

Process parameter optimization for 3D printing of photocurable resins in hydrogel media

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Abstract

The aim of this work was to develop a low-cost 3D printing method operating in hydrogel environment and to find suitable process parameters and input materials. The proposed approach enables inexpensive fabrication of geometrically complex structures, including overhangs, without conventional support materials. A prototype device was created by modifying an FDM 3D printer with a syringe-based extrusion system, UV-curing module and dedicated vessel defining the printing workspace. Printing parameters were then optimized to achieve satisfactory resolution both in air & hydrogels. Preliminary experiments demonstrated that commercial photopolymer resins and hydrogels were inadequate for gel-based printing due to inappropriate rheological characteristics of both. Multiple 3D printing pastes and polymer gels of varied composition were prepared and examined through rheological and photorheological analyses, enabling selection of candidates for application testing.

Using the optimized materials, beam specimens were printed and mechanically tested, with results compared to analogous samples produced via commercial DLP 3D printer. Among the hydrogel media, a guar-gum-based hydrogel containing 3% solids provided the most favorable support and rheology for DIW printing. The highest promise was shown by a paste formulated from a commercial ANYCUBIC resin with 5% amorphous silica, yielding prints of superior resolution, viscosity, adhesion and strength. Notably, beams printed in the guar-gum hydrogel showed significantly higher strength than DLP counterparts. Overall, the developed budget DIW technology in liquid media enables fabrication of simple, high-resolution, mechanically robust parts, with potential applications in bioprinting, delicate-material processing and complex-geometry fabrication.

Keywords

3D printing, photocurable resin, hydrogel media

1. INTRODUCTION

The dynamic development of 3D printing technology is today inseparably linked to advances in the field of polymers. Owing to their unique properties and broad possibilities for modification, polymers form the foundation of numerous innovations in the automotive, construction, electronics, medical and packaging industries (Alghamdi et al., 2021; Murr, 2016; Namazi, 2017). Increasing attention, however, is being paid not only to their functionality but also to issues related to production, recycling and environmental impact, which aligns with the sustainability priorities of the European Union (Warner et al., 2004).

Polymer technology – combining elements of chemistry, engineering and materials science – focuses on the development of new materials, the improvement of processing techniques and the reduction of costs and emissions (Pielichowski, 2003; Szlezyngier, 2012). Progress in this area is driven by advanced methods of catalysis, controlled synthesis and modern processing technologies (Fiedor et al., 2020; Hola et al., 2020; Petko et al., 2022; Topa et al., 2020).

One of the most promising directions is 3D printing in liquid environments. This approach enables more precise shaping of polymer structures, reduces defects and broadens potential

applications (Bhattacharjee et al., 2016; Wu et al., 2022; Zhao and He, 2020; Zhou et al., 2022). A key challenge remains the selection of suitable materials and process parameters.

The presented research focuses on the development of polymers printed in a hydrogel environment, with particular emphasis on process optimization and the analysis of the resulting material properties. This approach integrates knowledge from polymer chemistry, rheology, engineering and is consistent with current trends in the use of support baths and yield-stress fluids in embedded 3D printing (Compaan et al., 2019; Shiowski et al., 2021; Zeng et al., 2022).

2. OPTIMIZATION OF THE 3D PRINTING PROCESS IN HYDROGEL ENVIRONMENTS

Fabrication in hydrogel medium was carried out using a custom-built Direct Ink Writing (DIW) 3D printing system. The device was constructed on a mechanical frame conceptually similar to that used in conventional fused deposition modeling (FDM) printers. The printing system consisted of a motion platform enabling controlled movement of the printhead in the horizontal plane and a syringe-based extru-



sion unit designed for deposition of photocurable composite materials. Material extrusion was performed using a DIW printhead equipped with a syringe filled with the prepared photocurable composite. The extrusion process was controlled mechanically by a piston acting on the syringe plunger. The piston was driven by a carriage translating the rotational motion of a trapezoidal lead screw into linear displacement. The lead screw was powered by a stepper motor, enabling precise control of the plunger movement and consequently, the extrusion rate of the material. The extrusion speed was therefore regulated analogously to classical FDM printers by adjusting the rotational speed of the stepper motor driving the lead screw. The extrusion rate (E_{steps}), defined as the number of stepper motor steps required to extrude 1 mm of a resin track, was determined experimentally to be 98.5. This value ensured that the printed resin track did not spread laterally and did not exhibit discontinuities. The printhead was fitted with a nozzle with an internal diameter of 0.2 mm. The layer height during printing was set to 0.2 mm. This value was selected as an optimal compromise between reliable extrusion and shape retention of the deposited resin track. The use of smaller layer heights frequently led to clogging of the nozzle due to the high viscosity of the photocurable composite, whereas larger layer heights resulted in partial spreading of the uncured material before photopolymerization, which caused deformation of the printed structures. The movement speed of the printhead during deposition was set to 20 mm/s. This value was established during preliminary optimization experiments carried out prior to the present study. Higher printing speeds resulted in a noticeable deterioration in the quality and dimensional accuracy of the printed structures obtained using this system.

The printer was additionally adapted for fabrication in hydrogel environment. For this purpose, a flat-bottom vessel filled with a selected hydrogel was placed on the printing platform and served as the surrounding medium during the printing process. Before printing, the syringe installed in the extrusion unit was filled with the photocurable composite. The printing container was then filled with the hydrogel, forming a layer approximately 1 cm thick above the printed structures. During printing, the photocurable material was extruded from the syringe through the nozzle while the printhead moved according to the predefined toolpath. Simultaneously, the deposited material was exposed to ultraviolet radiation generated by a 405 nm UV-LED panel positioned beneath the printing vessel. This irradiation initiated rapid photopolymerization of the extruded resin, allowing the printed structures to be cured directly on the bottom surface of the hydrogel-filled container. The light intensity (UV irradiance) was 35 mW/cm² at a wavelength of 405 nm. The optimal light intensity was determined experimentally (by adjusting the supply voltage of the UV-LED diode panel) for a selected printing head movement speed of 20 mm/s, so that after passing through a hydrogel layer of approximately 1 cm thickness it provided preliminary curing of the resin, maintaining the desired shape/geometry while

