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SIFAT MEKANIK DAN FISIK *3D-PRINTED DENTAL PHOTOPOLYMER RESINS* DALAM KONDISI PEMROSESAN YANG BERBEDA

MECHANICAL AND PHYSICAL PROPERTIES OF 3D-PRINTED DENTAL PHOTOPOLYMER RESINS UNDER DIFFERENT PROCESSING CONDITIONS

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Abstrak

Resin fotopolimer telah banyak digunakan dalam bidang kedokteran gigi untuk membuat restorasi gigi sementara. Penelitian ini menyajikan karakterisasi lengkap mengenai resin fotopolimer *dental non-castable* yang dibuat menggunakan teknologi *3D-printing Digital Light Processing* (DLP). Spesimen dicetak dengan ketebalan lapisan 0,05, 0,075, dan 0,1 mm, diikuti dengan *post-cured treatments* di bawah sinar UV selama 10, 20, dan 30 menit. Serangkaian pengujian karakterisasi material dilakukan, meliputi uji kekerasan, kelembapan, dan pengukuran massa jenis. Hasil penelitian menunjukkan bahwa kekerasan dan kelembapan specimen dipengaruhi secara signifikan oleh *post-curing time*, sementara *post-curing time* yang lebih lama menghasilkan kekerasan spesimen yang lebih besar dan kadar air yang menurun. Peningkatan ketebalan lapisan menyebabkan penurunan nilai kekerasan secara bertahap. Nilai kekerasan maksimum 57,7 Shore D diamati pada spesimen cetak 3D, bersama dengan kadar air tertinggi 1,05% MC. Sesuai perkiraan, spesimen menunjukkan densitas yang konsisten (1,19 ± 0,02 g/cm^3) di seluruh ketebalan lapisan dan variasi *post-curing time*. Studi ini menyoroti pentingnya pemahaman mengenai pengaruh parameter proses terhadap sifat resin fotopolimer *dental-non castable* sebelum diimplementasikan secara klinis.

Keywords: *3D-printing*, resin foto polimer gigi, kekerasan, kelembapan, massa jenis.

Abstract

Photopolymer resins have widely applied in dentistry to fabricate temporary restorations. This work gives a complete characterization of a dental non-castable photopolymer resin prepared via Digital Light Processing (DLP) 3D printing. Specimens were printed at layer thicknesses of 0.05, 0.075, and 0.1 mm, followed by post-cured treatments under UV light for 10, 20, and 30 minutes. A series of material characterization tests were performed, including *assessments of hardness, moisture absorption behavior, and density measurements. The results indicate that hardness and moisture content are significantly impacted by post-curing time, while extended curing times resulted in greater specimen's hardness and decreased moisture content. An increase in layer thickness led to a gradual reduction in hardness. A maximum hardness value of 57.7 Shore D was observed in the 3D-printed specimen, along with a highest moisture content of 1.05% MC. As expected, the specimens exhibited consistent density (1.19 ± 0.02 g/cm³) throughout all layer thickness and curing time variations. This study highlights the critical need to understand how process parameters affect dental non-castable photopolymer resin properties prior to clinical implementation.*

Keywords: *3D-printing, dental photopolymer resin, hardness, moisture, density.*

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INTRODUCTION

The rapid development of science and technology in dentistry has led to groundbreaking innovations in restorative materials, enhancing both efficiency and biocompatibility[1]. Among these advancements, dental photopolymer resin stands out as a transformative material, which has become a pivotal in a wide range of dental procedures, ranging from direct fillings and the fabrication of temporary crowns to digital-based prosthetics produced using 3D printing technology[2,3]. Also known as additive manufacturing (AM), 3D printing is a transformative technology that constructs physical objects by precisely depositing material layer by layer based on a digital model[4,5]. Unlike traditional subtractive manufacturing, which carves out material, AM builds components from the ground up, enabling unparalleled design flexibility and customization.

