Original papers

Evaluation of optical and mechanical properties of crown materials produced by 3D printing

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Abstract

Background. The various advantages of crown materials produced using three-dimensional (3D) printers have increased their use in restorative and prosthetic dentistry in recent years. Accordingly, their optical and mechanical properties have become more important.

Objectives. To evaluate the mechanical, surface and optical properties of crown materials produced with 3D printing and computer-aided design (CAD)/computer-aided manufacturing (CAM), which has recently been used frequently in the clinic.

Materials and methods. The 3-point bending test was used to evaluate the mechanical properties of 2 different crown materials produced with 3D printing (Permanent Crown and VarseoSmile Crown Plus) and a crown material produced using CAD/CAM (Vita Enamic). After the initial color and surface roughness measurements were made, the specimens were immersed in 4 different solutions.

Results. The most translucent material was VarseoSmile Crown Plus ($p < 0.05$). In all specimens, coffee caused the most discoloration ($p < 0.05$). The effects of the solutions on the roughness were mostly observed in Permanent Crown specimens ($p < 0.05$). Vita Enamic showed the highest statistically significant values in terms of flexural strength ($p < 0.05$).

Conclusions. The stereolithographic technique among the materials produced by 3D printing can be recommended for use in restorations due to its higher flexural strength.

Key words: roughness, 3-point bending test, color, CAD/CAM, 3-dimensional printing

Background

Currently, the use of computer-animated design (CAD)/computer-aided manufacturing (CAM) devices is becoming increasingly widespread clinically in dental technology. Computer-animated design/CAM blocks have revolutionized the construction of indirect restorations, resulting in industrially manufacturable, high-performance materials.[1] Initially, ceramics were the only material option for making a CAD/CAM restoration. However, today, in addition to various dental ceramics, temporary and permanent restorations can also be fabricated using resin composite materials with CAD/CAM technology.[2]

Resin composite block materials for dental CAD/CAM applications are produced by compressing and polymerizing a filler material and a monomer. The mechanical properties of the new resin composite blocks, such as flexural strength, have been improved compared to conventional resin composite blocks.[3]

Current CAD/CAM resin composite materials are available for subtractive manufacturing procedures with a CAD/CAM milling machine, mostly in the form of industrially homogeneously produced blocks. These blocks have been shown to have superior properties compared to direct resin composite materials. These materials are used for permanent single restorations. Resin composite-based CAD/CAM materials consist of a resin composite polymer matrix and embedded ceramic-based filler particles.[4] Computer-animated design/CAM technologies, as well as rapid prototyping techniques (additive manufacturing and 3-dimensional (3D) printing), have a wide range of applications in many areas of dentistry. One of the most frequently employed areas of these systems is prosthetic applications. Currently, 3D printers play an effective role in facilitating and shortening the challenging clinical phases in prosthodontic applications and constitute an important part of the digital workflow.[5] Unlike conventional manufacturing, 3D printers offer faster and more cost-effective production. 3D printers have been successful in the production of temporary crown bridge prostheses. However, recently, manufacturers have launched products produced with 3D printers as permanent crown material.

Physical and mechanical properties play a major role in the long-term clinical success of restorative materials used in dentistry. However, the aesthetic success of a restoration depends on its capacity to mimic the appearance of natural teeth – in other words, its optical properties. The color of natural teeth is due to a combination of the optical properties of enamel and dentin. Due to the complex optical properties of natural teeth affecting their color, such as light reflection, diffusion, absorption, and light transmission, it is very difficult to achieve aesthetic restorations. Many studies have examined the optical scattering properties of newly developed aesthetic materials, such as color, opalescence, hue angle, color saturation (chroma), surface gloss, and light transmittance.[6,7] However, the number of studies evaluating the color stability of 3D printer-fabricated restorations remains limited.

