

INVESTIGATION OF FILLER DISPERSION IN SLA PHOTOPOLYMER RESINS AND ITS INFLUENCE ON MATERIAL PROPERTIES

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Abstract - This study investigates the influence of filler dispersion on the printability and mechanical performance of SLA photopolymer resins filled with fumed silica, calcium sulphate, and zeolite. Filled resin formulations with different weight percentages were prepared using combined mechanical stirring and ultrasonic mixing to achieve homogeneous dispersion prior to printing. The prepared suspensions were evaluated in terms of dispersion stability, sedimentation behaviour, and printability using a masked stereolithography printing process. Tensile specimens were fabricated according to ISO 527 and mechanically characterized through tensile testing, while microscopic observations were used to evaluate void formation and filler distribution. The results showed that filler type and concentration strongly affected resin behaviour and final mechanical properties. Fumed silica provided good dispersion stability at low concentration but significantly increased viscosity at higher loadings. Zeolite exhibited partial sedimentation and phase separation after three weeks of storage. Calcium sulphate showed the most promising overall behaviour. At 3 wt.% CaSO₄, the average peak load increased from 639.71 N for pure resin to 716.16 N, while tensile strength changed from 35.52 to 33.30 MPa. At 5 wt.% CaSO₄, tensile strength and peak load decreased to 24.46 MPa and 427.31 N, respectively. These results indicate that excessive filler loading can cause structural defects and mechanical degradation, while an intermediate filler concentration can provide improved load-bearing performance.

Keywords: Stereolithography (SLA), Photopolymer Resin, Filler Dispersion, Additive Manufacturing, Mechanical Properties.

1. Introduction

Additive manufacturing (AM), commonly referred to as 3D printing, has become one of the most important manufacturing technologies for producing complex geometries with reduced material waste, high design freedom, and rapid production capability. Initially developed mainly for rapid prototyping, AM is now increasingly used for functional and structural applications in industries such as aerospace, automotive, medical engineering, electronics, and tooling [1]. Among the various AM technologies, polymer-based processes represent the largest and most widely applied category due to their relatively low processing temperatures, material versatility, and cost efficiency [2].

Within polymer additive manufacturing, stereolithography (SLA) has attracted considerable interest because of its ability to produce components with very high dimensional accuracy, smooth surface finish, and complex geometrical features. SLA

operates through the layer-by-layer curing of liquid photopolymer resins using ultraviolet (UV) light. During this process, photo initiators absorb UV radiation and initiate radical polymerization reactions, resulting in the formation of a highly crosslinked thermoset polymer network [3]. Compared with extrusion-based technologies such as fused deposition modeling (FDM), SLA offers superior printing resolution and improved surface quality. However, despite these advantages, SLA-printed polymers often exhibit relatively brittle behaviour, limited toughness, and restricted load-bearing capability, which constrain their use in demanding engineering applications [4, 5].

To improve the performance of SLA materials, numerous studies have investigated the incorporation of fillers into photopolymer resins. Fillers are widely used in polymer composites to modify mechanical, thermal, rheological, electrical, optical, or functional properties. Depending on the application, fillers may consist of mineral particles,

ceramics, fibers, metallic powders, carbon-based materials, or bio-based reinforcements [6, 7]. In SLA systems, fillers such as silica, alumina, zirconia, cellulose, graphene, carbon nanotubes, and natural particles have been incorporated to improve stiffness, dimensional stability, wear resistance, thermal behaviour, and sustainability. Mineral fillers are particularly attractive because they are inexpensive, widely available, and capable of increasing structural rigidity and load-bearing behaviour when properly dispersed within the polymer matrix [8-10].

Despite the potential benefits of filled SLA systems, introducing fillers into liquid photopolymer resins presents several important challenges. One of the most critical factors is filler dispersion. A well-dispersed composite system enables effective stress transfer between the polymer matrix and the reinforcing particles, leading to improved structural consistency and mechanical performance. In contrast, poor dispersion results in particle agglomeration, sedimentation, void formation, and non-uniform filler distribution, which may create local stress concentration sites and significantly reduce mechanical strength. Dispersion quality is therefore directly related not only to the final material properties but also to print reliability and repeatability [11, 12].

The importance of dispersion becomes even more critical in SLA printing because the curing process strongly depends on optical behaviour within the liquid resin. Unlike extrusion-based techniques, SLA relies on the penetration of UV light through the resin layer. Once fillers are introduced, scattering and absorption phenomena can disturb light propagation and reduce curing efficiency [13]. Agglomerated particles behave as large scattering centers, decreasing curing depth and producing non-uniform polymerization across the printed layer. Incomplete curing can lead to weak interlayer adhesion, dimensional inaccuracies, and reduced mechanical performance. At higher filler loadings, these effects become increasingly significant due to the combined influence of particle concentration, optical interference, and increased viscosity [14].

Another major challenge in filled SLA systems is rheological stability. The addition of fillers generally increases resin viscosity, which affects resin flow, recoating behaviour, and leveling between layers during printing. Excessive viscosity may prevent proper resin redistribution after each curing cycle and can negatively influence print quality and process stability [15]. At the same time, highly concentrated filler systems are more susceptible to sedimentation and time-dependent instability due to density differences between the particles and the liquid resin. Sedimentation can cause variations in filler concentration during printing, resulting in inconsistent mechanical properties and heterogeneous structures throughout the printed

component. Consequently, achieving stable suspensions while maintaining acceptable printability remains a central challenge in the development of SLA composite resins [16, 17].

To address these issues, various filler dispersion and mixing strategies have been explored. Mechanical mixing is commonly used to promote particle wetting and distribute fillers within the liquid resin, while ultrasonic treatment provides localized cavitation forces capable of breaking particle agglomerates and improving suspension homogeneity [10]. The combined use of mechanical and ultrasonic mixing has been shown to improve dispersion quality, reduce sedimentation, and enhance the reproducibility of filled photopolymer systems. However, mixing parameters must be carefully controlled because excessive ultrasonic energy may introduce heat, alter resin rheology, or even affect photo initiator stability [18, 19].