Recently, there has been a significant trend in the use of photopolymer-based resins for digital dentistry applications, particularly in additive manufacturing techniques such as vat photopolymerization (Stereolithography and Digital Light Processing)[1,6,7]. This technology enables the production of dental models, aligner impressions, splints, and temporary restorations with high accuracy, versatility, reduced production time and fine surface finish compared to conventional methods[1,2,6]. Stereolithography (SLA) employs a laser beam to selectively cure liquid photopolymer resin layer by layer, following a pre-programmed digital design, until the complete 3D object is fabricated[8]. Unlike laser-based SLA, Digital Light Processing (DLP) technology uses a digital light projector to cure entire resin layers simultaneously through photopolymerization[9], resulting in faster printing of high-resolution parts with excellent surface quality[10]. While 3D printing has revolutionized dental prosthetics by enabling precise and efficient fabrication of fixed dental prostheses, its application remains constrained by the mechanical properties of available materials. Currently, 3D-printed resin lacks the necessary strength for permanent restorations, limiting its use primarily to interim prostheses[11]. This restriction highlights the ongoing need for advancements in resin formulations and manufacturing methods to enhance durability and expand the potential of additive manufacturing in long-term dental solutions.

Numerous studies have explored the advancement of AM applications in dentistry. Gul et al.[12] compared the wear and fracture resistance of various resins for SLA 3D-printed dental crowns after thermomechanical aging, supported by finite element analysis (FEA). Their study demonstrates that thermomechanical aging significantly influences the wear resistance and fracture behaviour of 3D-printed dental crowns. Lee et al.[13] evaluated the effect of printing temperature (room temperature, 50 °C, and 70 °C) on the mechanical properties and double bond conversion (DBC) of the printed parts for dental prosthetics fabricated via SLA technology. The specimens were tested under two conditions: without post-curing (green condition) and with post-curing using a UV lamp. The results showed that an increase in printing temperature (up to 70 °C) resulted in a higher DBC, lower viscosity, and enhanced mechanical properties. Additionally, Scanning Electron Microscopy (SEM) analysis of the fractured samples revealed smoother surfaces and more cohesive bonding at higher printing temperatures, indicating enhanced interlayer adhesion. In a study by You et al.[2], it was demonstrated that when fabricating trial dentures via SLA, a layer thickness of 100 μm was preferable to 50 μm due to its superior accuracy on the intaglio surface, a critical factor for clinical applications. Moreover, another study showed that layer thickness also affects the mechanical strength of vat photopolymerization printed parts. Reducing layer height during printing directly enhances the tensile and flexural strength of printed parts[14,15]. Furthermore, studies demonstrate that build orientation significantly affects the mechanical properties [16,17], dimensional precision[18], and surface topography[14] of final printed parts. The combination of a 150° printing angle and small-diameter support structures provides optimal results in terms of time efficiency and accuracy for printing denture frameworks using DLP technology[19].

As 3D printing technology becomes more widely adopted for creating dental restorations[1,7], especially with photopolymer resins, assessing their characteristics is essential to guarantee safety and clinical efficacy. The durability and clinical success of dental restorations are significantly influenced by the material's hardness[20]. In dentistry applications, hardness assessments not only reveal how well a material withstands chewing forces but also provide insights into polymerization quality, durability against wear, and long-term structural stability[21]. Consequently, hardness evaluation represents an essential phase in the validation of 3D-printed dental resins, ensuring that the resulting restorations are not only dimensionally accurate but also functionally reliable. To the best of the author's knowledge, research on the hardness of photopolymer resin materials in dentistry remains limited, with most studies focusing primarily on microhardness[22,23]; however, the Shore D test is a more appropriate method for such polymeric materials. Additionally, discussions on moisture content and density in 3D-printed dental parts are minimal, even though these factors greatly affect mechanical strength. Therefore, the present work examines the mechanical and physical properties of 3D-printed dental photopolymer resins across different layer thicknesses and post-curing times. Shore D-based hardness measurements, moisture content analysis, and density tests were employed to characterize the 3D-printed dental photopolymer resins.