Objectives

There are only a few studies[8–10] that evaluate the mechanical and optical properties of newly released crown materials produced with 3D printers, and the crown material has been on the market for a long time. Expected results from this study will be used to compare the 3D printer production method with CAD/CAM production in terms of mechanical and optical properties. Moreover, to ensure that the clinical success of the restoration is increased, its life is extended and costs resulting from repetitive restorations are avoided, we will identify the material that has ideal properties according to the results of the study. This study aimed to evaluate the mechanical, surface and optical properties of crown materials produced using 3D printers, which have recently started to be used frequently in clinics due to their significant advantages, such as advanced chemical and mechanical properties and ease of application. The null hypothesis of the study was that staining solutions would not cause any change in any optical and surface properties of the materials and that there is no difference between the materials in terms of optical, surface and mechanical properties.

Materials and methods

Sample size calculations were performed using the package program G*Power (v. 3.1.9.6.; Franz Faul, Kiel University, Germany). Based on a 40% effect size, 80% power, 5% tolerance, and 25% possible data loss, each group comprised 14 specimens (n = 14).

This study evaluated the mechanical, surface and optical properties of 2 different crown materials produced with a 3D printer (Permanent Crown (PC) and VarseoSmile Crown Plus (VSCP)), and a crown material produced using CAD/CAM (Vita Enamic (VE)) (Table 1, Fig. 1,2).

Surface roughness and color stability tests

To evaluate the optical and surface properties of the materials, disc-shaped specimens (n = 14) with a diameter of 5 mm and a thickness of 2 mm were prepared from all 3 materials. Color stability measurements were performed using a spectrophotometer (Vita Easyshade V Spectrophotometer; Vita Zahnfabrik, Bad Sackingen, Germany) to evaluate the optical properties of the materials. To evaluate the surface roughness of the materials, a profilometer (Surftest SJ-301-Mitutoyo; Mitutoyo, Kawasaki, Japan) was used; an area of 100×100 μm^2 was determined and surface roughness values were measured

Table 1. Properties of the materials used in this study

Material	Contents	Translucency/ color	Manufacturer
Vita Enamic	hybrid ceramic porous structure – sintered ceramic matrix infiltrated with polymer material inorganic ceramic 86% by weight: Fine feldspar ceramic enriched with aluminum oxide (58–63% silicon dioxide, 20–23% aluminum oxide, 9–11% sodium oxide, 4–6% potassium oxide, 0.5–2% boron trioxide), zirconia <1%, calcium oxide <1% organic polymer 14% by weight (urethane dimethacrylate, triethylene glycol dimethacrylate)	T/A1	Vita Zahnfabrik, Bad Sackingen, Germany
Permanent Crown	polymethylmethacrylate esterification products of 4,4′-isopropylphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6 trimethyl benzoyl) phosphine oxide; 30–50% by weight of inorganic filler (particle size 0.7 µm).	T/A1	Formlabs, Somerville, USA
VarseoSmile Crown Plus	hybrid ceramic esterification products of 4,40 isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6 trimethyl-benzoyl) phosphine oxide; 30–50% total filler by weight.	T/A1	BEGO, Bremen, Germany

T – translucent.