avoiding nozzle clogging caused by prematurely cured resin. The entire 3D printing process followed an operational scheme comparable to that used in conventional FDM 3D printing systems, with the main difference being the syringe-based extrusion mechanism and the simultaneous UV curing of the deposited photocurable composite in a hydrogel-based aqueous environment. After the 3D printing process, the sample was placed in an ultrasonic bath filled with isopropanol for 5 minutes at a temperature of approximately 20 °C. It was then dried under a laboratory fume hood for 20 minutes at approximately 20 °C. Finally, the printed object underwent UV post-curing (final curing) for 15 minutes in a custom-built post-processing chamber, equipped with UV light of 405 nm wavelength and an intensity of 20 mW/cm², at a temperature of approximately 30 °C. The temperature inside the chamber increased during operation of the UV LEDs despite the fact that they were actively cooled by fans.

Application tests showed that among the 10 formulations differing solely in silica content (from 0% wt to 10% wt, in increments of 1%), the best results were obtained for the composition containing 5% wt silica. In this case, the printed structures exhibited the highest quality and good detail resolution. For silica contents above 5% wt, however, frequent clogging of the 0.2 mm nozzle was observed, which significantly deteriorated print quality or prevented the printing process from starting. Attempts were made to use nozzles of larger diameter, but in every case the resulting prints exhibited poorer quality compared to those produced with the 0.2 mm nozzle, making this approach impractical. An additional challenge arose from the fact that the printer – still at the prototype stage – did not include a nozzle-clog detection system. As a result, leaving the process unattended could lead to damage of the extrusion system and in extreme cases, even to the destruction of the entire prototype.

As shown in Figure 1, both the extrusion rate and the printing speed have a significant impact on the quality of the printed structures (Dudek, 2013; Hikmat et al., 2021; Shahrubudin et al., 2019). Excessive material flow leads to rounded geometries

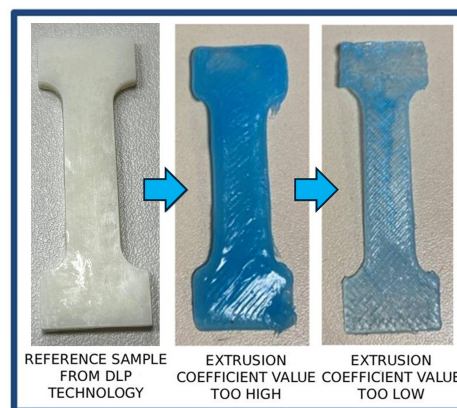


Figure 1. Comparison of models with different extrusion coefficient values.

and dimensions exceeding the intended values. Conversely, too low values of these parameters also result in prints that deviate from the target dimensions.

The conducted research showed that the most suitable medium for printing in agar-based hydrogel environment is agar-based hydrogel with a 3% concentration of the active substance (Fig. 2). Above this value, the hydrogel became excessively brittle – at concentrations of 4% and 5% the structures underwent complete degradation during the process – making printing in a hydrogel environment impossible. In contrast, hydrogels with lower concentrations (1% and 2%) exhibited a consistency similar to water and therefore did not provide the required support properties necessary for proper printing, which is consistent with observations reported for other yield-stress support baths (Compaan et al., 2019; Zhou et al., 2022).

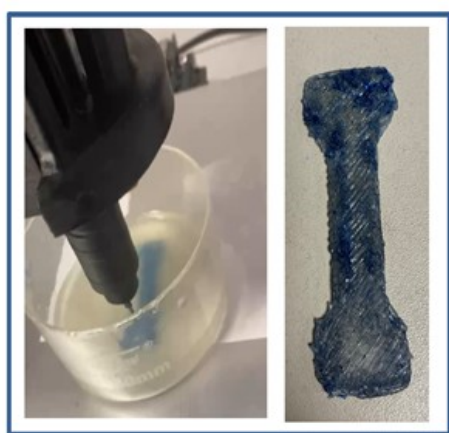


Figure 2. Images from the printing process in an agar-based hydrogel environment.

Further investigations involving agar, PVA and HEA hydrogels were discontinued due to their limited application potential. In the case of agar, the hydrogel structure was destroyed by the syringe–nozzle extrusion system. Hydrogels based on HEA and PVA were rejected because of insufficient support properties (Wu et al., 2022; Zhao and He, 2020).

The analysis of the measurement results demonstrated that prints produced in guar gum hydrogel exhibited significantly higher quality compared to those obtained in agar-based hydrogels, indicating favorable rheological properties of this system (Fig. 3). This is further supported by the dimensional measurements of the printed test samples relative to the model dimensions.

The guar gum hydrogel showed a stable viscosity profile – the viscosity curve as a function of shear rate progressed smoothly, without disruptions such as sudden spikes. This indicates good structural coherence of the material and the absence of effects such as agglomeration or coagulation confirms its homogeneity. Such stability also suggests the presence of thixotropic behavior, which facilitates the deposition of successive layers in 3D printing, similarly to other hydrogel-based support

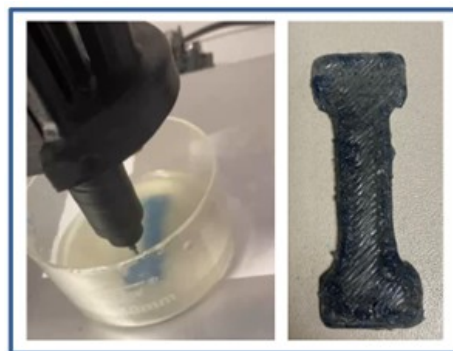


Figure 3. Images from the printing process in a guar gum hydrogel environment.