Previous studies have investigated a broad range of fillers for SLA applications. Fumed silica has been used to modify rheological behaviour and improve suspension stability [20]. Ceramic fillers such as SiO_2 , Al_2O_3 , ZrO_2 , and zeolite have been studied for their influence on curing depth, mechanical performance, and optical scattering [21, 22]. Bio-based fillers including cellulose fibers and agricultural particles have also received increasing attention due to their sustainability potential [23, 24].

Although many studies report improvements in stiffness or thermal behaviour, the relationship between filler concentration, dispersion quality, optical stability, and mechanical performance remains insufficiently understood, especially when considering practical resin preparation methods and printable filler concentrations. There is still limited understanding of how filler sedimentation, void formation, and dispersion homogeneity influence the mechanical behaviour of SLA-printed composites prepared under realistic processing conditions. The aim of this study is to investigate the dispersion behaviour of different fillers to evaluate their influence on printability and mechanical performance.

2. Materials and Methods

2.1 Materials

• Photopolymer Resin

In this study, a commercial UV-curable photopolymer resin, Phrozen Aqua-Clear Resin, was used as the base matrix for all composite formulations. This resin is a transparent, acrylate-based photopolymer specifically developed for masked stereolithography (MSLA) and SLA 3D-printing systems operating at a wavelength of 405 nm.

This resin was selected due to its high optical transparency, stable curing behaviour, and

compatibility with high-resolution SLA printers, including the Phrozen Sonic Mighty 8K used in this work. The transparency of the resin is particularly advantageous for studies involving filler incorporation, as it allows the influence of filler addition on light scattering, curing depth, and polymerization behaviour to be more clearly evaluated.

- **Fumed Silica**

Fumed silica powder was used as the filler material for the preparation of filled photopolymer resins (Figure 1a). The silica was supplied by Sigma-Aldrich (Merck KGaA, Germany) and is commercially identified as Silica, fumed powder. This material is an amorphous silicon dioxide (SiO_2) produced via a pyrogenic process, resulting in a highly pure filler with a distinctive aggregated morphology.

The fumed silica consists of extremely fine primary particles, which form branched, chain-like aggregates with characteristic dimensions in the submicron scale [25]. Although the primary particles are significantly smaller, the reported average particle size of 0.2–0.3 μm corresponds to these aggregates rather than to individual primary particles.

Fumed silica was selected for this study because of its well-defined physical characteristics, strong influence on rheology, and sensitivity to mixing conditions. Its tendency to form aggregates and to modify viscosity makes it an effective model filler for evaluating the efficiency of mechanical and ultrasonic mixing methods. Furthermore, silica is widely used and extensively reported in the literature for photopolymer and SLA applications, allowing meaningful comparison between the present results and previously published studies.

- **Calcium Sulphate**

In addition to fumed silica, calcium sulphate powder was used as a second filler material in this study to enable comparison between fillers with different morphology, surface characteristics, and rheological behaviour (Figure 1b). The calcium sulphate was supplied by Sigma-Aldrich (Merck KGaA, Germany) and is commercially identified as calcium sulphate, –325 mesh, 99% purity.

The material is provided in powder form with a particle size of –325 mesh, corresponding to fine micro-scale particles. Compared to fumed silica, calcium sulphate exhibits a significantly lower specific surface area and a more compact particle morphology. As a result, particle–particle interactions are generally weaker, and the tendency for network formation and strong thixotropic behaviour is reduced [26]. This makes calcium sulphate a suitable reference filler for evaluating how particle size, surface area, and morphology influence dispersion, viscosity, and printability in SLA resins.

From a processing perspective, calcium sulphate is less hygroscopic and less prone to forming strong agglomerates compared to high-surface-area fillers such as fumed silica. However, sedimentation may occur more readily due to the higher particle density and the absence of a percolated particle network [27]. Therefore, effective mixing and controlled processing conditions remain essential to achieve homogeneous dispersion prior to SLA printing.

Calcium sulphate was selected for this study to complement the use of fumed silica by providing a micro-scale, low-surface-area inorganic filler. The comparison between these two fillers allows systematic evaluation of the influence of filler morphology and surface characteristics on dispersion efficiency, rheological behaviour, sedimentation stability, and the final properties of SLA-printed composite materials.

- **Zeolite**

A third filler material investigated in this study was Zeolite, supplied by Sigma-Aldrich (Merck KGaA, Germany) (Figure 1c). The material was provided in powder form with a reported particle size below 20 μm and a quality level of 100, indicating suitability for research and development applications.

Zeolites are microporous aluminosilicate minerals characterized by a three-dimensional framework composed of SiO_4 and AlO_4 tetrahedra linked through shared oxygen atoms. This framework creates a network of well-defined pores and channels, which gives zeolites a high internal surface area and enables ion exchange and adsorption of various cations such as Na^+ , K^+ , Ca^{2+} , and Mg^{2+} [28].

Compared to fumed silica, zeolite does not form a percolated particle network and therefore exhibits a weaker thickening and thixotropic effect. However, compared to calcium sulphate, zeolite offers a more complex surface structure and higher adsorption capability, which can influence resin flow behaviour and sedimentation tendencies [29]. This makes zeolite a valuable filler for comparative analysis, allowing the influence of particle size, porosity, and surface chemistry on dispersion and printability to be systematically evaluated.

Zeolite was selected for this study to provide a micro-scale, porous inorganic filler that differs significantly from both high-surface-area fumed silica and dense, non-porous calcium sulphate. The fillers are presented in the next figure.