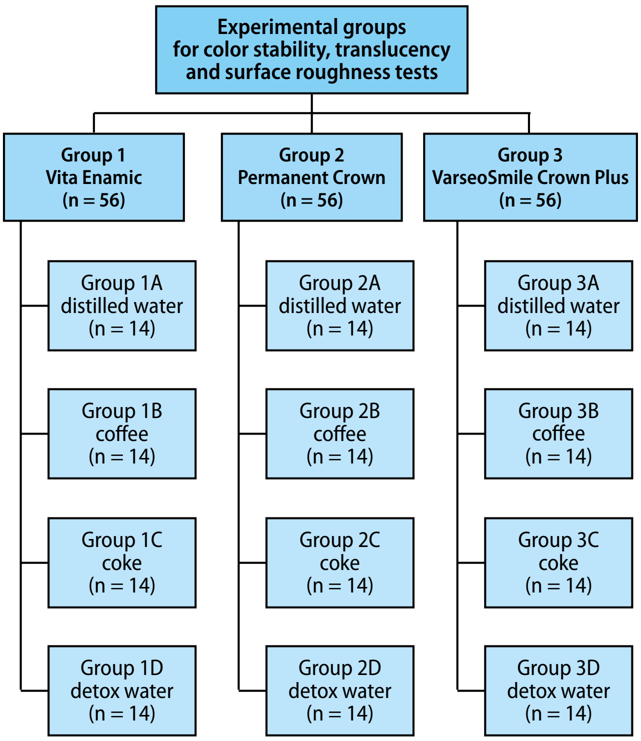

Fig. 1. Experimental groups for color stability, translucency, and surface roughness tests

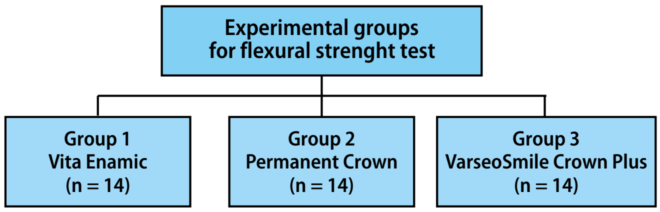

Fig. 2. Experimental groups for the flexural strength test

from 3 different planes. The mean of the measurement values obtained was recorded as the greatest surface roughness value of that specimen (ISO 4287).

After the initial color and surface roughness measurements, the specimens were kept in 4 different solutions (distilled water, coffee, coke, and detox water) for 15 min each day for a total of 14 days (Table 2). On the 7th day, color stability and surface roughness measurements were made and then placed in the solutions again. On the 14th day, the final color stability and surface roughness measurements were performed.

The color of the specimens was measured in a standard environment, under a standard light source, and on a white background with a spectrophotometer according

Table 2. Properties of the solutions used in the study

Solution	Manufacturer	Contents	Preparation	pH
Distilled water	–	–	–	6.74
Coffee	Nescafe Classic; Nestle, Vevey, Switzerland	instant coffee, sugar, flavoring, thickener, caffeine	2 g of instant coffee was dissolved in 200 mL of hot water	5.66
Coke	Coca-Cola, Atlanta, USA	water, sugar, caramel, phosphoric acid, natural sweeteners, caffeine	–	2.90
Detox water	Organik Smoothie Passion Red; Elite Naturel, Ankara, Turkey	organic watermelon juice (20%), organic strawberry puree (20%), organic banana puree (15%), organic apple puree (15%), organic pear puree (12%), organic black mulberry puree (12%), organic red beet juice (3%), organic black carrot juice (3%)	–	4.04

g – gram; mL – milliliter.

to the CIE-Lab scale, where L* represents the brightness of the material on a scale from 0 (black) to 100 (white); a* represents hue and chroma on the red–green axis; and b* represents hue and chroma on the yellow–blue axis. The spectrophotometer was properly calibrated before each measurement, following the manufacturer's instructions. The difference between 2 colored specimens or 2 time periods is represented as ΔE* (ISO/TR standard 28642:1999). L*, a* and b* values obtained from each specimen were recorded 24 h after specimen preparation, on day 7 and day 14. The color stability (ΔE) between day 7–24 h, day 14–24 h and day 7–day 14 for each specimen was calculated using the following equation:

$$\Delta E^* = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$$

$$\Delta E^* = [(L^*_1 - L^*_0)^2 + (a^*_1 - a^*_0)^2 + (b^*_1 - b^*_0)^2]^{1/2}$$