media used in embedded bioprinting (Ouyang et al., 2020; Shiowski et al., 2021; Zhou et al., 2022). Based on these findings, the guar hydrogel can be considered to exhibit near-optimal parameters for applications in hydrogel-supported printing environments. For comparison, the agar hydrogel displayed greater instability at medium and high shear rates. The observed fluctuations suggest that although agar can form a rigid matrix, its structure is less resistant to dynamic loading. Additionally, the need for high temperature during preparation and its rapid solidification may introduce structural inhomogeneities, which further deteriorate the rheological stability of the material. The poly(vinyl alcohol)-based hydrogel exhibited moderate viscosity and a distinctly nonlinear shear profile. This indicates the presence of a weakly crosslinked structure, despite the application of a triple freeze–thaw cycle. The disturbances in the curve may stem from insufficient physical crosslinking or structural heterogeneity arising from local variations in solvent content. Although the viscosity values were acceptable, the material did not achieve the level of stability comparable to guar gum. The least stable system was the hydrogel based on hydroxylated acrylates, synthesized via photopolymerization of an HEA solution with TPO photoinitiator. The resulting gel was prone to deformation and exhibited an irregular crosslinking process. Despite its elasticity and transparency, the lack of structural integrity and pronounced rheological variability disqualified it from further printing tests. The fluctuations visible on the viscosity curve may result from both its low initial viscosity and insufficient structural densification, making the material highly sensitive to shear forces.

3. RHEOLOGY AND PHOTORHEOLOGY

Rheological measurements were performed using a Physica MCR 302 rheometer (Anton Paar). Rheological measurements clearly confirmed that the properties of the hydrogels have a direct impact on print quality (Wu et al., 2022; Zhao and He, 2020; Zhou et al., 2022). Among all analyzed samples, only the guar hydrogel (3% wt) exhibited a smooth, continuous viscosity curve without irregularities or sudden directional changes (Fig. 4). In contrast to the remaining

materials, which showed pronounced fluctuations and jagged profiles, this indicates high stability and measurement repeatability – features that are particularly desirable when assessing rheological quality (Figs. 5–7).

Application tests demonstrated that the 3% wt guar gum hydrogel provided the best supportive properties required for 3D printing processes. The remaining hydrogels (PVA and HEA) did not meet the application criteria. In the case of HEA-based hydrogels in particular, despite their transparency and high degree of hydration, a clear lack of mechanical cohesion and difficulties in maintaining geometric integrity

were observed. These structures quickly deformed under their own weight and due to additional water absorption, which completely disqualified them from being used as a support medium or printable material. Due to insufficient rheological performance, they were not subjected to further additive manufacturing trials.

Hydrogels whose rheological curves exhibit a similar profile and comparable parameter values can be considered materials with properties close to the optimum for 3D printing processes carried out in a hydrogel environment (Compaan et al., 2019; Shiowski et al., 2021; Zhou et al., 2022). Systems with sig-

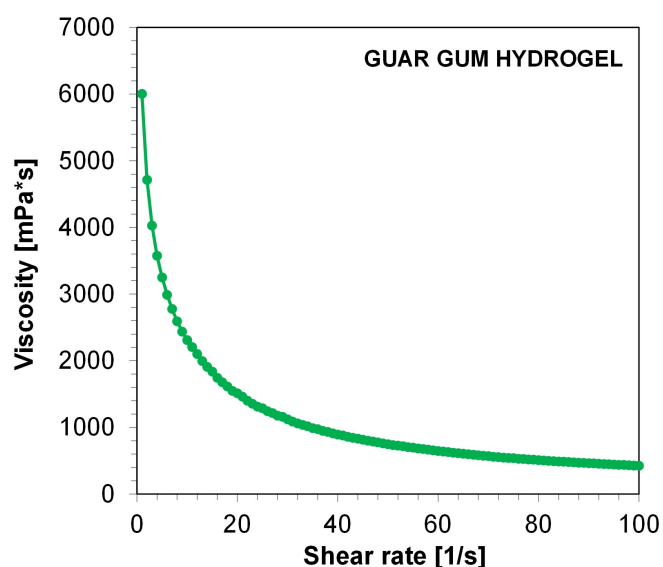


Figure 4. Graph of the viscosity-shear rate relationship for the guar gum-based hydrogel sample (3%).

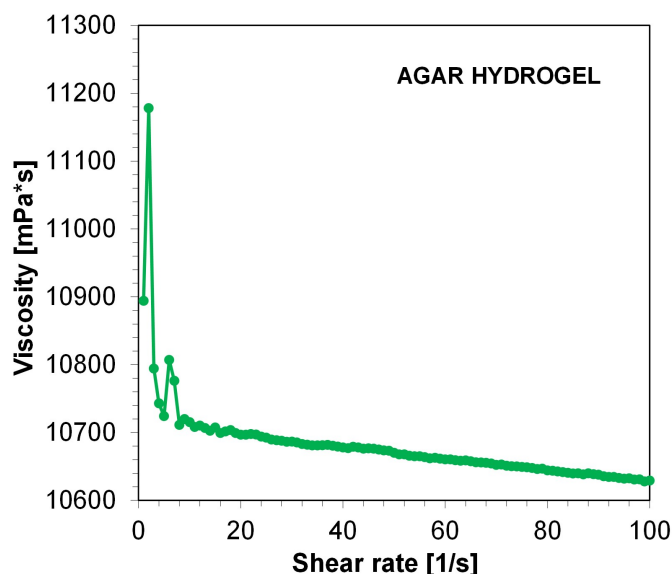


Figure 5. Graph of the viscosity-shear rate relationship for the 3% wt agar-based hydrogel sample.