RESEARCH METHODS

Specimen Preparation

Anycubic dental non-castable photopolymer resin was employed as the source material for manufacturing the specimens. Table 1 and Table 2 summarize the chemical compositions and properties of anycubic dental non-castable photopolymer resin. Fabrication of the specimens was performed using an Anycubic Photon Ultra DLP 3D printer (Figure 1a), employing a layer thickness of 0.05, 0.075 and 0.1 mm, a standard exposure time of 7 s and build orientation of 0° and 90°. A 7-second exposure time was chosen based on the resin manufacturer's general recommendation and supported by preliminary trials, which showed that this duration is sufficient to ensure complete layer curing without overexposure. The specimen was modeled utilizing SolidWorks 2019 with dimensions of 10 x 10 x 6 mm, as depicted in Figure 2a. Photon Workshop V2.1.24.RC7 (Figure 2b) was utilized to position the STL file on the printing platform and configure the printing parameters. Following the completion of the printing process, the printed specimens underwent systematic post-processing: initial gentle removal from the printing platform, subsequent washing in 96% alcohol liquid (5-minute immersion), and post-curing process under 405 nm UV light (10-, 20-, and 30-minute exposure) to achieve optimal material properties. Literature and resin manufacturer datasheets commonly recommend a post-curing duration of 5 to 60 minutes to optimize Shore D hardness and ensure the long-term stability of printed components[7,24,25,26]. All post-processing procedures were conducted using the Anycubic Wash and Cure 2.0 system (Figure 1b), with specimen handling maintained at 24 ± 1°C throughout preparation. The complete experimental variations in this study are presented in Table 3.

Table 1. Anycubic dental non-castable photopolymer resin chemical composition[27]

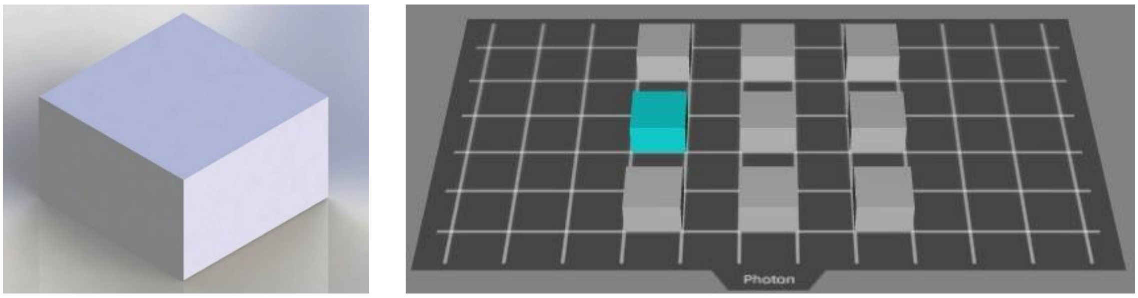
Chemical Name	**CAS No.**	**% by weight**
Epoxy acrylate resin	61788-97-4	40-50%
Monomer	13048-33-4	20-40%
Photoinitiators	947-19-3	3-5%
Colour pigment		2-5%

Table 2. Anycubic dental-non castable photopolymer resin properties[28]

Properties	**Value**	**Unit**
Density	1.05-1.13	g/cm^3
Viscosity (25°C)	100-150	mPa.s
Hardness	88	Shore D
Tensile strength	42-62	MPa
Elongation at break	11-20	%

(a) (b)

Figure 1. Additive manufacturing equipment. (a) Anycubic Photon Ultra 3D Printer, (b) Anycubic Wash and Cure 2.0



(a) (b)

Figure 2. (a) Specimen design, (b) Specimen configuration in Photon Workshop Slicer Software

Table 3. Experimental variations

Exposure Time (s)	**Layer Thickness (mm)**	**Post-Curing Time (minutes)**	**Build Orientation (°)**
7	0.05	10	0, 90
7	0.05	20	0, 90
7	0.05	30	0, 90
7	0.075	10	0, 90
7	0.075	20	0, 90
7	0.075	30	0, 90
7	0.1	10	0, 90
7	0.1	20	0, 90
7	0.1	30	0, 90

Hardness Testing

Hardness testing was conducted to evaluate the resistance of the printed specimens to localized surface deformation, which is indicative of their wear resistance, polymerization degree, and long-term mechanical stability. The hardness of specimens was evaluated using a Digital Shore D Durometer (Figure 4a) in accordance with ASTM D2240 testing standards. Measurements were taken at two different orientations on each specimen (Figure 3), on the top surface (0° orientation) and on the side surface (90° orientation), to account for potential anisotropy resulting from the layer-by-layer printing process. For each location, five readings were recorded, and the average value was used for further analysis. The indenter was applied perpendicularly to the surface with a consistent force, and the reading was recorded after 1 second of contact to minimize time-dependent deformation effects. Hardness values were compared across specimens fabricated with varying layer thicknesses and post-curing durations. Since hardness is a critical factor affecting the performance of dental restorations, especially under masticatory forces, this test provides essential insights into the suitability of the printed resin materials for clinical applications.

