



BASIC RESEARCH:

Comparison of the Physical and Mechanical Properties of Additively Manufactured Thermoplastics, 3D-Printed Resin, and Conventional Provisional Restorative Materials Comparación de las propiedades físicas y mecánicas de termoplásticos fabricados mediante fabricación aditiva, resina impresa en 3D y materiales restauradores provisionales convencionales

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Received: 16-IV-2026

Accepted: 12-VII-2026

ABSTRACT: To compare the physical and mechanical properties of a DLP-fabricated 3D-printed provisional resin and FDM-fabricated thermoplastic materials with those of conventional provisional restorative materials. In the additive manufacturing groups, a 3D-printed provisional resin, FDM-fabricated polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) were evaluated. The conventional materials consisted of a bis-acryl provisional composite resin and a polymethyl methacrylate (PMMA) resin. All specimens (n=10 per group) were prepared in accordance with the relevant manufacturers' instructions. Microhardness, water sorption, flexural strength, and elastic modulus were measured at baseline and after 14 days of storage in artificial saliva. Data were analyzed using parametric statistical methods ($p<0.05$). The bis-acryl provisional composite resin showed the highest Vickers microhardness and elastic modulus values, the lowest water sorption, and flexural strength comparable to the 3D-printed provisional resin but significantly higher than PMMA. The 3D-printed provisional resin performed similarly to bis-acryl and PMMA for microhardness and flexural behavior but exhibited higher water sorption. FDM-fabricated PLA and PETG showed lower performance across the evaluated properties ($p<0.05$). The bis-acryl provisional composite resin demonstrated the highest mechanical performance among the tested materials. The three-dimensional printed provisional resin showed properties comparable with polymethyl methacrylate, whereas the fused deposition modeling fabricated polylactic acid and polyethylene terephthalate glycol materials exhibited inferior physical and mechanical properties.

KEYWORDS: Dental materials; Printing; Three-dimensional; Polymethyl methacrylate; Flexural strength; Hardness tests.

RESUMEN: Comparar las propiedades físicas y mecánicas de una resina provisional impresa en 3D fabricada mediante procesamiento digital de luz (DLP) y de materiales termoplásticos fabricados mediante modelado por deposición fundida (FDM) con las de materiales restauradores provisionales convencionales. En los grupos de fabricación aditiva se evaluaron una resina provisional impresa en 3D, ácido poliláctico (PLA) y tereftalato de polietileno modificado con glicol (PETG) fabricados mediante FDM. Los materiales convencionales consistieron en una resina compuesta provisional bisacrílica y una resina de polimetilmetacrilato (PMMA). Todas las muestras (n=10 por grupo) se prepararon de acuerdo con las instrucciones correspondientes de los fabricantes. Se midieron la microdureza, la sorción de agua, la resistencia a la flexión y el módulo elástico al inicio y después de 14 días de almacenamiento en saliva artificial. Los datos se analizaron mediante métodos estadísticos paramétricos ($p < 0,05$). La resina compuesta provisional bisacrílica mostró los valores más altos de microdureza Vickers y módulo elástico, la menor sorción de agua y una resistencia a la flexión comparable a la de la resina provisional impresa en 3D, pero significativamente mayor que la del PMMA. La resina provisional impresa en 3D presentó un comportamiento similar al de la resina bisacrílica y el PMMA en cuanto a microdureza y comportamiento flexural, pero mostró una mayor sorción de agua. El PLA y el PETG fabricados mediante FDM mostraron un menor rendimiento en las propiedades evaluadas ($p < 0,05$). La resina compuesta provisional bisacrílica demostró el mayor rendimiento mecánico entre los materiales evaluados. La resina provisional impresa en 3D mostró propiedades comparables a las del polimetilmetacrilato, mientras que los materiales de ácido poliláctico y tereftalato de polietileno modificado con glicol fabricados mediante modelado por deposición fundida presentaron propiedades físicas y mecánicas inferiores.

PALABRAS CLAVE: Materiales dentales; Impresión; Tridimensional; Polimetilmetacrilato; Resistencia a la flexión; Pruebas de dureza.

INTRODUCTION

The purpose of using temporary restorations is to protect the pulp and periodontium, maintain occlusal and biomechanical functions, and fulfill aesthetic demands during the time required for the application of a permanent restoration on prepared teeth (1,2). Temporary restorations can be fabricated using either direct or indirect techniques. In the direct production technique, the temporary restoration is fabricated directly onto the prepared tooth in the patient's mouth. However, in the

indirect method, the restoration is produced on a dental mold and then transferred to the oral cavity (3). The direct method, while faster, has potential drawbacks, including possible irritation of adjacent tissues due to residual monomers and reported hypersensitivity-type reactions in susceptible individuals (4,5). Most of the disadvantages observed in the direct method are reduced by the indirect production of temporary restorations (3). In line with the pursuit of improved material performance and clinical outcomes, digital technologies have emerged as promising alternatives to traditional methods.