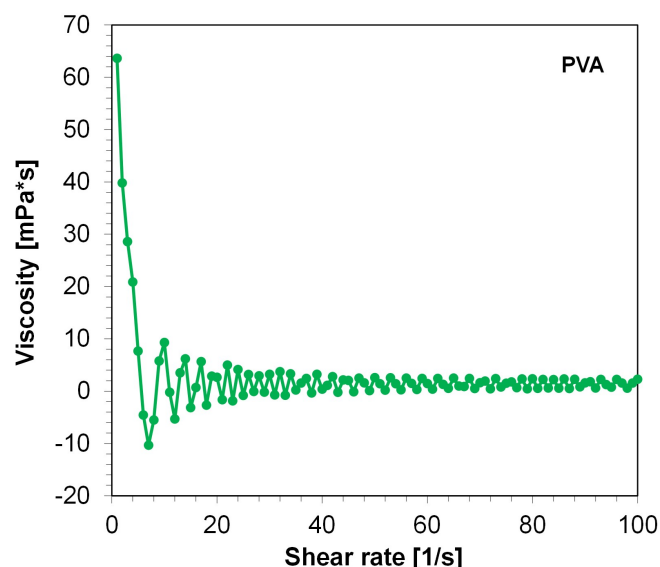


Figure 6. Graph of the viscosity-shear rate relationship for the 3% wt poly(vinyl alcohol)-based hydrogel.

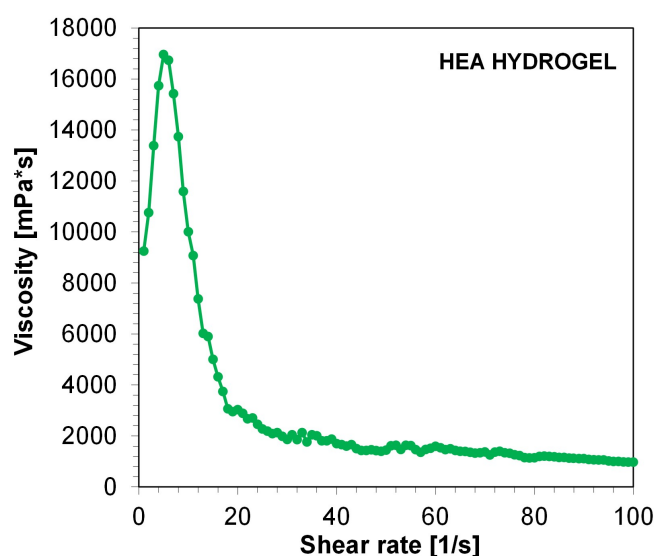


Figure 7. Graph of the viscosity-shear rate relationship for the hydrogel based on hydroxylated acrylates in a 1(HEA) : 4(H₂O) ratio.

nificantly lower or higher rheological parameters show limited suitability for shaping and stabilizing printed structures, which further confirms the applicability of the analyzed hydrogel in additive manufacturing.

After completing a detailed analysis of the hydrogel properties, the next stage of the study involved evaluating the rheology of resin pastes, including both commercial photopolymer resins and their modifications obtained through the incorporation of fillers (Figs. 8–9).

The analysis of the results confirmed that increasing the silica content leads to a noticeable rise in material viscosity, accompanied by an increase in shear resistance. The composition containing 2% wt silica exhibited the most stable rheological curve, suggesting improved dispersion of the filler particles within the resin matrix. In the case of the sample containing 1% wt silica, a rapid spike in viscosity was observed at the initial stage of the measurement, likely resulting from insufficient particle dispersion or the presence of agglomerates that disrupt uniform flow under shear forces (Padhi et al., 2015; Prabhakar et al., 2015).

The study clearly demonstrated that viscosity and shear stability are crucial for the applicability of materials in 3D printing technologies, especially within a hydrogel-supported environment (Maines et al., 2021; Melchels et al., 2010). Among all analyzed samples, only the 3% wt guar hydrogel exhibited a rheological profile considered optimal – characterized by a smooth, consistent curve and high repeatability of results. Materials exhibiting either excessively high or too low viscosity failed to provide adequate structural stability during shaping, which disqualified them from further application trials. The findings also showed that proper selection and modification of resin compositions using functional additives, such as

silica, can significantly enhance their rheological properties and broaden their potential applications (Aredla et al., 2024; Yadav et al., 2023).

However, ensuring a homogeneous dispersion of the filler phase remains a necessary condition, which requires optimization of the composite preparation methods. Rheological measurements of the commercial resins showed that the base materials, without functional additives, exhibited low viscosity – approximately $195 \text{ mPa} \cdot \text{s}$ for the ABS-Like PRO2 resin (Anycubic) and about $235 \text{ mPa} \cdot \text{s}$ for the TOUGH resin (Anycubic). With increasing silica content, a systematic rise in viscosity was observed, dependent on the applied shear rate. The sudden viscosity spike in the 1% wt paste can be explained by insufficient mixing of the sample, which led to particle agglomeration and local flow disturbances.

Considering that photopolymerization processes play a crucial role in additive manufacturing of structures from light-curable resins, photorheological measurements were also performed to analyze the mechanical properties in real time during UV exposure. The experiments were conducted using a photorheology module integrated with an Anton Paar rheometer, enabling dynamic measurements while simultaneously irradiating the sample with UV light at a wavelength of 405 nm. This parameter corresponds to the standard used in most commercial 3D printing systems operating via photopolymerization (e.g., SLA) (Maines et al., 2021; Melchels et al., 2010; Stansbury and Idacavage, 2016).

The characteristic intersection of the orange and blue curves, visible in the presented graphs, corresponds to the gelation point (Figs. 10–13). The sudden increase leading to the crossover of the moduli was associated with the activation of the UV-LED 405 nm diode, which initiated the photopoly-

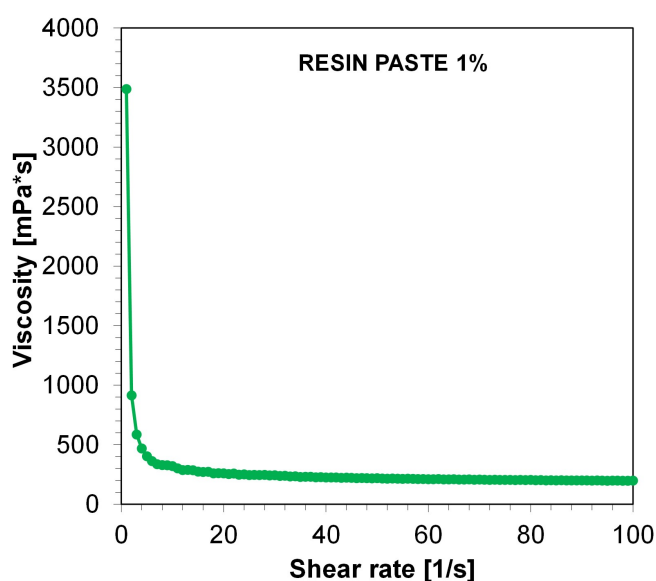


Figure 8. Graph of the viscosity–shear rate relationship for the resin paste sample containing 1% wt silica.