Three-point bending test

The study evaluated the mechanical properties, surface roughness, and optical properties of 2 different crown materials, PC (Formlabs, Somerville, USA) and VSCP (BEGO, Bremen, Germany) were produced with a 3D printer, and VE (Vita Zahnfabrik) was produced using CAD/CAM. The 3-point bending test was used to evaluate the mechanical properties of the materials. For this test, specimens 14 mm long, 4 mm wide and 1.2 mm thick were prepared. For each material group, 14 specimens were prepared (n = 14). CAD/CAM blocks were cut with a low-speed water-cooled diamond saw (Miracut 151; Metcon, Bursa, Turkey) to obtain bar-shaped specimens of these dimensions. Specimens were prepared with wet silicon carbide until the desired dimensions were achieved. Measurements were made using a micrometer (Mitutoyo Digimatic IP65; Mitutoyo). Specimens were stored dry at room temperature. Flexural strength values of the materials were measured using a universal testing machine (Shimadzu IG-IS; Shimadzu Corp., Kyoto, Japan) using a 3-point bending test with a support opening of 55 mm and a cross-speed of 1 mm/min (ISO 4049).

Flexural strength values of the specimens were calculated using the formula below:

$$\dot{e} = 3 \times F \times L/2b \times d^2$$

ė: Flexural strength of the material [kgf/cm^2]
F: Load causing breakage [kgf]
L: Distance of test specimen between supports [cm]
b: Width of test specimen [cm]
d: Thickness of the test specimen [cm]

Statistical analyses

Data analysis was performed using IBM SPSS v. 27.0 (IBM Corp., Armonk, USA) and was studied with a 95% confidence level. Frequency (n) and percentage (%) statistics are given for categorical (qualitative) variables, and mean (mean) and standard deviation (SD) statistics are given for numerical (quantitative) variables. Two-way and one-way analysis of variance (ANOVA) tests, which are parametric testing techniques, and Kruskal–Wallis and Mann–Whitney tests, which are non-parametric testing techniques, were used in the study. Additionally, Tukey's (homogeneous variance) and Games–Howell (inhomogeneous variance) tests were used for intragroup comparisons. Bonferroni correction (p/k = 4) was used when applying the Mann–Whitney test. The one-way ANOVA test is a testing technique used to compare k-independent groups (k > 2) in terms of a quantitative variable. Moreover, the one-way ANOVA test was used to compare variables with independent groups and their interaction in terms of a quantitative variable.

Results

Translucency

Material, solution and number of days were statistically significant in discoloration ($p < 0.05$). Each material showed a statistically significant change in translucency independent of solution type and holding time ($p < 0.05$). The most translucent material was determined as VSCP ($p < 0.05$). There was a statistically significant difference compared to other materials. Considering the duration, there was a difference between the initial translucency values and the 14th-day translucency values, but this value was not statistically significant ($p > 0.05$) (Table 3).

Color stability (ΔE)

Material, solution and time had a statistically significant effect on discoloration in all specimens ($p < 0.05$). When the solutions were compared with each other, the amount of discoloration was different between the solutions ($p < 0.05$). Coke and detox water were not statistically different from each other ($p > 0.05$), while the other solutions showed significant differences when compared with each other ($p < 0.05$). Coffee caused the most discoloration in all specimens ($p < 0.05$). Time also had a statistically significant effect on discoloration ($p < 0.05$) (Table 4).

Surface roughness

The effect of solutions on roughness was observed mostly on PC specimens. Specimens kept in detox water and coke showed higher roughness compared to the initial value ($p < 0.05$). The roughness values of 3 different specimen groups were statistically different from each other ($p < 0.05$). Vita Enamic specimens showed the least amount of roughness ($p < 0.05$) (Table 5).

Table 3. Means and standard deviations (SDs) of the translucency parameter (TP) of the experimental groups

Measurement periods by groups	Distilled water	Coffee	Coke	Detox water
VE-initially	5.45 ±1.05	5.27 ±1.77	5.72 ±0.99	5.7 ±2.10
PC-initially	9.44 ±2.44	10.09 ±2.74	7.85 ±2.81	8.6 ±3.16
VSCP-initially	17.25 ±3.47	18.18 ±5.10	17.74 ±5.23	15.29 ±4.04
VE-7th day	5.21 ±0.84	4.42 ±1.05	6.17 ±1.57	5.8 ±1.38
PC-7th day	9.46 ±2.34	6.66 ±2.60	9.73 ±2.43	7.5 ±2.09
VSCP-7th day	16.58 ±3.54	15.09 ±3.52	17.56 ±3.19	15.17 ±2.98
VE-14th day	4.77 ±0.65	4.56 ±1.12	5.25 ±1.04	5.59 ±1.03
PC-14th day	8.17 ±1.79	6.66 ±0.84	8.13 ±1.74	8.38 ±1.41
VSCP-14th day	14.82 ±4.50	13.86 ±2.83	15.85 ±4.64	13.48 ±3.12

VE – Vita Enamic; PC – Permanent Crown; VSCP – VarseoSmile Crown Plus.