The production of indirect restorations using the computer aided design-computer aided manufacturing (CAD-CAM) method is achieved with an additive or subtractive system. With the development of three-dimensional printing systems, an additive technique, the three-dimensional (3D), rapid, and automatic prototyping of dental materials and restorations has gained increasing attention in the field of dentistry in recent years (6). Recent advances in digital dentistry have increasingly incorporated additive manufacturing techniques (7).

Among additive manufacturing techniques used in dentistry, stereolithography (SLA) and digital light processing (DLP) are commonly used for the fabrication of resin-based dental restorations. While SLA systems polymerize photopolymerizable resin using an ultraviolet laser, DLP systems use a light projector to cure an entire image layer of light-sensitive resin simultaneously (8). SLA, on the other hand, uses an ultraviolet (UV) laser to polymerize photopolymerizable resin and produce high-precision products (9). In addition to resin-based additive manufacturing techniques, fused deposition modeling (FDM) is another 3D printing technology based on the layer-by-layer extrusion of thermoplastic filaments. Unlike SLA and DLP, FDM does not involve photopolymerizable resin; instead, thermoplastic materials are heated, extruded through a nozzle, and deposited sequentially to form the printed object (10,11). The workflow for producing dental restorations using a 3D printer with photopolymerizable dental resin is summarized as printing, post-washing, and post-curing processes (12). After printing, a final wash is typically performed to remove residual uncured resin from the surface (13).

Two thermoplastic materials commonly used in 3D printers with FDM technology are polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) (14). PLA has been investigated as

a biomaterial for tissue engineering and implant-related applications, whereas PETG has been used in orthodontic thermoplastic applications such as aligners (15,16). PLA has a low glass transition temperature and melting point, which results in lower thermal stability. Another disadvantage is that it is more sensitive to degradation caused by moisture and certain chemicals. However, PLA is a biodegradable material and is environmentally friendly. PETG possesses superior thermal stability, higher chemical resistance, and greater impact resistance compared to PLA, making it more durable, but it is not biodegradable (17). Both 3D-printable materials possess physical properties that make them potentially suitable for certain dental procedures (18). Although PLA is not specifically indicated as a provisional restorative material, its potential use for interim prosthetic applications has been investigated in limited experimental studies. Therefore, PLA was included in the present study as an exploratory FDM-fabricated thermoplastic material rather than as a clinically established provisional restorative material (19,20).

The aim of this study was to compare the physical and mechanical properties, including microhardness, flexural strength, elastic modulus, and water sorption, of additively manufactured thermoplastics and a 3D-printed provisional resin with those of conventional provisional restorative materials. Based on the available scientific background and previous literature, the research hypothesis of the present study was that the type of provisional restorative material and fabrication method would significantly affect the microhardness, water sorption, flexural strength, and elastic modulus of the tested materials.

MATERIALS AND METHODS

In this study, DLP-fabricated provisional resin, FDM-processed thermoplastics, and provi-

sional materials produced using conventional techniques were examined under a single experimental protocol. The materials and manufacturing methods evaluated in this study are summarized in Table 1. The minimum sample size was estimated a priori using a power analysis for one-way ANOVA (G*Power 3.1; Universität Düsseldorf,

Düsseldorf, Germany). Assuming an effect size of $f=0.65$, $\alpha=0.05$, and a power ($1-\beta$) of 0.95, the analysis indicated that 10 specimens per group would be sufficient ($n=10$). This sample size was also deemed adequate in light of the specimen numbers used in recent studies with comparable experimental designs (21,22).

Table 1. Materials used in the study.

Material (generic name)	Composition	Production Methods	Manufacturer	LOT Number
3D-printed provisional resin	3D Printing Polymer Resin N/A	Additive Manufacturing (DLP)	ArmaResin Arma Dental, Gebze, Kocaeli, Turkey	41400 TMP-A2-MM-0033
Bis-acryl composite	Base: 10-Ethoxylated Bisphenol A Dimethacrylate, Triethylene Glycol Dimethacrylate, Fillers, Titanium dioxide Catalyst: Ethoxylated Bisphenol A Dimethacrylate, Triethylene Glycol Dimethacrylate, Fillers, Accelerator and Pigments	Conventional (Automix)	Oratemp C&B, Prevest Denpro Limited, Jammu City, India	PK232421BB
Polymethyl methacrylate	Chemically Polymerized Polymethylmethacrylate (PMMA), 0.8% residual monomer	Conventional (Liquid/Powder)	Temdent Classic Schütz-Dental, Germany	2022000743
Polyethylene terephthalate glycol	Polyethylene Terephthalate Glycol	Additive Manufacturing (FDM)	PETG Creality, Shenzhen, China	1C424500276
Polylactic acid	Polylactic Acid	Additive Manufacturing (FDM)	PLA Basic, Bambu Lab, Austin, TX, USA	4A7CD7AF00000100