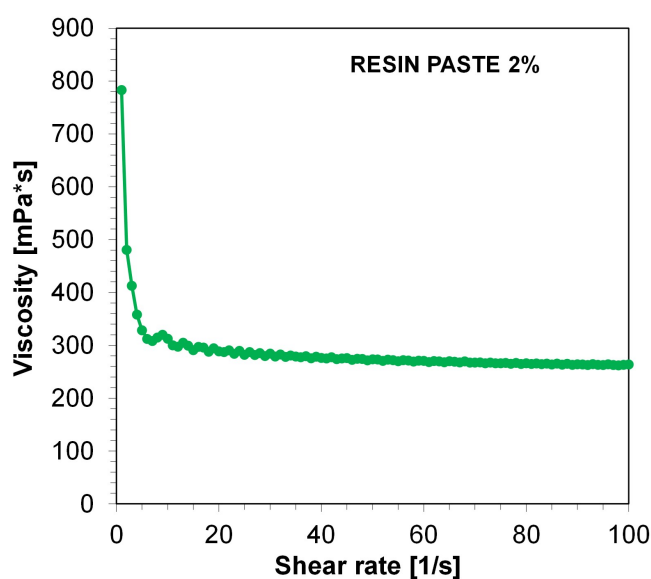


Figure 9. Graph of the viscosity–shear rate relationship for the resin paste sample containing 2% wt silica.

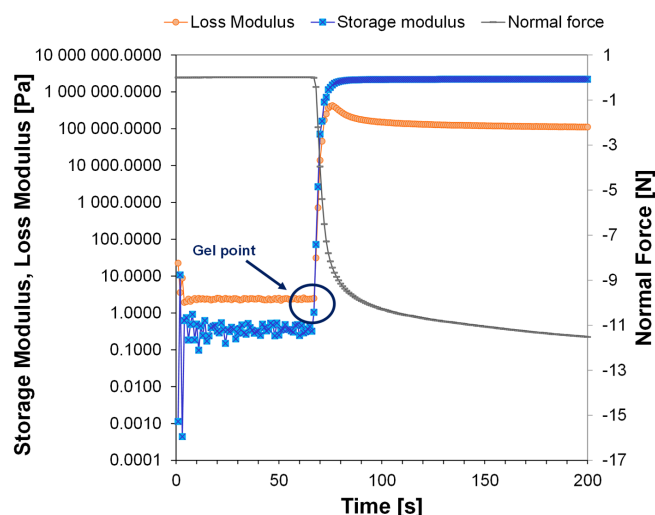


Figure 10. Graph of the dependence of normal force on the two moduli for the ABS-Like PRO2 resin.

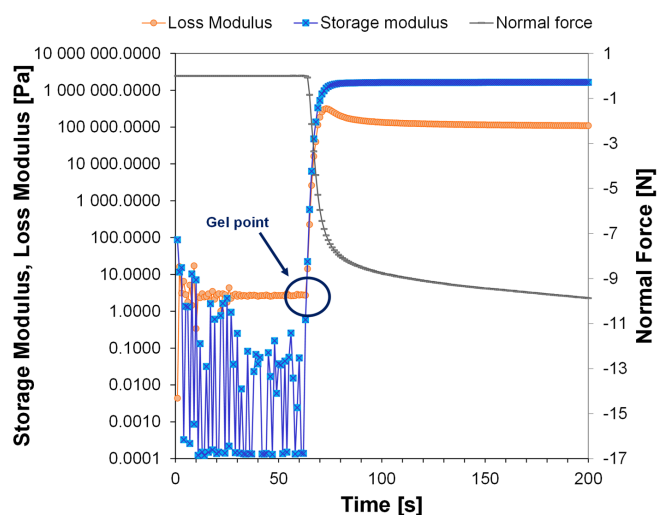


Figure 11. Graph of the dependence of normal force on the two moduli for the TOUGH resin.

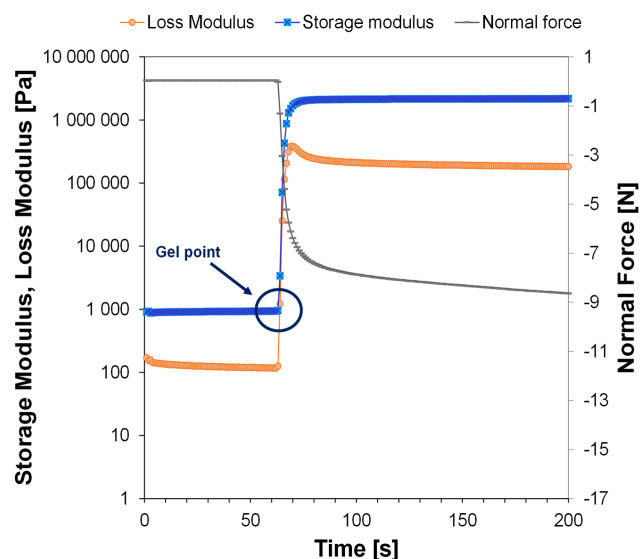


Figure 12. Graph of the dependence of normal force on the two moduli for the resin paste containing 1% wt silica.