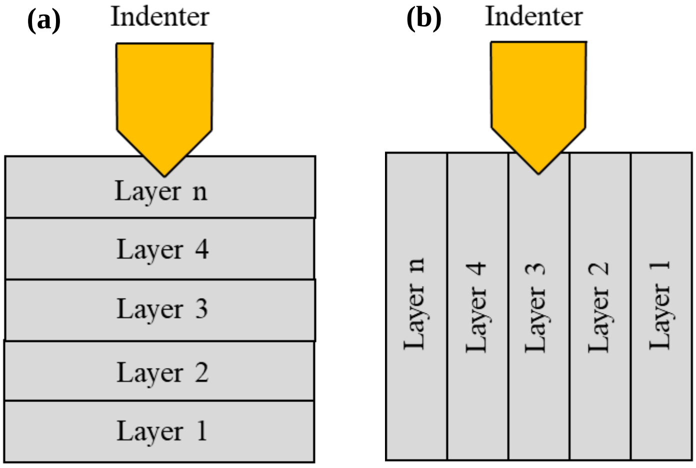


Figure 3. Hardness testing schematic. (a) Top surface (0° orientation), (b) Side surface (90° orientation)

Moisture Absorption Testing

An evaluation of moisture absorption was carried out in accordance with ASTM standard D570. The moisture content (MC) of the specimens was measured by drying them in an OHAUS MB95 moisture analyzer (Figure 4b) for 10 minutes at 105°C. Moisture content refers to the quantity of water contained within a material. Based on thermogravimetric analysis, the moisture analyzer determines the specimen mass before the integrated halogen dryer heats it, causing moisture to evaporate. The moisture analyzer provides real-time mass measurements of the specimen throughout the entire drying cycle, displaying the results continuously. The output is presented as percent moisture content (%MC), representing moisture mass relative to the material's total mass after drying. Three replicate tests were performed for every data set in the moisture absorption analysis.

Density Testing

Density measurements were performed to determine the mass-to-volume ratio of the printed specimens. The density of each specimen was calculated using the Archimedes' principle, in accordance with ASTM D792 standards. Each specimen was first weighed in air using an analytical balance OHAUS PX224 (Figure 4c) with a precision of 0.0001 g. Subsequently, the specimen was immersed in distilled water, and the submerged weight was recorded. All measurements were conducted at room temperature (23 ± 2 °C), and each specimen was measured three times to ensure reproducibility. Density analysis is particularly important for 3D-printed dental resins, as deviations in density may indicate incomplete polymerization, internal voids, or variations in material distribution, all of which could compromise the structural integrity and clinical reliability of the final product.


(a) (b) (c)

Figure 4. Testing equipment. (a) Digital Shore D Durometer, (b) Moisture analyser, (c) OHAUS analytical balance PX224

Statistical Analysis

A one-way ANOVA was employed to analyze the experimental data and determine the significance of differences among the test groups. This method was selected because it is suitable for comparing multiple groups means simultaneously, which allows for a robust evaluation of the independent variable's effect on the measured response. A 95% significance level ($\alpha = 0.05$) was established for all tests. A result was considered statistically significant if the p-value was below 0.05 or if the F-value exceeded the critical F-value.

RESULTS AND DISCUSSION

Hardness

The hardness of photopolymer resins is crucial in assessing their appropriateness for dental and industrial uses. As depicted in Figure 5, the hardness of the specimens varies depending on the curing time and layer thickness used during the printing process. The highest hardness value of 57.7 Shore D was achieved at a minimal layer thickness of 0.05 mm combined with a 30-minute post-curing duration. Whereas the lowest hardness value of 41.9 Shore D was recorded for specimens fabricated with a 0.1 mm layer thickness and limited post-curing duration (10 minutes). The observed trend shows that hardness increases as the layer thickness decreases. This trend is evident in the hardness values obtained for specimens with a post-curing time of 20 minutes. As the layer thickness was reduced from

0.1 mm to 0.05 mm, the hardness increased correspondingly from 45.1 Shore D to 52.5 Shore D (with an intermediate value of 49.6 Shore D at 0.075 mm). The statistical significance of this effect is confirmed by ANOVA ($\alpha = 0.05$), which yielded an F-value of 105.59 for the 20-minute group, greatly exceeding the F-crit value of 3.88. Thus, layer thickness is a significant factor influencing specimen hardness. Specimens manufactured with thinner layer thicknesses consistently exhibited slightly higher hardness values, primarily due to enhanced polymer chain alignment and decreased interlayer porosity during the printing process[15]. This observation aligns with previous studies suggesting that decreased layer thickness enhances the mechanical integrity of photopolymer-based materials[14,15].