PRODUCTION OF SPECIMENS

3D-printed provisional resin: A CAD software (Tinkercad, Autodesk, Montreal, QC, Canada) was used to design the specimens to be fabricated from a 3D-printed provisional resin (ArmaResin Temp, A2; Arma Dental, Gebze, Turkey; lot: 41400 TMP-A2-MM-0033 using an additive manufacturing technique. Rectangular prism-shaped specimens with dimensions of 2x2x25 mm were designed

for the flexural strength tests, and specimens with dimensions of 2x15x15 mm were designed for the Vickers microhardness and water sorption measurements. All designs were exported in STL format. The specimens were printed using a dental DLP printer (Straumann P series Rapid Shape, Institut Straumann, Basel, Switzerland) with layer thickness of 50 μm . During specimen fabrication, the recommended printing parameters for the corresponding resin were defined in the printer

software. All specimens were printed in the same orientation, with their long axis parallel to the build platform, and no support structures were used.

For the flexural strength and elastic modulus measurements, 20 specimens were fabricated for ArmaResin; 10 specimens were tested after 24 h of storage, and a separate set of 10 specimens was tested after artificial saliva storage. For the Vickers microhardness and water sorption measurements, 10 specimens were fabricated; baseline and post-storage measurements were performed on the same specimens. After printing, the specimens were removed from the build platform and cleaned in an ultrasonic bath (Straumann P Wash, Straumann, Basel, Switzerland) containing 96% isopropyl alcohol at room temperature for 3+3 min. The specimens were then dried with compressed air and visually inspected to ensure that no uncured resin remained on the surfaces. A post-curing procedure was subsequently performed in a Straumann P cure device (Institut Straumann, Basel, Switzerland) for 4 min according to the manufacturer's instructions. After post-curing, all specimens were stored in distilled water at room temperature for 24 h before baseline measurements. The base edges of all 3D-printed specimens were carefully finished using silicon carbide abrasive papers (600 and 1200 grit) under running water to remove any residual flash or overhangs. The final dimensions of the specimens were verified using a digital caliper (Digimatic Caliper, Mitutoyo, Tokyo, Japan), and all values were confirmed to be within ± 0.1 mm of the nominal dimensions.

Bis-acryl composite: Bis-acryl composite provisional resin (OraTemp C&B, Prevest Denpro, Jammu City, India) was used to prepare samples using metal molds with negative spaces of 2x2x25 millimeter (20 pieces) and 15x15x2 millimeter (10 pieces). After the molds were positioned and stabilized on a glass plate, the cavities were gently filled with the bis-acryl composite to avoid air entrapment. Then, a new glass slab was placed

on top, and the curing reaction was allowed to complete for 2 minutes and 30 seconds according to the manufacturer's instructions. After the hardened specimens were removed from the molds, the excess flash was trimmed, and their dimensions were checked with a digital caliper. Specimens exhibiting air entrapment, porosity, or dimensional deviations were discarded and replaced to achieve the required sample size.

Polymethyl methacrylate (PMMA): Polymethyl methacrylate (PMMA) (Temdent Classic, Schütz-Dental, Germany) specimens were prepared using metal molds with negative cavities of 2x2x25 millimeters and 15x15x2 millimeters. Following the manufacturer's instructions, the powder and liquid were mixed in the specified ratios. Once the resulting mixture reached the appropriate consistency, it was placed into the metal molds, which had previously been stabilized on a glass plate, and the cavities were filled carefully to avoid air entrapment before placing another glass slab on top. The material was allowed to polymerize for 6 minutes according to the manufacturer's instructions. After removal from the molds, the specimens were allowed to complete the final curing reaction for an additional 2 minutes. Then, the excess flash was trimmed, and the dimensions were verified using a digital caliper. Specimens exhibiting air entrapment, porosity, or dimensional deviations were discarded and replaced to achieve the required sample size.

