0.9545. Thus, the value of the coverage factor $k$ was equal to standardized variable, read from the tables of normal distribution in natural sciences, corresponding to the confidence level $\alpha = 0.95$ [24, 25].

Table 2 presents the results of tests of four strength parameters of acrylic material, including 5 configurations of fibers and the control group.

The analysis of bending strength parameters showed that the samples reinforced with aramid fibers (Group 3) achieved the highest maximum bending force, corresponding to the highest limit stress values in the range of elastic strain. The samples reinforced with glass and carbon fibers were the least resistant. In this category of strength parameters, the values for the maximum bending force were 98.14 ± 8.73 N and 100.28 ± 5.82 N at the limit stress value of 117.77 ± 10.2 MPa and 120.34 ± 6.91 MPa, respectively.

The groups had the same sizes. After checking the normality of the distribution using the Shapiro-Wilk test and the homogeneity of the variance between groups using the Levene's test, Student's t-test for independent samples was used to compare the means. The samples reinforced with aramid, glass and carbon fibers were selected for the analysis. For the strength parameters $F_{max}$ and σ, the following null hypothesis was made: The mean strength parameters in individual groups are equal. Alternative hypothesis: The mean strength parameters differ significantly in individual groups.

Student's t-test for $F_{max}$ and σ parameters showed a significant difference between aramid, glass and carbon fibers as well as glass-aramid hybrid ($p < 0.05$). Only for the groups between aramid fibers and the carbon-aramid hybrid, no significant differences were found between the strength parameters ($p = 0.12$).

The highest value of Young's modulus was demonstrated for samples reinforced with carbon fibers (Group 2). The highest deflection values that corresponded to the lowest values of Young's modulus in relation to the control test were demonstrated by samples reinforced with glass fibers. It should be emphasized that the highest value of Young's modulus, the highest stiffness of the tested sample, and thus smaller susceptibility to bending strain.

Student's t-test for deflection parameters ε and Young's modulus did not show significant differences between means for samples reinforced with aramid fibers and carbon-aramid and glass-aramid hybrids ($p < 0.05$).

PMMA reinforcement with carbon fiber also turned out insufficient but caused significant improvement of the tested material stiffness. The value of Young's modulus increased as compared to the control test by 30 %, which confirmed the results of tests performed by Ruyter *et al*. [26].

Aramid fibers are the state-of-the-art high-resistant artificial fibers. In comparison to glass fiber composite materials broadly used in the technology, aramid fiber composite materials are characterized by good resistance to corrosion and possible reduction of material weight by 15 % [19].

The increased strength of acrylic material reinforced with aramid fibers was confirmed by many authors [17, 19, 20]. The use of Kevlar fiber bundles resulted in increased strength of the reinforced PMMA by 30 % on average, which has been confirmed by our tests. Due to small weight, these fibers, at specific weight content in material, significantly increased its bending resistance in comparison to carbon or glass fibers [19].

When analyzing the obtained results, one may conclude that in the case of the glass-aramid hybrid, the limit stress related to elastic strain was higher by 12 % in relation to the control test, and that of the carbon-aramid hybrid by 17 %.

During the tests of the glass-aramid hybrid, Vallittu and Narva [27] found that already the addition of glass fibers to acrylic resin with a concentration of 12.4 % by weight increases its impact strength to 74 $kJ/m^2$ as compared to 8 $kJ/m^2$ for non-reinforced PMMA. Therefore, in order to refer to the above-mentioned results, further research should be extended with the performance of impact strength tests. On the other hand, in the case of samples with carbon fibers only and samples reinforced with carbon-aramid hybrid, the dark color of PMMA disqualified carbon fibers as the reinforcement of the denture acrylic plate.

## CONCLUSIONS

Based on the comparison of mechanical properties of acrylic material reinforced with glass, carbon and aramid fibers, and glass-aramid and carbon-aramid hybrids, it may be concluded that:

– very good strength parameters were shown in the case of aramid fiber reinforcement, which may be used in clinical conditions of occlusal loading of the denture acrylic plate within molars, where cracking and breaking of that plate occurs most frequently;

– addition of glass fibers to aramid fibers optimizes strength parameters of acrylic material due to improved elasticity, which, in clinical terms, may have a positive impact on the equalization of occlusal loading transferred by the denture plate to the mucosa basis in the process of its settlement during chewing;

– the addition of carbon fibers to aramid fibers is equally beneficial, however they are too stiff, which may cause cracking thereof during numerous bending when chewing, and another weakness is their black color which is unfavorable for the denture aesthetics.

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