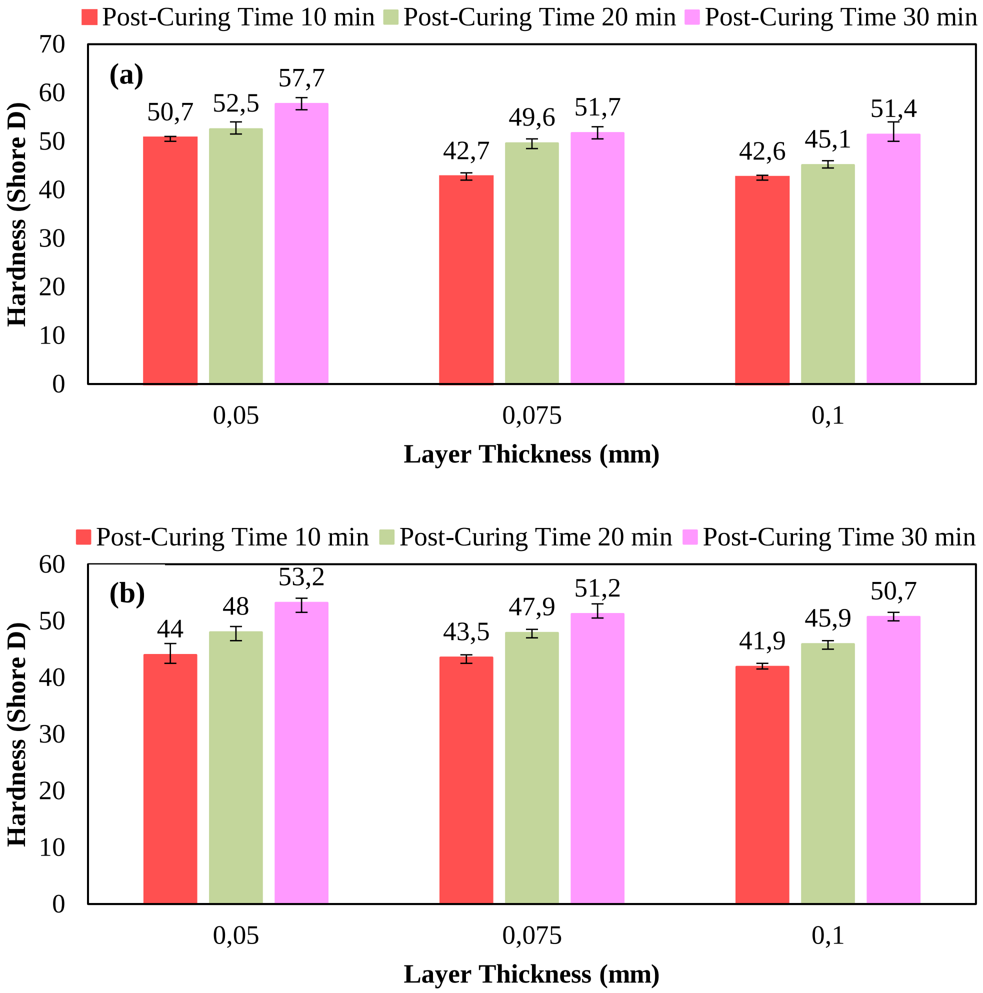


Figure 5. Hardness values of specimens with different layer thicknesses and post-curing time treatments. (a) Top surface (0° orientation), (b) Side surface (90° orientation)

A strong correlation was observed between post-curing duration and hardness development, indicating the critical role of curing time in determining final mechanical properties. For instance, at a constant layer thickness of 0.1 mm, the hardness values corresponding to post-curing times of 10, 20, and 30 minutes were 42.6, 45.1, and 51.4 Shore D, respectively, demonstrating a positive correlation. Furthermore, ANOVA results for the 0.1 mm layer thickness group ($\alpha = 0.05$) showed that the calculated F-value (90.72) significantly exceeded the critical value (F-crit = 3.88). This confirms that post-curing duration had a statistically significant effect on the hardness of the specimens. Extended post-curing durations resulted in increased hardness measurements, suggesting enhanced polymerization completion in the printed specimens. Extended exposure to UV light during post-curing improves the cross-linking density of the photopolymer resin, thus resulting in a more rigid and robust polymer network[29].