Polylactic Acid (PLA) and Polyethylene Terephthalate Glycol (PETG): CAD software (Tinkercad, Autodesk, Montreal, QC, Canada) was used to design specimens made from the thermoplastic polymers PLA (Bambu Lab, Austin, TX, USA) and PETG (Creality, Shenzhen, China). For the flexural strength tests, rectangular prism-shaped specimens with dimensions of 2x2x25 millimeters were designed. For the Vickers microhardness and water sorption measurements, rectangular prism-shaped specimens with dimensions of 2x15x15 millimeters were designed. The resulting designs were

printed using a Bambu Lab X1 Carbon 3D printer (Bambu Lab, Austin, TX, USA), which uses fused deposition modeling (FDM). The printing parameters used for PLA and PETG are summarized in Table 2.

Table 2. Manufacturing parameters for polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) materials.

Process parameter	PLA values	PETG values
Nozzle temperature	200°C	255°C
Bed temperature	60°C	70°C
Printing speed	60 mm/s	55 mm/s
Infill density	100 %	100 %
Layer height	0.16 mm	0.14 mm
Raster angle	0°	0°

MEASUREMENT OF VICKERS MICROHARDNESS VALUES

A ZwickRoell ZHV10 Vickers hardness tester (Zwick-Roell ZHV10 hardness tester Kennesaw, GA, USA) was used to measure the microhardness values. Prior to microhardness testing, the measurement surfaces were standardized by wet grinding with silicon carbide abrasive papers (600 and 1200 grit) under running water; each grit was applied for 30 s. Specimens were then rinsed with distilled water and air-dried. Three indentations were made on each specimen under a load of 300 g with a dwell time of 10 s (23). To minimize the interaction between the traces, a 500 micrometer (µm) gap was left between them. The three indentation values were averaged to obtain a single specimen-level HV value, which was used for statistical analysis. Later, the specimens removed from the hardness device were examined under 10x magnification (Olympus BX41M-LED, Japan) and the images were transferred to digital media and recorded (Olympus SC30, Japan). These images were transferred to the Image J software (Image J1.41, Wayne Rasband, National Institutes

of Health, Bethesda, MD, USA). Prior to measurements, the pixel-to-micrometer scale was spatially calibrated using an image of a standardized stage micrometer (calibration slide) captured under the exact same 10x optical magnification. This calibration was applied to the software's Set Scale function to ensure accurate length conversion. After the necessary optimizations were made, the indentation diagonals were measured in micrometers. The measurements were converted to Vickers microhardness (HV) values using a program defined in the Excel application using the formula

$$HV = 0.1891 \frac{F}{d^2}, d = \frac{d_1 + d_2}{2},$$

(Vickers hardness test procedure to ISO 6507, ASTM E384). To simulate the oral environment, the specimens were kept in artificial saliva in an airtight container at 37 degrees Celsius for 14 days (Professional Dietetics, Italy). Although distilled water accelerates hydrolytic degradation, artificial saliva was selected to more closely simulate the complex ionic composition and intraoral chemical environment that provisional restorations encounter during clinical service (24). Following this storage, the Vickers hardness value measurements were repeated.

MEASUREMENT OF WATER SORPTION VALUES

The weight of the specimens was measured and recorded in grams using a precision digital scale (Denver Instrument TB-224, Germany). The specimens were then subjected to 14-day artificial saliva storage at 37°C in a closed container, using 10 mL of artificial saliva per specimen (total volume adjusted according to the number of specimens). The specimens were placed with sufficient spacing to minimize specimen-to-specimen contact during storage. The artificial saliva solution was renewed weekly (every 7 days). At the end of the 14 days, the specimens were cleaned with distilled water and dried using a compressed air

spray, and the weight measurement process was repeated. The weight increase values after storage were converted to micrograms (μg) and divided by the specimen volume, and water sorption values were recorded as micrograms per cubic millimeter ($\mu\text{g}/\text{mm}^3$). This simplified fluid uptake protocol was applied to measure the net mass variation of the materials, simulating clinical net fluid retention without the initial extreme desiccation cycles described in the ISO 4049 standard. This direct fluid uptake approach without prior prolonged dehydration is recognized to more accurately reflect the immediate clinical exposure of provisional restorations (25).

MEASUREMENT OF FLEXURAL STRENGTH AND ELASTIC MODULUS VALUES

Following the International Organization for Standardization (ISO) standard 10477:2004, 20 test bars of each material were produced with dimensions of 25×2×2 millimeter (mm). Ten specimens of each material were subjected to a bending strength test initially and 10 others underwent the same test after 14 days storage in artificial saliva. A three-point bending strength test was conducted using a universal testing machine (Shimadzu AG-IS, Shimadzu, Japan). The force was applied to the center of the materials. The test was conducted using a 5000 newtons (N) load, a speed of 1 millimeter per minute (mm/min), and a support distance of 20 millimeter (ISO 10477). Each specimen was tested until it broke or reached the maximum curvature allowed by the flexural strength device. To calculate the flexural strength, the formula σ (1) was used, and to calculate the elastic modulus, the formula E (2) was used. The flexural strength values were recorded in Megapascals (MPa), and the elastic modulus values were recorded in Gigapascals (GPa). Here,