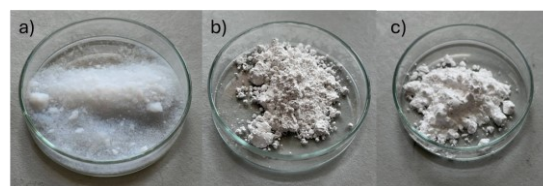


Figure 1: Used fillers in the study: a) Fumed Silica, b) Calcium Sulphate, c) Zeolite

2.2 Methods

• Preparation of Filled Resins

To investigate the influence of filler type and filler loading on the properties of the photopolymer resin, composite formulations were prepared by dispersing three different fillers into an SLA photopolymer resin. The fillers used in this study were fumed silica, calcium sulphate, and zeolite (Figure 1). For each filler, five weight fractions were targeted: 1 wt.%, 3 wt.%, 5 wt.%, 7 wt.%, and 9 wt.%.

For each formulation, 50 g of photopolymer resin was used as the base material. The required amount of filler was calculated according to the desired weight percentage relative to the total mixture mass. Table 1 presents the calculated filler masses for each formulation.

Table 1. Filler amounts used for 50 g resin

Filler content (wt.%)	Filler mass (g)	Resin mass (g)
1 wt.%	0.51 g	50 g
3 wt.%	1.55 g	50 g
5 wt.%	2.63 g	50 g
7 wt.%	3.76 g	50 g
9 wt.%	4.95 g	50 g

Initially, a total of 15 formulations were planned (3 fillers $\times$ 5 weight fractions). However, during the preparation process it was observed that fumed silica significantly increased the viscosity of the resin. When the filler concentration exceeded 3 wt.%, the mixture rapidly became highly viscous and exhibited gel-like behaviour, making proper mixing and handling impossible. As a result, the formulations containing 5 wt.%, 7 wt.%, and 9 wt.% fumed silica could not be successfully prepared.

A total of 12 formulations were successfully prepared and processed, consisting of:

- 2 wt. levels for fumed silica (1 wt.% and 3 wt.% only)
- 5 wt. levels for calcium sulphate
- 5 wt. levels for zeolite

All mixing procedures were carried out under low ambient light conditions to prevent premature photopolymerization of the resin.

• Mechanical Mixing Procedure

A magnetic stirrer was used for the mechanical pre-mixing of the photopolymer resin and fillers. During the experiments, the mixing was performed at controlled rotational speeds to ensure proper wetting of the fillers and to avoid agglomeration. For each formulation, 50 g of resin was weighed using a digital analytical balance with an accuracy of ± 0.01 g and transferred into containers. The calculated amount of filler (according to Table 1) was then weighed separately. The filler addition was

performed slowly over approximately 3 minutes to avoid agglomeration and to facilitate proper wetting of the particles by the resin.

Mechanical mixing was carried out under the following conditions:

- Stirring speed: 450 rpm
- Mixing time: 25 minutes
- Temperature: 23 °C

• Ultrasonic Mixing Procedure

Following the mechanical pre-mixing step, probe ultrasonication (Hielscher Ultrasonics) was applied to further improve the dispersion quality and to break possible particle agglomerates. Ultrasonic treatment was performed using a probe ultrasonic processor (maximum power 200 W) operating at a frequency of approximately 20 kHz. To prevent overheating and possible degradation of the photopolymer resin, the sonication was performed in pulse mode under controlled conditions.

Ultrasonication parameters were set as follows:

- Amplitude: 30% of maximum power
- Pulse mode: 10 s ON / 30 s OFF
- Total effective sonication time: 4 minutes
- Total processing time: 16 minutes

The ultrasonic probe tip was positioned approximately 1.5–2 cm below the surface of the resin and kept away from the container walls and bottom to ensure efficient cavitation and uniform energy distribution.

After completion of the ultrasonic treatment, the mixture was subjected to a secondary magnetic stirring step at 200 rpm for 10 minutes to remove entrapped air bubbles and to ensure uniform particle distribution throughout the resin.

To evaluate the long-term stability and dispersion behaviour of the formulations, the samples were kept in storage for approximately three weeks before further analysis. After this storage period, the samples were removed from the dark container and visually inspected to assess:

- possible sedimentation of the fillers
- changes in viscosity
- phase separation
- overall dispersion stability

The samples were then prepared for further testing and characterization in the subsequent stages of the study, see Figure 4.

• MSLA Print

All specimens in this study were fabricated using a commercial masked stereolithography (MSLA) 3D printer, Phrozen Sonic Mighty 8K. This printer operates based on an LCD-based vat photopolymerization process, in which ultraviolet (UV) light is selectively transmitted through a high-resolution monochrome LCD panel to cure liquid photopolymer resin layer by layer.

The printing parameters were defined and controlled using CHITUBOX (version 1.1.0) slicing software. The printer is equipped with an LCD-based

masking system with a resolution of 7680×4320 pixels, corresponding to a build area of $218.88 \times 123.12 \times 235 \text{ mm}^3$ ($X \times Y \times Z$). The high resolution enables precise fabrication of fine geometrical features.

The parts were printed as tensile specimens to be able to implement standard tensile tests in the next step for mechanical characterization, according to the 1BA geometry, following the specifications of ISO 527 (Figure 2). The dimensions of the printed specimens were in full accordance with the standard, ensuring comparability of the obtained mechanical data.