Table 4. ΔE means and standard deviations (SDs) of the experimental groups

Measurement periods by groups	Distilled water	Coffee	Coke	Detox water
VE-7th day	0.74 ±0.28	6.69 ±0.69	3.84 ±0.40	3.74 ±0.42
PC-7th day	1.18 ±0.33	10.9 ±1.15	5.21 ±0.45	5.08 ±0.43
VSCP-7th day	1.17 ±0.31	15.61 ±2.10	8.01 ±0.62	7.86 ±0.93
VE-14th day	1.08 ±0.30	7.86 ±0.55	4.52 ±0.54	4.37 ±0.61
PC-14th day	1.66 ±0.35	13.91 ±1.71	7.23 ±0.48	6.99 ±0.37
VSCP-14th day	1.85 ±0.32	19.54 ±1.30	10.6 ±1.31	9.73 ±1.12

VE – Vita Enamic; PC – Permanent Crown; VSCP – VarseoSmile Crown Plus.

Table 5. Surface roughness means and standard deviations (SDs) of the experimental groups

Measurement periods by groups	Distilled water	Coffee	Coke	Detox water
VE-initially	0.19 ±0.01	0.19 ±0.01	0.18 ±0.03	0.19 ±0.02
PC-initially	0.17 ±0.08	0.16 ±0.07	0.17 ±0.06	0.17 ±0.03
VSCP-initially	0.33 ±0.20	0.33 ±0.1	0.33 ±0.14	0.33 ±0.18
VE-7th day	0.21 ±0.03	0.22 ±0.04	0.21 ±0.03	0.21 ±0.03
PC-7th day	0.20 ±0.08	0.19 ±0.09	0.30 ±0.11	0.26 ±0.06
VSCP-7th day	0.34 ±0.11	0.33 ±0.11	0.39 ±0.19	0.30 ±0.13
VE-14th day	0.23 ±0.06	0.23 ±0.05	0.25 ±0.05	0.23 ±0.04
PC-14th day	0.20 ±0.09	0.18 ±0.08	0.30 ±0.16	0.26 ±0.09
VSCP-14th day	0.35 ±0.11	0.35 ±0.10	0.35 ±0.11	0.38 ±0.18

VE – Vita Enamic; PC – Permanent Crown; VSCP – VarseoSmile Crown Plus.

Table 6. Flexural strength means and standard deviations (SDs) of experimental groups

Measurement periods by groups	VE	PC	VSCP
Flexural strength	386.20 ±50.55	220.20 ±38.28	39.60 ±4.00

VE – Vita Enamic; PC – Permanent Crown; VSCP – VarseoSmile Crown Plus.

Flexural strength

A statistically significant difference was found between the groups in the 3-point bending test ($p < 0.05$). Vita Enamic was the material that showed the highest statistically significant values in terms of flexural strength among the materials ($p < 0.05$), whereas VSCP exhibited the lowest statistically significant values ($p < 0.05$). The flexural strength values of the PC material were statistically significantly higher than the VSCP material ($p < 0.05$) (Table 6).

Discussion

Resin-ceramic hybrid materials are materials whose physical properties are very close to those of natural teeth, show less wear than composite resin and cause less wear to the antagonist's tooth. However, they are more prone to discoloration, which limits the longevity and quality of aesthetic restorations.[11] In this study, the effect of exposing hybrid ceramic materials produced by different methods to different staining solutions on the optical and surface properties of the materials was evaluated. The flexural strength of the materials was also evaluated. Coffee, coke and detox water were chosen as staining solutions due to their frequent consumption. The specimens in the control group were kept in distilled water. According to coffee producers, it takes an average of 15 min to consume a cup of coffee.[12] Considering this time, the materials were kept in the solutions for 15 min every day for a total of 14 days.