F is the applied maximum load (N), l is the distance between the supports (mm), b is the width, h is the height of the specimen (mm), and d is the deflection amount corresponding to F (mm).

$$\sigma = \frac{3Fl}{2bh^2} \quad (1)$$

$$E = \frac{Fl^3}{4bh^3d} \quad (2)$$

During three-point bending, the PLA and PETG specimens did not fracture within the pre-defined endpoint/displacement limits of the testing device and continued to bend until test termination. Therefore, a distinct failure point could not be identified under the present experimental setup, and flexural strength and elastic modulus could not be calculated for these materials. Accordingly, PLA and PETG were excluded from the flexural strength and elastic modulus statistical analyses.

All statistical analyses were performed using IBM SPSS Statistics, Version 27.0 (IBM Corp., Armonk, NY, USA). The Shapiro-Wilk test was used to assess the normality of the data, and Levene's test was used to evaluate the homogeneity of variances. Continuous variables are presented as mean $\pm$ standard deviation. The level of statistical significance was set at $p < 0.05$.

The statistical analysis was performed separately for each tested property according to the experimental design and measurement structure. For Vickers microhardness, a two-way mixed analysis of variance (ANOVA) was used, with material as the between-subject factor and storage time as the within-subject factor, because the same specimens were measured before and after artifi-

cial saliva storage. When appropriate, pairwise comparisons were performed to evaluate differences among materials and changes after storage.

For water sorption, one-way ANOVA was used to compare the materials, because water sorption was calculated only after the storage period and storage time was not included as a factor. Tukey's post hoc test was used for multiple comparisons among materials.

For flexural strength and elastic modulus, two-way ANOVA was performed with material and storage time as independent factors, because separate specimens were tested at baseline and after 14 days of artificial saliva storage. The material $\times$ storage time interaction was also evaluated. Since PLA and PETG specimens did not exhibit a distinct fracture under the present testing conditions, flexural strength and elastic modulus values could not be calculated for these materials; therefore, they were excluded from the corresponding two-way ANOVA analyses. When significant main effects or interactions were detected, Tukey's post hoc test and pairwise comparisons were used where appropriate.

RESULTS

The data obtained during the study are presented in Table 3.

Vickers microhardness values differed significantly among the tested materials both before and after artificial saliva storage. Before storage, the highest Vickers microhardness value was observed for the bis-acryl composite provisional resin (43.53 ± 5.60), which was significantly higher than those of all other materials ($p < 0.001$). The 3D-printed provisional resin (20.95 ± 0.49) and PMMA (18.80 ± 1.04) showed similar microhardness values ($p = 0.356$), and both materials exhibited significantly higher values than PLA (12.66 ± 0.62) and PETG (12.03 ± 0.55) ($p < 0.001$). No signifi-

cant difference was observed between PLA and PETG ($p = 0.982$). After 14 days of artificial saliva storage, Vickers microhardness values decreased significantly in all tested materials, with the specific within-material p values presented in Table 3.

Water sorption differed significantly among the tested materials ($p < 0.001$). The highest water sorption value was observed for PLA ($18.71 \pm 5.09 \mu\text{g}/\text{mm}^3$), and this value was significantly higher than those of the other materials. The 3D-printed provisional resin ($11.02 \pm 0.26 \mu\text{g}/\text{mm}^3$) showed significantly lower water sorption than PMMA ($14.66 \pm 0.52 \mu\text{g}/\text{mm}^3$) ($p = 0.044$). The lowest water sorption was observed for the bis-acryl composite provisional resin ($3.40 \pm 0.33 \mu\text{g}/\text{mm}^3$), followed by PETG ($7.42 \pm 3.61 \mu\text{g}/\text{mm}^3$). Based on mean values, water sorption followed the order PLA > PMMA > 3D-printed provisional resin > PETG > bis-acryl composite provisional resin.

For flexural strength, two-way ANOVA revealed a significant effect of material ($p < 0.001$) and a significant material $\times$ storage time interaction ($p = 0.007$), whereas the main effect of storage time was not significant ($p = 0.601$). Overall, the bis-acryl composite provisional resin showed the highest flexural strength values, followed by the 3D-printed provisional resin and PMMA. At baseline, no significant difference was observed between the bis-acryl composite provisional resin ($125.80 \pm 15.42 \text{ MPa}$) and the 3D-printed provisional resin ($119.22 \pm 20.66 \text{ MPa}$) ($p = 0.645$), and both materials showed significantly higher flexural strength values than PMMA ($85.42 \pm 11.70 \text{ MPa}$) ($p < 0.001$). After 14 days of artificial saliva storage, the flexural strength of the bis-acryl composite provisional resin increased, whereas PMMA showed a decrease and the 3D-printed provisional resin showed only a minor change. Pairwise comparisons showed no significant change in flexural strength after storage for the 3D-printed provisional resin ($p = 0.700$) or PMMA ($p = 0.058$), whereas a significant increase was

observed for the bis-acryl composite provisional resin ($p=0.016$) (Figure 1).