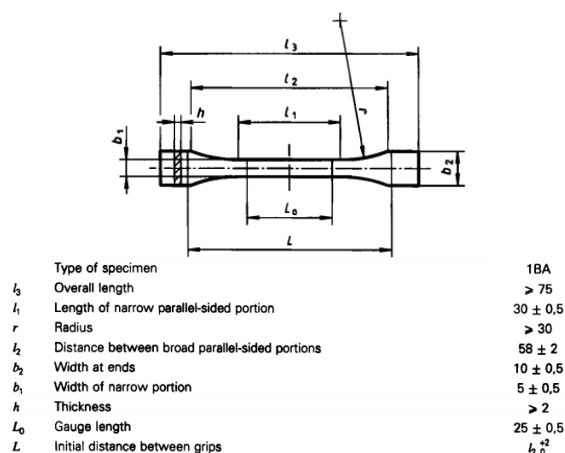


Figure 2: Specification of ISO 527 with 1BA geometry (All dimensions in mm) [30]

The printing process followed a layer-by-layer photopolymerization mechanism, where each layer of the resin was selectively cured by UV light according to the sliced digital model. Bottom layers were exposed for a longer duration to ensure strong adhesion to the build platform, while subsequent layers were cured using optimized exposure times.

The printed specimens were cured for 2 minutes under controlled conditions. The enclosed design of the unit ensures uniform UV exposure while preventing external light interference. This post-curing step was essential to achieve full crosslinking of the photopolymer resin and to improve the structural stability of the printed parts.

Also, a UV curing unit (Anycubic Wash & Cure System) was used for the post-processing of the 3D printed samples. After printing, the parts were subjected to ultraviolet (UV) light exposure to complete the polymerization process and enhance their final mechanical properties.

• Tensile Test

Tensile tests were performed using the universal testing machine (UTM) from the Instron 3400 Series, a dual-column table model designed for high-precision mechanical characterization. The system is equipped with a maximum load capacity of up to 100 kN, allowing accurate measurement of both low- and high-strength materials.

Tensile tests were conducted using appropriate grips to securely hold the specimens and ensure uniform load distribution during testing. The system software enables automated data acquisition, including stress-strain curve generation, from which key mechanical properties such as tensile strength, Young's modulus, and elongation at break were determined.

The high stiffness of the frame and precise load control ensure reliable and reproducible results, which is essential for comparing the mechanical performance of filled and unfilled resin systems.

Tensile tests were carried out using Instron testing machine under control conditions. A load cell with a maximum capacity of 10 kN was selected for all experiments. Although lower-capacity load cells such as 5 kN are commonly used for polymeric materials, it was considered that such a range might not be sufficient to ensure complete fracture of all specimens, particularly for filled systems with increased stiffness. Therefore, a 10 kN load cell was employed to guarantee that the full failure behaviour of all samples could be accurately captured without reaching the measurement limit. Figure 3 shows the situation of a sample after finishing the tensile test.

The tests were conducted at a crosshead speed of 10 mm/min. Preliminary trials were performed at lower speeds (1 mm/min and 5 mm/min); however, these resulted in excessively long testing times without providing additional benefits in terms of data quality. In contrast, a speed of 10 mm/min offered a suitable balance between testing duration and reliable fracture behaviour, ensuring consistent and reproducible results. Furthermore, this testing speed lies within the recommended range specified by the relevant standard.

As mentioned in the previous section, all tensile specimens and tests were conducted based on 1BA geometry of ISO 527. According to Figure 2, the initial distance between the grips was set to 60 mm, while the gauge length was defined as 25 mm, as prescribed by the 1BA configuration.

For each sample composition, five specimens were printed and tested to ensure repeatability, minimize the influence of outliers, and report the average mechanical performance. The force and displacement data were continuously recorded, allowing the generation of stress-strain curves.



Figure 3: Fracture of the sample after tensile test

3. Results and Discussion

3.1 Dispersion Results

The dispersion behaviour of the fillers within the photopolymer resin was first evaluated based on visual observation of the prepared samples. The assessment focused on the homogeneity of the mixtures, the presence of agglomerates, and the overall distribution of the filler particles within the resin matrix. This evaluation was implemented first immediately after the process (Figure 4) and again after three weeks of storage (Figure 5).



Figure 4: The situation of the samples immediately after the process

The dispersion behaviour of the fillers within the photopolymer resin was first evaluated immediately after the mixing process. Visual inspection of the samples revealed clear differences in homogeneity, optical appearance, and rheological behaviour depending on both filler type and concentration.

For the calcium sulphate (CaSO_4) samples, a relatively homogeneous dispersion was observed at lower filler contents (1 wt.% and 3 wt.%). The mixtures appeared slightly turbid, indicating the presence of dispersed particles without visible phase separation. As the filler loading increased (5 wt.% to 9 wt.%), the samples became progressively opaquer due to increased light scattering. Despite this, the distribution remained visually uniform immediately after mixing, suggesting effective initial dispersion.

The zeolite-filled samples showed a similar trend in terms of increasing turbidity with higher filler content. At low concentrations (1 wt.% and 3 wt.%), the samples appeared relatively transparent, indicating a lower degree of light scattering. At higher loadings, the mixtures became opaquer; however, no immediate sedimentation or phase separation was observed. Visual clarity at lower concentrations suggests good initial dispersion, although this observation alone does not necessarily indicate long-term stability.

In contrast, the behaviour of fumed silica differed significantly depending on the filler concentration. At 1 wt.%, no significant increase in viscosity was observed, and the sample remained relatively fluid with no visible sedimentation or noticeable turbidity. The mixture appeared homogeneous, indicating that at this low concentration, the filler was well dispersed without strongly affecting the rheological properties of the resin. At 3 wt.%, an

increase in viscosity became noticeable, and the mixture exhibited a more structured appearance, suggesting the onset of particle–particle interactions and network formation within the resin. No visible sedimentation was observed; however, the change in flow behaviour indicates a transition toward a more interconnected particle system. At higher concentrations, the system became highly viscous and exhibited gel-like characteristics, preventing further processing beyond 3 wt.%.

Overall, immediately after mixing, all filler systems exhibited acceptable dispersion quality from a visual standpoint. However, clear differences in rheological response and optical behaviour suggest that the dispersion mechanisms vary significantly depending on filler type.