Considering the data obtained in the case of the study, staining solutions were observed to cause changes in the optical and surface properties of the materials. However, there was a statistically significant difference between the materials in terms of optical, surface and mechanical properties, and the null hypothesis was rejected. According to our results, the most translucent material was determined to be VSCP in all experimental groups. The light transmittance of resin-containing materials is related to multiple refractions and reflections at the matrix/filler interface, which is affected by the difference in refractive index between the filler particles and the matrix.[13] The VSCP we used in our study has a low filler ratio and was the material with the highest translucency. This may be explained by the view that when a material has a low filler content, light penetration will be easier.[14]

When the discoloration values were examined, coffee caused the most discoloration in all specimens. No difference was observed between coke and detox water in terms of discoloration values. Intralavan et al. evaluated the discolorations of VE and VSCP materials after exposure to distilled water, coffee and coke. In their study, coffee also caused the most discoloration in the materials.[11] Alsilani et al. evaluated the effect of coffee and coke on the color stability and surface roughness of 3 different CAD/CAM materials, including VE. In their study, coffee caused high discoloration in the VE material.[15] Sarıkaya et al. compared the color stability of 2 different hybrid ceramics, including VE, after being immersed in coffee and energy drinks, and found that coffee caused the most discoloration in the materials.[16] Abouraya et al. evaluated the effect of exposure of 3 aesthetic monolithic block materials, including VE, to coffee, coke and distilled water on the discoloration of the materials. Vita Enamic material exhibited the highest discoloration values after being kept in coffee.[17] Our results are consistent with these studies. In this study, we aimed to evaluate the mechanical and optical effects that alcohol-free beverages can have on materials. In addition, we aimed to assess the effects of detox water, which has begun to be consumed frequently due to the increasing interest of individuals in healthy nutrition, on the mechanical and optical properties of materials.

This absorption and penetration of colorants into the organic phase of the materials is likely due to the compatibility of the yellow colorants of coffee and the polymer phase.[18] In this study, the specimens immersed in detox water and coke exhibited higher roughness compared to the initial value. Chowdhury et al. studied the effect of exposure of a nanohybrid composite resin to tea, coffee and coke on the surface roughness and color stability of the material, and reported the highest surface roughness values were for specimens immersed in coke.[19] Meenakshi et al. evaluated the effect of 3 different solutions (artificial saliva, orange juice and coke) on the surface roughness and color stability of 2 composite resins. The highest surface roughness values were observed in coke groups.[20] Escamilla-Gómez et al. evaluated the relationship between the surface degradation of composite resins immersed in different acidic solutions and *Streptococcus mutans* biofilm formation. Surface degradation of composite resins was found to be related to the pH of the solution and *S. mutans* biofilm formation was associated with an increased surface roughness of composite resins.[21] Elwardani et al. evaluated the effect of exposure of 2 different composite resins to different solutions (coke, orange juice and distilled water) on the surface roughness and discoloration of the materials. The groups showing the highest surface roughness were coke groups.[22] The surface properties of the composite resin, especially microhardness and roughness, can be greatly influenced by the overall chemical composition of beverages, the type of acid present in their formulation, as well as the strength of the individual acidic components.[23] Furthermore, composite resin materials tend to wear under ascending conditions.[24] Researchers have noted that low-pH foods and beverages with acidic properties cause erosive wear of dental restoration materials. High acidity can have a greater softening effect on the resin matrix, thereby promoting the dislodging of filler particles and thus increasing the surface roughness of the composite resin.[19] In this study, the solutions with the lowest pH were coke and detox water. The reason why these 2 solutions caused the highest surface roughness in the materials may be because these solutions have lower pH values than coffee and distilled water. However, it has been reported that the larger the filler size, the greater the surface roughness.[25] Therefore, the lowest surface roughness values observed in VE groups in this study may be due to the smaller size of the fillers in this material compared to the other 2 materials.