For elastic modulus, two-way ANOVA showed a significant effect of material ($p<0.001$), whereas the main effect of storage time ($p=0.509$) and the material $\times$ storage time interaction ($p=0.874$) were not significant. The bis-acryl composite provisional

resin showed significantly higher elastic modulus values than both the 3D-printed provisional resin and PMMA ($p<0.001$). No significant difference was observed between the 3D-printed provisional resin and PMMA ($p=0.806$). These findings indicate that elastic modulus was mainly affected by material type, while 14 days of artificial saliva storage did not significantly affect elastic modulus values.

Table 3. Mechanical and physical properties of the tested provisional restorative materials before and after artificial saliva storage.

Material	Before storage	After storage	Within-material p value
Vickers microhardness (VHN)			
3D-printed provisional resin	20.95 $\pm$ 0.49b	19.81 $\pm$ 0.44b	<0.001
Polymethyl methacrylate	18.80 $\pm$ 1.05b	16.77 $\pm$ 0.70c	<0.001
Bis-acryl composite	43.53 $\pm$ 5.60a	38.12 $\pm$ 3.37a	0.002
Polylactic acid (PLA)	12.66 $\pm$ 0.62c	11.41 $\pm$ 0.36d	<0.001
Polyethylene terephthalate glycol (PETG)	12.03 $\pm$ 0.55c	11.63 $\pm$ 0.50d	0.028
Water sorption ($\mu\text{g}/\text{mm}^3$)			
3D-printed provisional resin	—	11.02 $\pm$ 0.26c	—
Polymethyl methacrylate	—	14.66 $\pm$ 0.52b	—
Bis-acryl composite	—	3.40 $\pm$ 0.33e	—
Polylactic acid (PLA)	—	18.71 $\pm$ 5.09a	—
Polyethylene terephthalate glycol (PETG)	—	7.42 $\pm$ 3.61d	—
Flexural strength (MPa)			
3D-printed provisional resin	119.22 $\pm$ 20.66a	116.47 $\pm$ 8.05b	0.700
Polymethyl methacrylate	85.42 $\pm$ 11.70b	75.05 $\pm$ 11.20c	0.058
Bis-acryl composite	125.80 $\pm$ 15.42a	144.84 $\pm$ 16.65a	0.016
Polylactic acid (PLA)	Not determined	Not determined	—
Polyethylene terephthalate glycol (PETG)	Not determined	Not determined	—
Elastic modulus (GPa)			
3D-printed provisional resin	1.97 $\pm$ 0.30b	1.79 $\pm$ 0.24b	—
Polymethyl methacrylate	2.01 $\pm$ 0.26b	2.02 $\pm$ 0.41b	—
Bis-acryl composite	4.76 $\pm$ 0.95a	4.58 $\pm$ 1.18a	—
Polylactic acid (PLA)	Not determined	Not determined	—
Polyethylene terephthalate glycol (PETG)	Not determined	Not determined	—

Note. Values are presented as mean $\pm$ standard deviation. Different superscript lowercase letters within the same property and storage column indicate statistically significant differences among materials ($p<0.05$). The within-material p values are reported only for variables for which storage-related pairwise comparisons were interpreted. Water sorption was calculated only after artificial saliva storage; therefore, storage time was not included as a factor. For flexural strength, two-way ANOVA showed a significant material effect ($p<0.001$) and a significant material $\times$ storage time interaction ($p=0.007$), whereas the main effect of storage time was not significant ($p=0.601$). For elastic modulus, two-way ANOVA showed a significant material effect ($p<0.001$), whereas storage time ($p=0.509$) and the material $\times$ storage time interaction ($p=0.874$) were not significant; therefore, within-material p values are not reported. Flexural strength and elastic modulus values for PLA and PETG could not be calculated because these specimens did not exhibit a distinct fracture point within the predefined testing limits.

