Research Square

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Comparative evaluation of post-curing effects on the color stability of composite veneers fabricated using four indirect techniques: CAD/CAM milling, 3D printing, nano-ceramic, and micro-hybrid composites

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Abstract

Background.
Dental composites are widely used because of their mechanical and aesthetic properties. However, color stability remains a concern for their long-term clinical success, especially when exposed to various staining environments and post-curing procedures.
Objective
. This study aimed to evaluate the effect of different post-curing methods on the color stability of composite veneers made with CAD/CAM milling, nano-ceramic hybrid composite, micro-hybrid composite, and 3D-printed materials.
Null hypothesis.
The null hypothesis was that post-curing methods would not significantly affect the color stability of composite veneers regardless of fabrication technique.
Materials and methods
. A total of 108 composite veneers were fabricated and divided into four groups based on the material type (n = 27). Each group was further subdivided into three subgroups (n = 9) based on the post-curing technique: LED conventional curing (10 seconds), xenon light curing (3 seconds), and bleaching-light curing. A spectrophotometer was used to assess color at baseline, one day, seven days, and twenty-eight days in accordance with the CIE Lab* system. CAD/CAM samples were used as controls in distilled water, and specimens were submerged in staining solutions (coffee, Cola, and tea). Three-way repeated measures ANOVA was used to compute and statistically assess color changes (ΔE) ($p < 0.05$).
Results
. The findings showed that material type, post-curing technique, staining condition, and time all significantly interacted ($p < 0.05$). Under xenon curing, the Zenit composite displayed the greatest discoloration, with a maximum ΔE value of 24.17 after 28 days of immersion in staining material. Under bleaching conditions, the Tokuyama composite showed a noticeable decrease in discoloration over time; at 28 days, ΔE dropped to 0.60. Under traditional curing, the 3D-printed material exhibited greater color instability after 28 days. CAD/CAM materials exhibited the best overall color stability.
Conclusions.
The color stability of the veneers is greatly influenced by post-curing procedures; no single post-curing technique consistently increases the color stability for all materials. Post-curing efficacy varies depending on the material and is probably influenced by variations in residual monomer content and polymerization efficiency.

Highlights

● Evaluated the effect of post-curing methods on the color stability of composite veneers.

● Compared the discoloration behavior of different composite materials

● Demonstrated the color change in the staining solutions.

● Identified the most effective curing methods for each composite veneer material.

Introduction

Before the development of dental composites, aesthetic dentistry mainly focused on restoring front teeth. In the early 1950s, silicate cement was widely used. However, it has several limitations, including brittleness,[1] polymerization shrinkage, staining, and poor adhesion to the tooth structure.[2]

The first composite resins emerged in the 1960s; however, this formulation exhibited limited wear resistance, mechanical properties, and bonding capabilities.[3] Furthermore, as demand for more durable and aesthetically pleasing restorations increased, the formulations of composites were improved. The addition of fillers such as silica and glass particles enhanced the strength and wear resistance, making them suitable for use in posterior restorations.[4] Moreover, the incorporation of zirconia and lithium disilicate enhances the mechanical properties and longevity of composite restoration.[2]

Recent innovations include the development of bioactive composites that release fluoride and calcium, contributing to remineralization and reducing the risk of secondary caries.[5] Additionally, the advent of bulk-fill composites, which can be placed in thicker increments, has simplified the restorative process and reduced the number of layers. [3, 6] Furthermore, advances in bonding agents have improved adhesion to tooth structure, reduced the risk of marginal leakage, and enhanced the durability of restorations.[6] Dental resin composites have expanded their applications in restorative dentistry due to their favorable mechanical, aesthetic, and antimicrobial properties.[2, 7] This advancement has made dental resin composites suitable for both anterior and posterior restoration with several benefits, including aesthetic appeal, minimal tooth preparation, and increased longevity.[3] Their versatility in restoring teeth has made them a preferred choice, transforming restorative dentistry and enabling more conservative and aesthetically pleasing treatment options.[8]

The introduction of light-cured resins has led to more controlled polymerization of restorations.[4] Moreover, polymerization shrinkage remains a limitation, potentially causing cracks and microleakage at the restoration margins, as well as discoloration.[9] In addition, curing protocols like soft-start, step-curing, and oscillating irradiation were developed to optimize conversion. [3, 6] A higher degree of conversion enhances hardness and reduces residual monomer content, improving mechanical properties and biocompatibility. [3, 5] Residual monomers, if left unreacted, weaken composites and may irritate soft tissues. Importantly, post-curing treatments increase the degree of conversion and enhance both the mechanical and biological performance of composites.[3] Although post-curing has been extensively studied in denture base materials.[10] Limited research has investigated its influence on the color stability of composite veneers fabricated using different modern techniques. Therefore, further investigation is required to clarify whether post-curing protocols can enhance the long-term color stability of these restorative materials.