Dayan and Çelik Güven evaluated the flexural strength and modulus of elasticity of 5 different CAD/CAM blocks, including VE. They reported that the ceramic-containing material, IPS e.max®CAD, had the highest flexural strength and modulus of elasticity values. Although the VE material contained 86% feldspathic ceramics, contrary to expectations, it exhibited lower flexural strength than resin nanoceramics. The researchers explained that this is because the ceramic part of the VE material contains porous feldspathic porcelain, unlike other hybrid materials.[26]

This study aimed to compare this disadvantage, which may affect the flexural strength of VE, with hybrid ceramic materials produced with 3D printers.

In this study, crown materials produced with 3D printing showed lower flexural strength values compared to the VE material produced using CAD/CAM. Digholkar et al. evaluated the flexural strength and microhardness of temporary restorative materials produced with 3D printing, CAD/CAM technology and traditional methods. They reported that the material produced using CAD/CAM showed the highest flexural strength values. This result is consistent with our study. The researchers reported that the reason why the material produced with CAD/CAM showed the highest flexural strength values may be due to the provision of optimum curing conditions.[27] Researchers have noted that the nature of the incremental layers in additive manufacturing technology can initiate crack propagation and cause structural failure of the material. The bond between layers is weaker than the bond within the layer itself. This is explained by the number of residual stresses and pores that accumulate during ultraviolet polymerization application and material shrinkage.[28] Park et al. evaluated the flexural strength of resin materials produced with 3D printing and found that the material produced with the stereolithography (SLA) technique exhibited higher flexural strength values. The researchers stated that the reason for the higher flexural strength of the material produced with the SLA technique is the surface morphology of the printed material. The surface of the material has a smoother structure as each layer is completed as if it is drawn with a laser beam during production with the SLA technique. In an area where the bond between layers is weak, if the surface is rough, fracture occurs faster. For this reason, the smoother surface of the material is effective in high flexural strength values.[29] The PC material produced with the 3D printer examined in this study was produced using the SLA technique. Because the flexural strength values of this material were higher than the VSCP material, one can conclude that the production of this material using SLA may be the reason.

Limitations

This study has some limitations due to the nature of in vitro research. While restorative materials are exposed to staining agents from food and drink in the oral cavity, they are constantly rinsed with saliva and brushed with oral hygiene techniques. These factors may affect the coloration of the materials or the roughness that may occur on the surface. Although this study does not include these procedures, it is among the limited number of studies evaluating the optical and mechanical properties of crown materials produced with 3D printers.

Conclusions

Since coffee causes the most color change in all materials, it can be suggested that patients with this type of restoration should be careful in terms of coffee consumption. Since VE has low roughness values, it can be recommended for dental restorations because it is advantageous in terms of fewer problems such as discoloration and plaque accumulation in the selection of restorative materials. It can be concluded that materials produced using the SLA technique among the materials produced with 3D printing can be recommended for restorations due to their higher flexural strength. Further studies are needed to evaluate the clinical success of the materials examined in this study.

Supplementary data

The Supplementary materials are available at https://doi.org/10.5281/zenodo.11922634. The package includes the following files:

Supplementary Fig. 1. Experimental groups as tested for color stability, translucency and surface roughness tests.

Supplementary Fig. 2. Experimental groups as tested for flexural strength test.

Supplementary File 1. Statistical analysis report.

Supplementary Table 1. Properties of the materials used in this study.

Supplementary Table 2. Properties of the solutions used in the study.

Supplementary Table 3. Means and SDs of the TP of the experimental groups.

Supplementary Table 4. ΔE means and SDs of the experimental groups.

Supplementary Table 5. Surface roughness means and SDs of the experimental groups.

Supplementary Table 6. Flexural strength means and SDs of the experimental groups.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication

Not applicable.

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