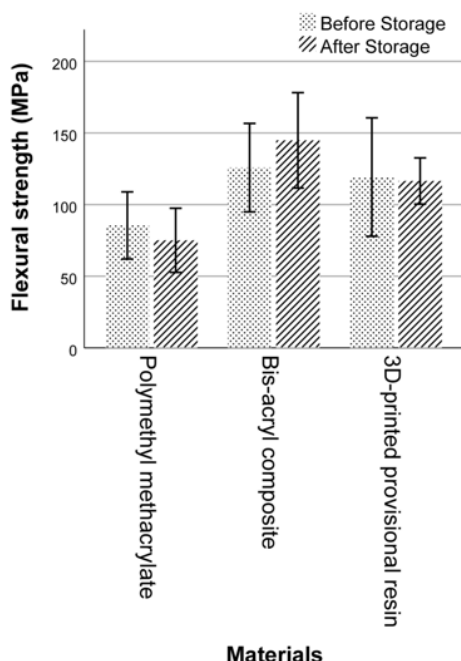


Figure 1. Flexural strength values of the tested materials before and after storage in artificial saliva.

DISCUSSION

The results of the present study demonstrated significant differences among the tested materials with respect to microhardness, flexural strength, elastic modulus, and water sorption. These findings support the research hypothesis that the type of provisional restorative material and fabrication method significantly influence these properties. The increasing use of 3D printing technology (additive manufacturing) in dental practice is becoming more apparent over time (6,7). This trend has directly influenced the development of temporary dental restorations. In this study, temporary restorations produced using additive manufacturing were compared with conventionally used temporary restorative materials. The flexural strength, elastic modulus, microhardness, and water sorption of the tested materials were evaluated as parameters associated with potential clinical performance and service longevity (26-28). In this framework, the mechanical and physical properties were assessed using standardized test setups, with the aim

of presenting fabrication method-related differences in material behavior in a clinically interpretable and comparable manner.

Temporary restoration materials require sufficient surface hardness in relation to wear, dimensional change, the stability of occlusion, and the ability to maintain the restoration in the mouth for the required duration (26,29,30). The control group consisted of Bis-acryl composite provisional resin and PMMA self-curing resins. Bis-acryl provisional composite resins typically contain multifunctional dimethacrylate monomers (Bis-GMA or TEGDMA), which contribute to improved mechanical performance (31). Conventional PMMA-based provisional resins are chemically polymerized and primarily composed of monofunctional methyl methacrylate monomers, resulting in a less cross-linked polymer network compared with bis-acryl composite resins (32). Consistent with this, the microhardness values of Bis-acryl provisional composite resin were significantly higher than those of PMMA. 3D-printed provisional resin and PMMA showed similar microhardness values. Dental resins fabricated using additive manufacturing reduce disadvantages associated with PMMA, such as the formation of air bubbles or porosity during manual or automatic mixing as reported in the literature (33). These findings indicate that the 3D-printed provisional resin showed microhardness comparable to PMMA under the tested conditions (34,35). PLA and PETG showed significantly lower microhardness values compared with the control materials. A significant decrease in hardness was observed in all tested materials after 14-day artificial saliva storage. Nevertheless, the control materials and the 3D-printed provisional resin maintained higher microhardness values than PLA and PETG after storage under the present *in vitro* conditions.

Temporary restoration materials are exposed to saliva for the duration they remain in the mouth. During this process, the sorption of water and

saliva by the material causes dimensional changes, discoloration, reduced retention, and edge fractures. With the formation of a gap between the tooth and the restoration, food retention, caries, and periodontal concerns arise in the affected tooth (24). Accordingly, temporary restoration materials produced using additive manufacturing were evaluated for water sorption behavior. The results showed that the bis-acryl provisional composite resin exhibited the lowest water sorption, and the 3D-printed provisional resin exhibited significantly lower water sorption than PMMA. PLA and PETG, which were fabricated using the FDM technique, showed divergent water sorption behavior. While PLA exhibited the highest water sorption among all tested materials, PETG demonstrated relatively low water sorption, being lower than PMMA and the 3D-printed provisional resin and exceeded only by the bis-acryl provisional composite resin. Under the tested conditions, these findings suggest that PETG be more suitable than PLA when low water sorption is prioritized for temporary applications.

The flexural strength and elastic moduli of temporary restorations obtained through additive manufacturing technology are important for evaluating the structural integrity and suitability of restorations (28). Samples fabricated from the 3D-printed provisional resin exhibited flexural strength values comparable to those of the bis-acryl provisional composite resin and significantly higher than those of PMMA. The values for 3D-printed provisional resin and Bis-acryl provisional composite resin were significantly higher than those of PMMA. After the specimens were subjected to a 14-day artificial saliva storage, no significant change was observed in the flexural strength of the 3D-printed provisional resin and PMMA-containing material, but a significant increase was seen in the flexural strength of the Bis-acryl provisional composite resin. Notably, all materials for which flexural testing was performed met or exceeded the minimum flexural strength requirement of 50 MPa specified in ISO 10477, both at baseline and after artificial saliva

storage (36). The elastic modulus values of Bis-acryl provisional composite resin were significantly higher than those of the other materials. In addition, the elastic modulus values of the 3D-printed provisional resin showed similar properties to PMMA. The 3D-printed provisional resin showed flexural strength and elastic modulus values comparable to those of the bis-acryl provisional composite resin and PMMA under the tested conditions.