As shown in Figure 5, the top side ((0° orientation) and the side surface (90° orientation) of the specimen exhibit different levels of hardness. Specimens printed at a 0° orientation, with layers parallel to the loading surface, showed greater hardness than those printed at 90°, where layers were perpendicular to the surface during testing. The 0° orientation exhibited a maximum hardness of 57.7 Shore D, approximately 8.45% higher than the 53.2 Shore D measured at 90° orientation. ANOVA further confirmed a significant effect of build orientation (0° vs. 90°) under these specific parameters (layer thickness of 0.05 mm LT with a post-curing time of 30 min), with a calculated F-value (47.09) well above the critical value (5.31). This variation arises from the anisotropic properties inherent in DLP's layer-by-layer process, as interlayer adhesion is typically less robust than bonding within layers[30]. Consequently, the mechanical resistance to surface deformation is greater in specimens with horizontal layer alignment (0°), leading to improved hardness performance. Notably, these findings highlight the critical role of build orientation in optimizing the mechanical properties of DLP-printed components, especially for applications requiring high surface durability. However, it also emphasizes the need for a balance between hardness and other mechanical properties such as toughness and elasticity. Excessive hardness may lead to brittleness, potentially causing cracking or chipping under cyclic loading conditions in oral environments[31].

Moisture Absorption

Figure 6 illustrates the relationship between layer thickness and moisture absorption for specimens subjected to varying post-curing durations. As presented in Figure 6, post-curing time significantly influences the moisture absorption behavior of printed photopolymer resins. The experimental results demonstrated an inverse relationship between post-curing duration and moisture absorption, with extended post curing-treated specimens showing significantly reduced water uptake compared to minimally cured samples. This is confirmed by the ANOVA results, showing that the moisture content of specimens with a 0.05 mm layer thickness was significantly influenced by the post-curing time, as indicated by an F value of 51.91, which greatly exceeded the critical value (F-crit = 5.14). This trend can be attributed to the enhanced polymerization and network density achieved during extended post-curing, which reduces the availability of hydrophilic sites and unreacted monomers that tend to attract and retain water molecules. The crosslinked polymer chains formed during adequate curing provide a more compact and less permeable structure, thereby limiting the diffusion of water into the material[32]. Conversely, insufficient post-curing leads to a higher presence of unpolymerized regions and increased free volume within the matrix[33], facilitating moisture penetration. In this study, the maximum moisture absorption (1.05% MC) was observed in specimens fabricated with a 0.05-mm layer thickness and subjected to 10 minutes of post-curing. By contrast, specimens printed at 0.1 mm layer thickness and post-cured for 30 minutes demonstrated the lowest water uptake at 0.42% MC. Interestingly, our results demonstrate a non-linear relationship between layer thickness and specimen moisture absorption, with no consistent monotonic trend observed across the tested thickness range (0.05, 0.075, and 0.1 mm).

Density

Density is a fundamental physical property that describes the compactness and internal uniformity of a material. Figure 7 presents the density measurements of printed specimens as a function of both layer thickness and post-curing duration. As shown in Figure 7, density measurements remained consistent (1.19 ± 0.02 g/cm³) regardless of processing parameters (layer thickness and post-curing time). No significant trends were observed across the different groups. These results indicate that specimen density is not significantly affected by layer thickness or post-curing time. While curing time plays a more substantial role in enhancing mechanical strength, it does not meaningfully alter the density that is established during the initial printing process.