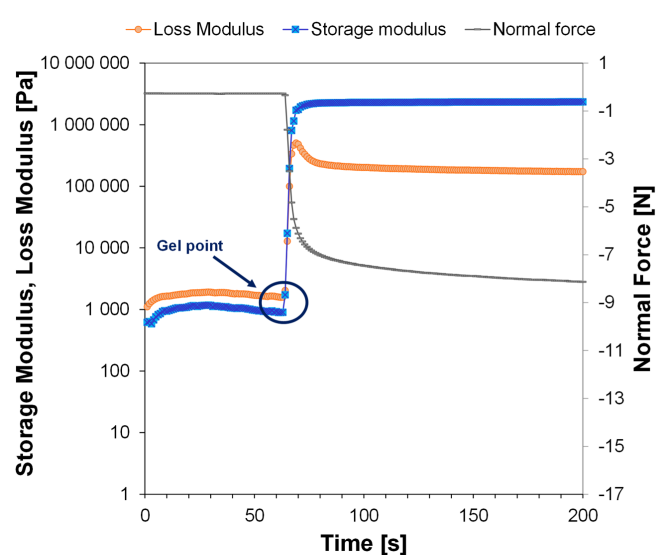


Figure 13. Graph of the dependence of normal force on the two moduli for the resin paste containing 2% wt silica.

merization of the sample placed in a 0.1 mm gap between the working plate and the vertically positioned spindle. This resulted in a rapid increase in the viscosity of the system. An important indicator of structural changes occurring during crosslinking was also the behavior of the normal force. For samples with higher filler content, the final value of this parameter was lower, which may indicate incomplete crosslinking or the presence of insufficiently cured regions, a phenomenon also discussed in studies on photopolymer networks and dental resins (Jandt and Sigusch, 2009; Stansbury and Idacavage, 2016).

The results clearly confirmed significant differences in the curing behavior between the unmodified base resins (ABS-Like PRO2 and TOUGH) and the composites containing silica. For the ABS-Like PRO2 resin, the curing process proceeded relatively smoothly and the crossover of G' and G'' occurred

approximately 75 s after the start of the measurement (i.e., 15 s after UV initiation). The crossover point marks the transition of the material from the liquid state to the gel phase. The normal force changed in a linear and stable manner, suggesting uniform and gradual formation of the polymer network.

In the case of the TOUGH resin, the gelation point was recorded slightly earlier, around the 70-s mark. However, the G' and G'' curves exhibited a more unstable trajectory while visible fluctuations indicated structural heterogeneity and the potential occurrence of microscopic swelling or phase separation phenomena.

A different crosslinking behavior was observed for the silica-modified resin pastes. In the composition containing 1% wt filler, the gelation point occurred later, approximately 85 s

after the start of the measurement. The G' and G'' curves showed a smoother course than in the base resins, suggesting that the presence of the solid phase restricts the mobility of polymer segments and delays the crosslinking process. At the same time, the resulting network exhibited greater stability, as evidenced by the smooth dynamics of the G' increase.

In the sample containing 2% wt silica, the crossover of the moduli occurred more quickly (around the 80-s mark) and the growth of G' was markedly more rapid. Such behavior indicates that a higher filler concentration promotes the formation of nucleation sites for the crosslinking reaction, accelerating the spatial polymerization process. Simultaneously, the normal force showed a tendency to increase sharply in the final phase of the measurement, which may be associated with stress accumulation within the crosslinked structure, a typical effect in materials with higher particle packing density.

In summary, the photorheological analysis demonstrated that the presence of silica in resin pastes affected not only the mechanical properties after curing but also significantly modified the course of the polymerization process itself. Lower filler concentrations delay gelation, whereas higher concentrations accelerate it while increasing the risk of internal stress development. Therefore, proper optimization of resin formulations with respect to photorheological behavior is crucial for ensuring a balance between processing performance and the final quality of additively manufactured structures (Maines et al., 2021; Ouyang et al., 2020).

The obtained results confirm that photorheology is an effective tool for analyzing the curing kinetics of photosensitive formulations and for assessing the influence of composition on material behavior during UV exposure. This is particularly important in 3D printing technologies, where gelation time, curing rate and mechanical properties of individual layers directly translate into dimensional accuracy, durability and the quality of final components. From a materials engineering perspective, these data can be used to optimize photopolymer formulations in terms of reactivity and processing parameters. This enables better adjustment of printing conditions (exposure time, UV intensity, layer thickness) to the characteristics of a given composition, thereby minimizing defects such as excessive shrinkage, delamination or insufficient curing of deeper layers.

4. MECHANICAL TESTING OF COMPOSITE MATERIALS

To complement the rheological results and to obtain a more comprehensive understanding of material behavior during the 3D printing process, mechanical tests of the fabricated structures were also performed. As a reference point, an identical model was used – printed from the same base resin that served as the matrix for the resin pastes (Fig. 14). However, in this case, the printing was carried out using a DLP printer rather than the custom DIW-based device (Maines et al., 2021,

Melchels et al., 2010). An ELEGOO Mars 4 DLP 3D printer was used. The standard layer exposure time was 2 s, the bottom layer exposure time was 30 s, the number of bottom layers was 5 and the layer thickness was 0.03 mm. The light intensity was 4 mW/cm² at a wavelength of 405 nm. Additionally, after the 3D printing process, the samples were subjected to post-processing according to a procedure analogous to that used for the samples printed using the DIW technique.



Figure 14. Reference model printed using DLP technology.

The thickness (a_0) and width (b_0) of the specimens were measured using a digital caliper with a resolution of 0.01 mm (Fig. 15). For each specimen, measurements were performed at three different locations within the gauge section. The average value was taken as the specimen dimension and used to determine the nominal cross-sectional area (S_0). The reported values represented the mean $\pm$ standard deviation for three specimens. The measurement uncertainty associated with the caliper was ± 0.02 mm.

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A universal testing machine MTS Insight 50 (MTS Insight™, Eden Prairie, Minnesota, USA) equipped with a ± 50 kN load cell, was used for the mechanical tests. Tensile tests were performed in accordance with ISO 527, using mechanical clamping grips and anti-slip inserts to prevent specimen slippage. The crosshead speed was 10 mm/min and the initial gauge length was set to 35 mm.