After a storage period of three weeks, significant changes in the dispersion state of the samples were observed, revealing differences in long-term stability that were not apparent immediately after mixing.

The zeolite-filled samples exhibited clear phase separation, characterized by the formation of a sediment layer at the bottom and a more transparent upper phase. However, the upper phase retained a slight yellowish coloration, indicating that complete sedimentation had not occurred. This suggests the presence of a concentration gradient, where a reduced but still measurable amount of filler remains dispersed in the resin. Therefore, the observed transparency is attributed to a lower particle concentration rather than complete particle separation. This behaviour indicates partial sedimentation and semi-stable dispersion. Microscopic images of the mixtures in the liquid state revealed distinct differences in filler distribution depending on the filler type. In the case of zeolite, only a limited number of filler particles were observed within the resin phase. This indicates that a significant portion of the zeolite particles had sedimented over time, leading to a reduced particle concentration in the upper liquid phase (Figure 6).



Figure 5: The situation of the samples three weeks after the process

The calcium sulphate (CaSO_4) samples also showed sedimentation after storage, with the formation of a dense layer at the bottom of the container. Compared to zeolite, the upper phase remained more turbid, indicating a higher residual

particle concentration in suspension. Nevertheless, the overall behaviour suggests progressive sedimentation over time, particularly at higher filler loadings. The dispersion can therefore be considered less stable, with a tendency toward phase separation.

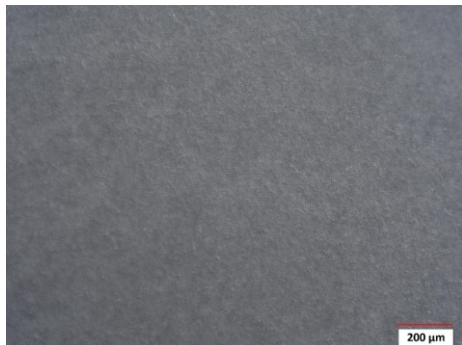


Figure 6: Microscopic image from zeolite (5 wt. %) in liquid state three weeks after mixing

Regarding microscopic images, the calcium sulphate-filled system exhibited a markedly different behaviour. Many white particles were clearly visible throughout the resin, even after three weeks of storage (Figure 7). This observation suggests that a substantial fraction of the calcium Sulphate particles remained dispersed within the resin, indicating improved dispersion stability compared to zeolite.



Figure 7: Microscopic image from CaSO_4 (5 wt. %) in liquid state three weeks after mixing

In contrast, the fumed silica samples showed no visible sedimentation or phase separation even after three weeks. The samples maintained a homogeneous appearance, which can be attributed to the formation of a percolated particle network within the resin matrix. This network structure effectively suppresses particle movement and prevents sedimentation. However, this improved stability is limited to amount of weight percentage, and it cannot be increased to 5 wt.% or more because of an increase in viscosity, which can be problematic during printing and further processing (Figure 8).

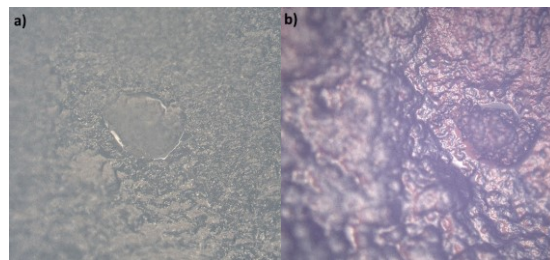


Figure 8: Microscopic image from fumed silica and changes in viscosity: **a)** 3 wt.%, **b)** 5 wt. %

Overall, the long-term behaviour highlights a clear distinction between the filler systems. While calcium Sulphate shows a lower sedimentation, zeolite exhibits a more gradual separation characterized by a concentration gradient. Fumed silica, on the other hand, provides excellent dispersion stability through network formation, however at the expense of flowability in higher concentrations.

Based on the dispersion observations and stability analysis, the suitability of each filler system for further processing and 3D printing was evaluated.

The zeolite-filled samples were excluded from further investigation due to their insufficient dispersion stability. Although partial transparency was observed in the upper phase, this behaviour was attributed to phase separation and the formation of a concentration gradient rather than stable dispersion. Therefore, zeolite was considered an unsuitable filler for the intended application.

For calcium sulphate (CaSO_4), higher filler loadings of 7 wt.% and 9 wt.% were also excluded. These samples exhibited increased transparency after storage, which was associated with particle sedimentation and phase separation. As a result, these formulations were considered unsuitable due to their poor long-term stability.

In the case of fumed silica, the formulation with 3 wt.% was excluded due to the increase in viscosity, which negatively affected the processability of the resin and led to difficulties during printing. In contrast, the 1 wt.% silica sample maintained acceptable viscosity and showed no sedimentation, making it suitable for further investigation.

Based on these criteria, the following formulations were selected as suitable candidates for further processing and 3D printing:

- Fumed silica (1 wt.%)
- Calcium Sulphate (1 wt.%, 3 wt.%, and 5 wt.%)

These selected samples provided a balance between dispersion quality, stability, and processability, and were therefore used in the subsequent printing and mechanical evaluation stages.

3.2 Printing Parameter Optimization

The printing parameters for pure resin were initially defined as a baseline for comparison. A layer height of 0.05 mm, normal exposure time of 10.3 s, and bottom exposure time of 32.5 s were selected. The lifting speed was set to 60 mm/min, and a rest time of 3 s after retracting was applied to allow sufficient resin leveling between layers.

Upon the addition of fillers, the printing parameters required systematic adjustment due to changes in optical and rheological properties of the resin. These adjustments were carried out through an iterative trial-and-error approach, where printing failures such as incomplete curing, poor layer adhesion, and surface defects were used as indicators for parameter optimization.