In the present study, PLA and PETG were included as exploratory FDM-fabricated thermoplastic groups rather than as clinically established provisional restorative materials. This approach allowed their physical and mechanical behavior to be compared with that of conventional provisional materials under a standardized experimental protocol. Among the additive manufacturing techniques used in dentistry, DLP is one of the most commonly applied methods (10,11). In addition, recent studies have explored the use of FDM technology for the experimental fabrication of temporary restorations (20,37). One study comparing the accuracy and precision of models produced using DLP and FDM reported that DLP exhibited greater shrinkage and distortion than FDM (38). These findings suggest that FDM offered certain advantages in dimensional stability, which motivated its inclusion for comparative evaluation in the present study. Positive data related to FDM technology allowed the inclusion of two materials produced with this technology in the study, PLA and PETG, with the latter showing lower water sorption values than PMMA and 3D-printed provisional resin. However, under the evaluated conditions, PLA and PETG showed less favorable outcomes than the conventionally used temporary restorative materials.

This study was conducted under *in vitro* conditions; therefore, the laboratory setting cannot fully replicate the oral environment. Mechanical loading was applied at a 90° angle, whereas intraoral forces act in different directions, magnitudes,

and patterns. In addition, some FDM-fabricated thermoplastic specimens did not exhibit a distinct fracture within the limits of the present experimental setup, precluding failure-based calculations and their inclusion in the corresponding statistical analyses. Furthermore, water sorption was evaluated using a simplified net fluid uptake protocol rather than the strict ISO 4049 desiccation method. Therefore, the reported values represent net mass variation and do not account for the simultaneous solubility or leaching of unreacted monomers. The outcomes were also influenced by manufacturing and process related parameters (e.g., printing orientation, layer thickness, printer type and calibration, batch variability, and post-processing procedures such as washing, post-curing for photopolymer resins or extrusion temperature, raster pattern for FDM), and variations in these factors yielded different results than those observed under the present standardized conditions. Because both material type and manufacturing method differed between groups, the comparisons reflect the combined effect of the tested products and fabrication workflows rather than isolating the effect of manufacturing method alone; accordingly, the findings primarily represent the performance of the specific commercially available materials tested under the present manufacturing and aging conditions and were not generalized to the corresponding polymer classes. Therefore, the results were interpreted within these limitations, and further studies using alternative manufacturing settings and clinically relevant aging and loading protocols are warranted.

CONCLUSIONS

Within the limitations of this *in vitro* study, the research hypothesis was partially supported. The tested provisional restorative materials showed significant differences in Vickers microhardness, water sorption, flexural strength, and elastic modulus; however, not all pairwise comparisons among materials were significant, and the

effect of artificial saliva storage was not significant for all tested properties.

The bis-acryl provisional composite resin showed the highest Vickers microhardness and elastic modulus values and the lowest water sorption. Its flexural strength was comparable to that of the 3D-printed provisional resin and significantly higher than that of PMMA.

The 3D-printed provisional resin showed Vickers microhardness and elastic modulus values comparable to PMMA and lower water sorption than PMMA, while maintaining flexural strength comparable to the bis-acryl provisional composite resin under the tested conditions.

The FDM-fabricated PLA and PETG materials showed lower microhardness values than the conventional provisional materials and the 3D-printed provisional resin. PLA showed the highest water sorption, whereas PETG showed relatively low water sorption. Because PLA and PETG did not exhibit a distinct fracture point within the predefined testing limits, their flexural strength and elastic modulus values could not be calculated.

CONFLICT OF INTEREST: The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE: The authors declare that this study has received no financial support.

AUTHOR CONTRIBUTION STATEMENT: Conceptualization and Design: M.C.A., E.S., S.T. and N.T.; Literature Review: S.T. and M. D.; Methodology and Validation: M.C.A., E.S. and M. D.; Formal Analysis: M.C.A. and E.S.; Investigation and Data Collection: M.C.A. and E.S.; Resources: S.T., N.T. and M. D.; Data Analysis and Interpretation: M.C.A., E.S., S.T., M. D. and N.T.; Writing - Original Draft Preparation: M.C.A. and E.S.; Writing - Review & Editing: M.C.A., E.S., S.T., M. D. and N.T.; Supervision: M. D., N.T. and S.T.

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