Table 1 presents the results of static tensile tests performed on polymer samples fabricated under different environmental conditions. The key mechanical parameters determined include the yield strength $R_{p0.2}$ and the ultimate tensile strength R_m , along with geometric characteristics of the specimens such as thickness and cross-sectional area.

Table 1. Summary of experimental mechanical strength test data for the samples (mean $\pm$ SD).

Sample type	$R_{p0.2}$ [MPa]	R_m [MPa]	a_0 [mm]	b_0 [mm]	S_0 [mm ²]
Reference sample	1.19 ± 0.08	15.2 ± 0.36	2.89 ± 0.06	11.05 ± 0.10	31.93 ± 0.72
PVA	3.90 ± 0.28	8.4 ± 0.36	2.95 ± 0.18	11.90 ± 0.75	35.11 ± 2.96
HEA	0.60 ± 0.09	2.8 ± 0.26	1.80 ± 0.24	13.60 ± 0.75	24.48 ± 3.34
Guar gum 3%	9.70 ± 0.55	23.6 ± 0.85	2.10 ± 0.08	10.90 ± 0.20	22.89 ± 0.96
Agar 3%	0.40 ± 0.08	1.8 ± 0.20	2.07 ± 0.20	12.10 ± 0.50	25.05 ± 2.50
Air	1.30 ± 0.18	5.6 ± 0.40	1.50 ± 0.08	11.00 ± 0.20	16.50 ± 0.92

The comparison of the mechanical results with the observed morphology of the specimens indicates a clear relationship between print quality and the values of ultimate tensile strength (R_m) and yield strength ($R_{p0.2}$). The highest values of both tensile strength R_m and yield strength $R_{p0.2}$ were obtained for the specimen printed in 3% guar gum hydrogel ($R_m = 23.6 \pm 0.85$ MPa, $R_{p0.2} = 9.70 \pm 0.55$ MPa). These values exceed the R_m and $R_{p0.2}$ values obtained for the reference model produced by the DLP technique, which may indicate that the applied manufacturing approach ensures a stable and repeatable fabrication process (Padhi et al., 2015; Yadav et al., 2023). In the image, the specimen printed in 3% guar gum hydrogel exhibits a relatively compact structure and clearly preserved printing paths (Fig. 15b). Despite small material accumulations along the edges, the core structure of the specimen remains uniform, which facilitates efficient stress transfer.

The reference specimen exhibited moderate values ($R_m = 15.2 \pm 0.36$ MPa). Its surface appears relatively smooth. However, small pores and material heterogeneities are visible, which may initiate local stress concentrations and limit the maximum strength (Fig. 14).

The lowest mechanical properties were observed for specimens printed in 3% agar hydrogel ($R_m = 1.8 \pm 0.20$ MPa, $R_{p0.2} = 0.40 \pm 0.08$ MPa) and HEA hydrogel ($R_m = 2.8 \pm 0.26$ MPa, $R_{p0.2} = 0.60 \pm 0.09$ MPa). The images show a more irregular geometry and significant material accumulation along the edges, indicating lower stability of the printing process in these hydrogels. Such defects lead to increased porosity and structural heterogeneity, which in turn reduces resistance to mechanical loading (Figs. 15c and 15d).

The specimen printed in PVA hydrogel exhibited intermediate values ($R_m = 8.4 \pm 0.36$ MPa, $R_{p0.2} = 3.90 \pm 0.28$ MPa). The deformation of the edges and partial material flow observed in the image suggest reduced stability of the printing paths, which may result in local structural weakening (Fig. 15e).

In summary, the highest mechanical parameters were observed for specimens printed in guar gum hydrogel, which correlates with the most compact and homogeneous printed morphology. In contrast, the lowest values were recorded for agar and HEA, where the observed geometric irregularities and surface defects indicate less stable structural formation conditions during the printing process.