For calcium sulphate (CaSO_4)-filled samples, a clear trend was observed with increasing filler content. At 1 wt.% and 3 wt.%, the normal exposure time was increased to 14 s and the bottom exposure time to 42 s. This adjustment was necessary due to increased light scattering caused by the filler particles, which reduced the effective light penetration depth and hindered complete curing of each layer. Additionally, the lifting speed was reduced from 60 mm/min to 45 mm/min to compensate for the increased viscosity of the suspension and to ensure stable layer separation.

At 5 wt.% CaSO_4 , further adjustments were required. The exposure time was increased to 16 s and the bottom exposure time to 47 s, reflecting the stronger attenuation of light at higher filler loadings. Moreover, the lifting speed was further reduced to 40 mm/min to minimize mechanical stress during layer separation. The rest time after retracting was also increased from 3 s to 4 s, allowing sufficient time for the more viscous resin to reflow and form a uniform layer before subsequent curing.

In contrast, the silica-filled sample at 1 wt.% required only moderate parameter modifications. Due to the finer particle size and lower impact on light scattering, silica did not significantly hinder light penetration compared to CaSO_4 . However, a slight increase in viscosity was observed compared to pure resin, indicating a more viscous and less flowable system. However, this change was not severe enough to significantly hinder the printing process or layer formation. To compensate for this increased viscosity, minor adjustments in the printing parameters were applied. The exposure time was increased from 10.3 s to 12.3 s to ensure sufficient curing of each layer. Additionally, the lifting speed was slightly reduced from 60 mm/min to 50 mm/min to facilitate a more stable layer separation and reduce mechanical stress during the printing process.

Overall, the results demonstrate that increasing filler content leads to reduced light penetration and increased viscosity, both of which significantly

influence the printing process. Therefore, higher exposure times, lower lifting speeds, and longer resting times were required to ensure successful printing. These findings highlight the importance of adapting printing parameters to the specific filler type and concentration to achieve reliable fabrication of filled photopolymer systems. Table 2 shows the overview of printing parameters of each sample, and Figure 9 shows the appearance of printed samples. As mentioned before, transparent base resin was used to enable clear visual observation of filler dispersion within the material. This allowed qualitative evaluation of the distribution and optical effects of different fillers.

According to Figure 9, the specimen containing 1 wt.% silica remained highly transparent, indicating that the addition of silica at low concentration preserved the optical clarity of the resin and did not significantly affect its appearance.

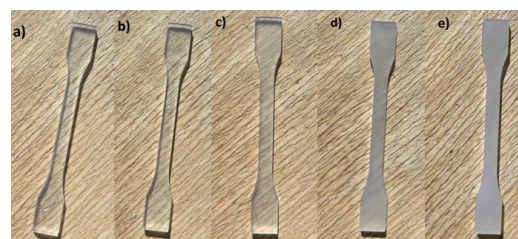


Figure 9: Appearance of printed samples: **a)** Pure resin, **b)** Silica 1 wt.%, **c)** CaSO_4 1 wt.%, **d)** CaSO_4 3 wt.%, **e)** CaSO_4 5 wt.%

Table 2. Print Parameters for Different Resin Systems

Parameter	Pure Resin	Silica 1 wt.%	CaSO_4 1, 3 wt.%	CaSO_4 5 wt.%
Layer height (mm)	0.05	0.05	0.05	0.05
Bottom layers	6	6	6	6
Exposure time (s)	10.3	12.3	14.0	16.0
Bottom exposure time (s)	32.5	37.0	42.0	47.0
Transition layers	6	6	6	6
Transition type	Linear	Linear	Linear	Linear
Rest time after retracting (s)	3	3	3	4
Lifting distance (mm)	8	8	8	8
Bottom lifting distance (mm)	8	8	8	8
Lifting speed (mm/min)	60	50	45	40
Bottom lifting speed (mm/min)	60	60	60	60
Retract speed (mm/min)	150	150	150	150

In contrast, the incorporation of calcium sulphate resulted in a progressive loss of transparency with increasing filler content. At 1 wt.%, the specimens were still partially transparent, whereas at 3 wt.% only limited transparency was observed. At 5 wt.%, the specimens became almost completely opaque, indicating a strong scattering effect of the filler particles and a significant alteration of the optical properties of the resin.

3.3 Analyzing the Printed Parts and Tensile Tests

Microscopic observations from printed parts reveal important differences in the internal structure of samples investigated (Figure 10). The pure resin exhibits a relatively homogeneous matrix; however, a considerable number of voids are present throughout the structure. These voids act as stress concentration sites and can initiate premature failure under mechanical loading. A similar behaviour is observed in the sample containing 1 wt.% fumed silica, where voids are still clearly visible. In some regions, the presence of silica may even contribute to trapping air during mixing due to a slight increase in viscosity. As a result, no significant improvement in structural integrity is achieved at this filler content.

In contrast, the calcium sulphate-filled samples show a noticeable reduction in the number of voids, particularly at 1 wt.% and 3 wt.%. This suggests that the presence of CaSO_4 particles may facilitate a more compact structure or reduce air entrapment during processing. At 1 wt.%, the number of voids is relatively low, and the particles are well dispersed within the matrix, resulting in a uniform structure. As the filler content increases to 3 wt.%, a further reduction in voids is observed, indicating improved structural compactness and more effective particle

distribution. However, at 5 wt.%, the number of voids increases again, accompanied by the formation of particle-rich regions. This leads to a more heterogeneous structure, where the presence of both voids and local particle accumulations can act as stress concentration sites and negatively affect the mechanical performance.