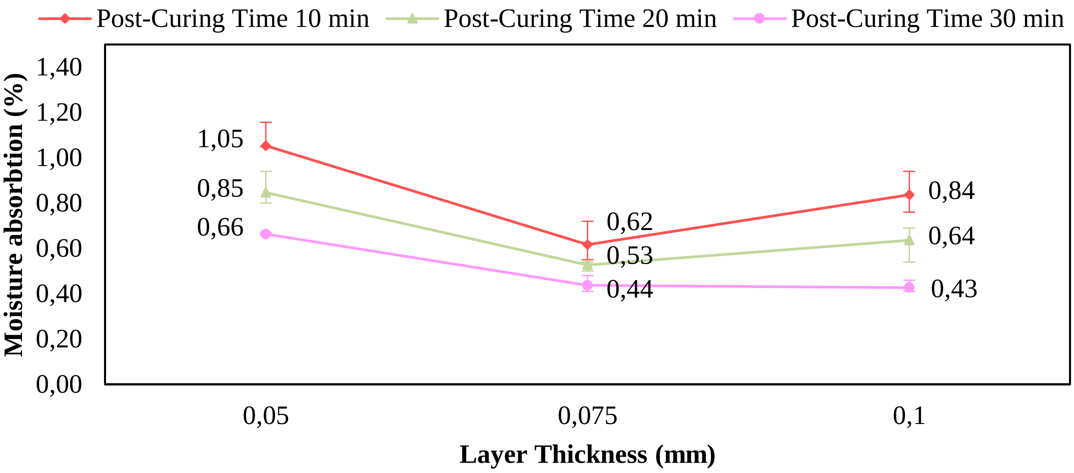


Figure 6. Moisture absorption properties of specimens under varying layer thicknesses and post-curing time treatments

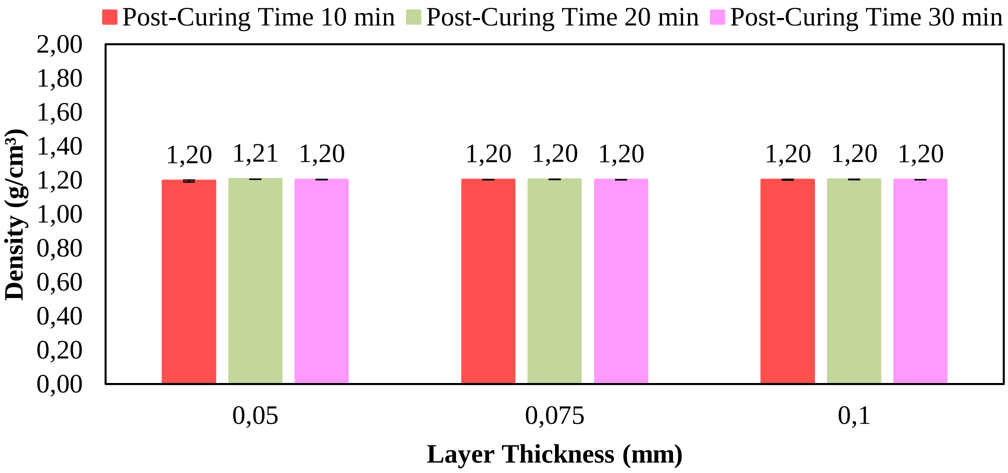


Figure 7. Density of printed specimens under different layer thicknesses and post-curing times

CONCLUSION

In this work, the physical and mechanical behavior of 3D-printed dental photopolymer resins is evaluated. The effects of process parameters, including layer thickness and curing time, on the characteristics (hardness, moisture absorption, and density) of dental photopolymer resin specimens were also analyzed. Based on our findings, we derive the following conclusions:

1. Curing time has a significant effect on the hardness of dental photopolymer resin specimens. The hardness of the specimens tended to increase with longer curing times, indicating that the post-UV curing process plays a significant role in enhancing the cross-linking of resin molecules. Additionally, layer thickness had a limited effect on

hardness, with hardness values tending to decrease as the layer thickness increased. Among all tested conditions, the combination of 0.05 mm layer thickness and 30-minute post-curing yielded the highest hardness (57.7 Shore D). Specimens printed at 0° orientation exhibited significantly higher hardness values than those printed at 90° orientation.

2. The specimen's moisture content showed a significant decrease with increasing curing time, implying that a longer curing process reduces the availability of hydrophilic sites and increases resistance to water penetration. In contrast, variations in layer thickness did not have a significant effect on moisture content. 0.1 mm layer thickness coupled with 30-minute post-curing produced specimens with 0.42% MC, the lowest water uptake recorded.
3. The density of the specimens remained relatively stable (1.19 ± 0.02 g/cm³) across variations in layer thickness and curing time, indicating that density is primarily determined by the intrinsic properties of the photopolymer resin. No significant changes in density were observed as a result of variations in these two parameters.

Future works will investigate the effect of processing parameters on the surface quality of dental photopolymer resin specimens. The findings are expected to contribute to optimizing additively manufacturing processes, improving surface characteristics, and enhancing the clinical performance of dental restorations manufactured using photopolymer resin materials via vat photopolymerization-based 3D printing.

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