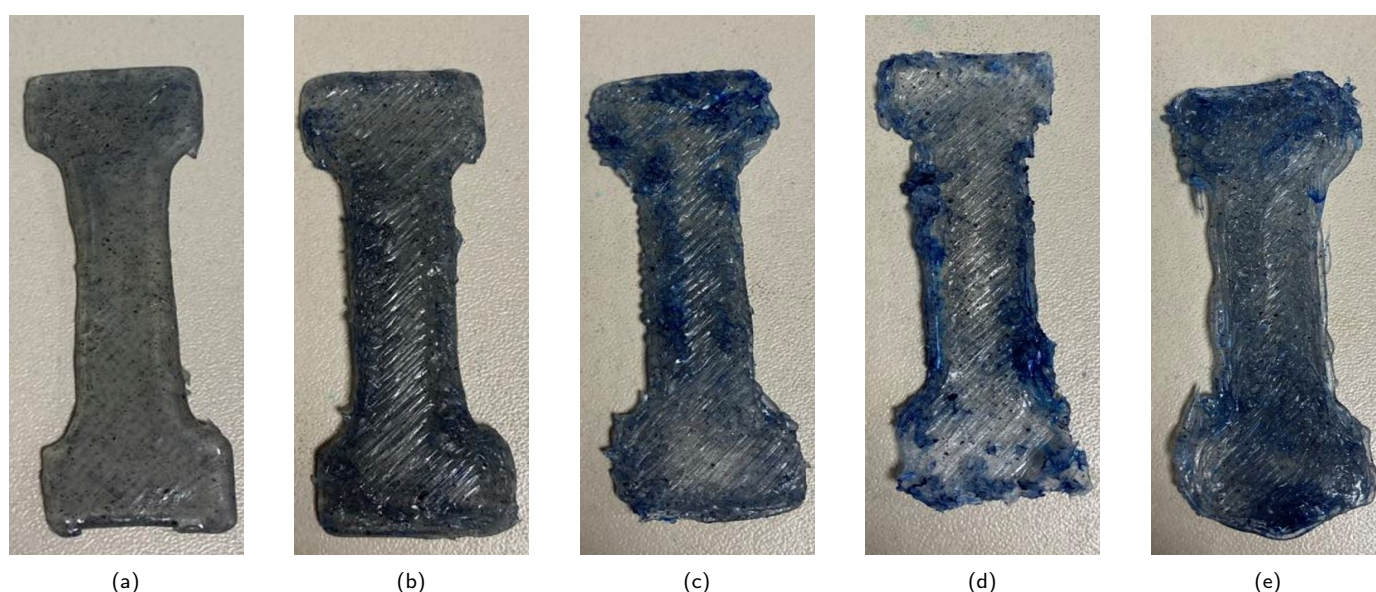


Figure 15. Model printed in: a) ambient atmosphere, b) 3% guar gum hydrogel, c) 3% agar hydrogel, d) an HEA hydrogel, e) a PVA hydrogel.

For each experimental condition, three independent specimens were tested and the results are presented as mean $\pm$ standard deviation (SD). In general, the obtained standard deviations are relatively small compared with the corresponding mean values, indicating good repeatability of the measurements within each experimental group. The lowest variability of the ultimate tensile strength R_m was observed for the agar-based and HEA-based groups, suggesting relatively consistent mechanical response of the specimens prepared in these environments. In contrast, slightly higher dispersion of results was observed for the guar gum and air conditions, although the magnitude of the standard deviations remained moderate relative to the measured mean values.

To evaluate the statistical significance of differences between the investigated printing environments, a one-way analysis of variance (ANOVA) was performed for both mechanical parameters: the yield strength $R_{p0.2}$ and the ultimate tensile strength R_m . The ANOVA analysis confirmed statistically significant differences between the investigated groups for both parameters. For the ultimate tensile strength R_m , the analysis yielded $F(5, 12) = 1013.96$ with $p < 0.001$. Similarly, statistically significant differences were observed for the yield strength $R_{p0.2}$, with $F(5, 12) = 532.6$ and $p < 0.001$. These results indicate that the printing environment significantly affects the mechanical performance of the fabricated structures.

In particular, the guar gum environment produced the highest average R_m value, while the agar and HEA environments resulted in the lowest strength levels. A similar tendency can also be observed for the yield strength $R_{p0.2}$, where the guar gum condition again exhibits the highest average values, whereas the HEA and agar environments show considerably lower values. This indicates that the surrounding medium may significantly affect both the elastic-plastic transition and the ultimate strength of the material.

The geometric parameters of the specimens (a_0 , b_0 and S_0) were internally consistent, as the reported cross-sectional areas agree with the measured dimensions and their propagated standard deviations. However, some groups, particularly HEA, agar and PVA, exhibited moderate dimensional scatter, indicating that geometric variability may also contribute to the dispersion of the mechanical results. Although the measured standard deviations of the geometric parameters are relatively small, the visual inspection of the specimens reveals local surface irregularities and edge roughness typical for extrusion-based printing in hydrogel environments. Therefore, the dimensional variability reported here should be interpreted as an approximation of the nominal specimen dimensions rather than a full description of local geometric irregularities. Due to the limited number of specimens tested in each group ($n = 3$), the statistical analysis should be interpreted as indicative rather than fully conclusive. Nevertheless, the observed differences between the investigated printing environments are considerably larger than the within-group variability, suggesting that the reported trends are robust and reflect the influence of the printing medium on the mechanical performance of the printed structures.

5. SUMMARY AND CONCLUSIONS

The objective of the research work presented in this paper was to develop a low-cost 3D printing method implemented in a hydrogel environment and to identify the optimal process parameters and materials enabling stable 3D printing under such conditions.

The conducted studies demonstrated that successful implementation of the printing process in a hydrogel medium requires an appropriate adjustment of the rheological properties of both supporting and printing material. Among the analyzed systems, only guar gum hydrogel at a concentration of 3% wt exhibited a stable viscosity profile and shear-thinning behavior, providing adequate support for the extruded material and enabling the fabrication of structures with good geometric accuracy.

Modification of commercial photopolymer resins through the addition of silica resulted in an increase in viscosity and significant changes in the photopolymerization kinetics. Rheological and photorheological analyses indicated that formulations containing approximately 2–5% wt silica provided the most stable flow properties and a favorable crosslinking process. At the same time, it was confirmed that insufficient dispersion of filler particles may lead to local rheological disturbances and deterioration of print quality.

Mechanical testing revealed that samples produced in guar gum hydrogel achieved the highest tensile strength values, even exceeding those of reference samples fabricated using the DLP method. This result indicates that the hydrogel environment may positively influence the stability of the forming process and the homogeneity of the material structure.

The obtained results confirm that the combination of an appropriately selected hydrogel with modified photocurable resins constitutes a promising platform for 3D printing technologies based on photocurable materials in a supporting medium. The developed method may find applications, among others, in bioprinting, fabrication of structures with complex geometries, processing of materials sensitive to gravity or requiring support during forming, as well as in advanced multi-material 3D printing systems. Future work in this area should focus on scaling the developed method to enable its application in the fabrication of structures with more complex geometries.

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SYMBOLS

a_0	initial thickness of the specimen, mm
b_0	initial width of the specimen, mm
E_{steps}	extrusion rate (stepper motor steps per millimeter), –
F	F -statistic value from the analysis of variance (ANOVA), –
G'	storage modulus (elastic behavior of the material), Pa
G''	loss modulus (viscous behavior of the material), Pa
n	number of tested specimens within an experimental group, –
p	probability value for statistical significance assessment, –
R_m	ultimate tensile strength of the polymer specimen, MPa
$R_{p0.2}$	offset yield strength (0.2% plastic strain criteria), MPa
S_0	nominal cross-sectional area of the specimen, mm ²

Abbreviations

DLP	Digital Light Processing
FDM	Fused Deposition Modeling
SLA	Stereolithography
TPO	Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide

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