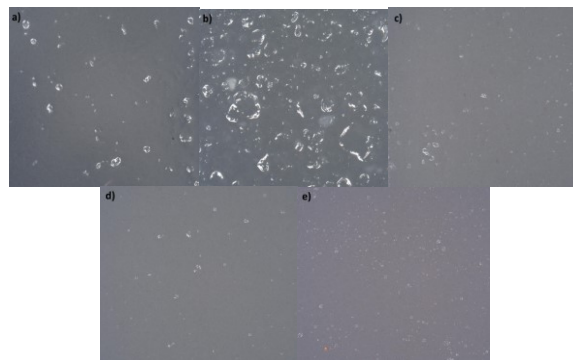


Figure 10: microscopic images from printed parts: **a)** Pure resin, **b)** Silica 1 wt.%, **c)** CaSO_4 1 wt.%, **d)** CaSO_4 3 wt.%, **e)** CaSO_4 5 wt.%

However, this improvement is not accompanied by a corresponding increase in ductility or intrinsic strength. The presence of emerging agglomerates at this concentration introduces localized stress concentrations, which limit the overall mechanical performance. Therefore, the improvement in load at peak should be understood as a structural effect related to force distribution rather than a fundamental enhancement of the material's strength. As mentioned, for the evaluation of the mechanical behaviour of the parts, tensile tests for each sample were done and repeated 5 times to increase the accuracy of the results. Stress/Strain diagrams were also depicted during the tests. Figures 11 and 12 show stress/strain diagrams for two samples.

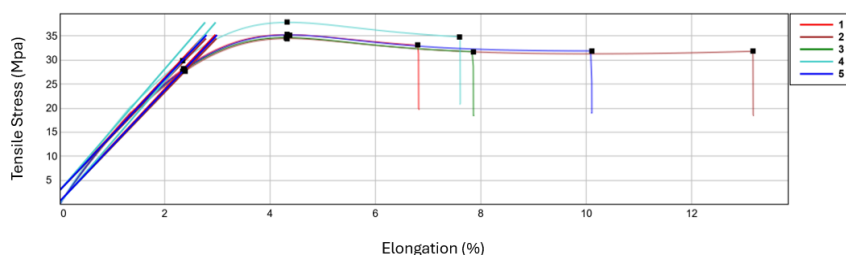


Figure 11: Stress/Strain diagram for pure resin

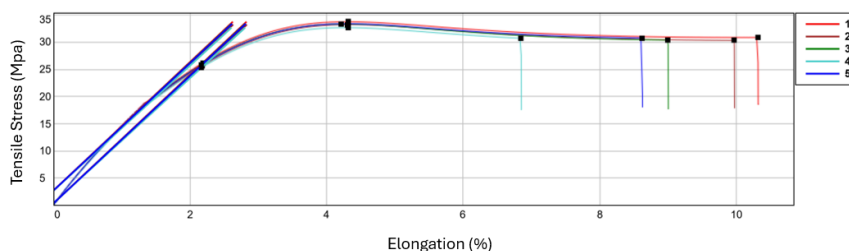


Figure 12: Stress/Strain diagram for resin with 3 wt.% of CaSO_4

An interesting behaviour is observed for the CaSO_4 3 wt.% sample. While the tensile strength does not significantly exceed that of the pure resin, the peak load shows a noticeable increase, reaching the highest value among all tested samples. This can be interpreted as a positive effect, indicating an improved overall load-bearing capacity of the material. At this filler content, the CaSO_4 particles contribute to stress transfer within the matrix,

allowing the composite to sustain higher applied forces before reaching its maximum load. In this sense, the material exhibits a partially reinforced structure, where the filler supports the applied load and enhances resistance to deformation under increasing force. Figure 13 shows the comparison of maximum tensile stress and peak load for each sample.

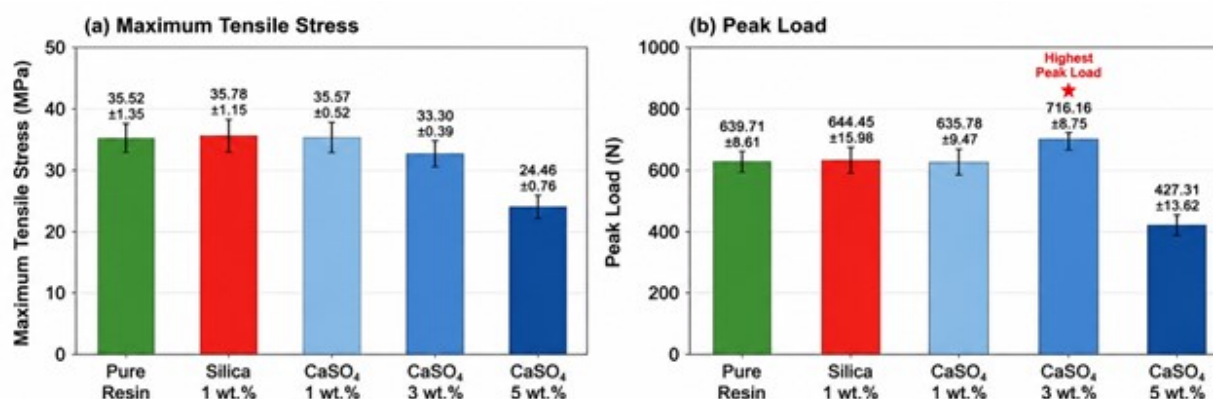


Figure 13: Comparison of **a)** maximum tensile strength, **b)** peak load for each sample

The tensile test results further support the observations from microscopy pictures. For both the pure resin and the silica 1 wt.% sample, the mechanical properties remain largely unchanged. Tensile strength, elongation at break, and load at peak show only minor variations, indicating that the addition of a small amount of silica does not

significantly reinforce the material. Similarly, the CaSO_4 1 wt.% sample shows no substantial improvement in mechanical performance, despite the slight reduction in voids observed microscopically. Tables 3 - 5 show result of tensile test for pure resin, CaSO_4 3 wt.% and CaSO_4 5 wt.%.

Table 3. Tensile test results for pure resin

Sample	Maximum Tensile Stress (MPa)	Elongation at break (%)	Peak load (N)	Young's Modulus (MPa)	Width (mm)	Thickness (mm)
1	35.29	6.80	635.80	1171.49	5.56	3.24
2	34.51	13.16	626.41	1137.48	5.62	3.23
3	34.70	7.85	643.89	1160.86	5.71	3.25
4	37.85	7.59	647.23	1265.16	5.31	3.22
5	35.23	10.10	645.21	1158.64	5.60	3.27
Average	35.52	9.10	639.71	1178.72	5.56	3.24
Standard deviation	1.35	2.58	8.61	49.87	0.15	0.02

Table 4. tensile test results for resin with 3 wt.% of CaSO_4

Sample	Maximum Tensile Stress (MPa)	Elongation at break (%)	Peak load (N)	Young's Modulus (MPa)	Width (mm)	Thickness (mm)
1	33.77	10.31	717.03	1180.99	5.50	3.86
2	33.25	9.97	711.69	1159.34	5.53	3.87
3	33.37	8.99	730.14	1176.89	5.64	3.88
4	32.69	6.84	706.70	1150.22	5.60	3.86
5	33.41	8.61	715.26	1173.11	5.49	3.90
Average	33.30	8.94	716.16	1168.11	5.55	3.87
Standard deviation	0.39	1.37	8.75	12.89	0.07	0.02

At higher filler content (5 wt.% CaSO_4), the mechanical performance deteriorates significantly. A sharp decrease in load at peak, tensile strength, and stiffness is observed. This behaviour is directly linked to the pronounced agglomeration and structural inhomogeneity observed in microscopic images. The formation of large particle clusters leads to weak interfaces and stress concentration zones, resulting in premature failure under load.

Overall, the results demonstrate that increasing filler content does not necessarily lead to improved

mechanical performance. While low filler contents (1 wt.%) have minimal impact, and intermediate content (3 wt.%) can enhance load-bearing capacity, excessive filler addition (5 wt.%) leads to structural defects and mechanical degradation.

Therefore, an optimal filler content exists, and in this study, 3 wt.% CaSO_4 can be considered an optimal point in terms of load bearing, although it does not represent a universal improvement across all mechanical properties.

Table 5. tensile test results for resin with 5 wt.% of CaSO_4

Sample	Maximum Tensile Stress (MPa)	Elongation at break (%)	Peak load (N)	Young's Modulus (MPa)	Width (mm)	Thickness (mm)
1	24.25	10.12	423.11	882.32	5.32	3.28
2	24.84	7.77	432.96	915.87	5.38	3.24
3	25.18	7.24	439.40	903.43	5.42	3.22
4	23.23	6.63	405.46	865.90	5.42	3.22
5	24.79	6.63	435.60	924.03	5.44	3.23
Average	24.46	7.68	427.31	898.31	5.40	3.24
Standard deviation	0.76	1.44	13.62	23.99	0.05	0.02

4. Conclusions

This study investigated the dispersion behaviour of different fillers, including fumed silica, zeolite, and calcium sulphate, in SLA photopolymer resins and evaluated their influence on printability and mechanical properties.

The results showed that filler type and concentration play a critical role in determining both the processability and performance of the resin. Among the investigated fillers, silica exhibited significant limitations due to its strong effect on viscosity. While 1 wt.% silica showed no major change in viscosity or mechanical behaviour, increasing the concentration to 3 wt.% resulted in a noticeable increase in viscosity, leading to processing and printing difficulties. However, an important positive aspect of silica-filled samples was the preservation of optical transparency after printing. Compared to other fillers, silica maintained a relatively clear appearance, which can be considered a significant advantage for applications where visual clarity or light transmission is required.

Zeolite samples demonstrated relatively good visual transparency after storage; however, this behaviour was associated with particle sedimentation and instability of dispersion. The observed yellowish coloration indicated that partial separation occurred over time, making zeolite an unreliable filler for maintaining homogeneous mixtures.

In contrast, calcium sulphate showed more stable and promising behaviour. Microscopic analysis revealed that at lower concentrations (1 wt.% and 3 wt.%), the number of voids decreased, and a more uniform structure was achieved. At 3 wt.%, the material exhibited the highest load at peak, indicating an improved load-bearing capacity due to effective stress transfer between matrix and filler. However, further increasing the filler content to 5 wt.% resulted in structural heterogeneity, increased void formation, and significant deterioration in mechanical properties.

Mechanical testing confirmed that low filler contents (1 wt.%) had minimal influence on tensile strength and elongation. The 3 wt.% calcium sulphate sample showed an improvement in load-bearing capability but also indicated the onset of more brittle behaviour. At 5 wt.%, all mechanical properties, including strength, stiffness, and energy absorption, decreased considerably due to agglomeration and poor dispersion.

Overall, the study demonstrates that increasing filler content does not necessarily lead to improved material performance. Instead, optimal filler concentration exists, and in this work, 3 wt.% calcium sulphate was identified as a relatively optimal composition in terms of load-bearing performance, although it does not improve all mechanical aspects simultaneously.

Based on the results obtained, several recommendations can be made for future experimental work and practical applications:

- Careful control of filler concentration is essential, as excessive filler content leads to agglomeration and performance degradation. Maintaining low to moderate filler loadings is recommended to achieve a balance between processability and mechanical performance.
- Optimization of the mixing process can further improve dispersion quality. Parameters such as ultrasonic power, mixing time, and temperature control should be systematically optimized to minimize void formation and ensure homogeneous particle distribution.
- Quantitative rheological, sedimentation, and particle-size analyses should be performed to better characterize filler dispersion and printability.
- Degassing techniques should be considered to reduce entrapped air during mixing, especially in systems containing silica, where viscosity effects are more pronounced.
- Printing parameters such as exposure time and layer curing conditions should be adjusted for filled resins, as filler particles influence light scattering and curing behaviour.

Future research in this field can focus on testing a larger number of specimens and applying statistical analysis.

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