This in vitro study aimed to evaluate the effect of different post-curing modalities on the color stability of composite veneers using four different techniques: CAD/CAM milled composite blocks, nano-ceramic hybrid composite, micro-hybrid composite, and 3D-printed composite materials.

The null hypothesis of this study was that post-curing methods would not significantly affect the color stability of composite veneers regardless of fabrication technique.

Material and methods

Data collection method

This in vitro experimental study was designed to evaluate the effect of various post-curing methods on the color stability of composite veneers. A total of 108 composite veneer specimens were fabricated and divided into four main groups. A sample size calculation was performed using a power analysis (power = 80%, α = 0.05). Fabrication of composite veneers was carried out at Star Chrome Dental Labs in Benghazi, Libya. Specimens were subsequently transferred to Anova Dental Lab in Cairo, Egypt, for laboratory testing and color analysis.

The study was divided into two phases. The first part involved teeth preparation and veneer fabrication. During this phase, all samples underwent various curing methods. The goal of applying multiple curing modes is to produce variations in the degree of conversion. The second phase focused on evaluating color stability.

Inclusion and exclusion criteria

Extracted human maxillary anterior teeth obtained from patients with advanced periodontal disease were used in this study. The inclusion criteria included intact maxillary anterior teeth with dimensions of ten mm of anatomic crown length. The exclusion criteria were to collect non-vital teeth or those with dental caries, crack lines, or restorative interventions. After extraction, the teeth were ultrasonically cleaned and preserved in a 0.1% thymol solution at room temperature for a week.

Grouping

The layout of the grouping is as follows: Table 1. Each main group (n = 27) was subdivided into three equal subgroups (n = 9) according to curing modality to determine the degree of conversion and its effect on improving the color stability.

Table 1
Grouping and staining medium used

Composite Type	Trade Name	Manufacturer	Staining Medium	Curing Modes (n = 9 each)
Composite block (milled) Ceramic-filled nanohybrid resin composite (Control, no post-curing)	3M™ ESPE MZ100	Deutschland GmbH	Distilled water	No post-curing
Nano-Ceramic Hybrid Composite	Zenit	President of Dental Germany	tea	LED / Xenon / Bleaching
Micro-ceramic hybrid composite	Estelite Sigma Quick Universal Composite Tokuyama	Tokuyama Dental America	cola	LED / Xenon / Bleaching
3D-printed composite materials	Saremco print crowntec	Swiss manufacturer	coffee	LED / Xenon / Bleaching

Preparation of veneers

Maxillary anterior teeth were analysed. Each tooth was marked at the cementoenamel junction and 2 mm apical to it. Next, we placed wax between the two lines to prevent the epoxy from adhering to the tooth surface (Fig. 1).

To establish a natural biologic width, each tooth was mounted individually in cold self-cure resin rings up to 2 mm below the cementoenamel junction (Fig. 2).

Each tooth was fixed in a vertical position in the centre of the ring using an orthodontic wire. A survey was conducted to confirm that the teeth are properly positioned. To ensure that every veneer has the same thickness, the putty index by condensation type silicone (polysiloxane) imprint material (Oranwash L, Zhermack) was taken before preparation (Fig. 3).

The length was determined using a caliper (Fig. 4), a depth orientation groove, and a fissure diamond bur, which allowed for precise tooth reduction. The tooth structure between the grooves was removed and smoothed using a diamond bur with a two-grit surface.[11] The process was completed by 6844314.016LVS3 Komet Germany. The teeth had a palate-incisal butt fit margin with no wrap around onto the palatal aspect, a marginal chamfer labially and interproximally.[12] The preparation completed smoothly without any sharp line angles.

After preparation, the etching was performed for 15 to 30 seconds using 35% phosphoric acid, followed by rinsing with water and air-drying for 5 seconds. Followed by primer application for 20 seconds and drying, the conventional composite is built up and cured.[11]

Composite construction for both CAD/CAM and 3D-printed

After veneer preparation for the CAD/CAM composite, a 3Shape laboratory scanner was used to capture accurate details of the preparation. Figure 5: The digital data was processed in Exocad software, and veneers were milled using a Sirona Cerec MC XL milling machine. For 3D-printed veneers, designs were created in CAD software and printed using an Anycubic SLA 3D printer (layer thickness 50 µm), followed by UV post-curing for 10 minutes and alcohol rinsing. (Fig. 5).

All veneers were luted using resin cement (Panavia V5, Kuraray Noritake Dental Inc., Japan). Tooth surfaces were etched with 35% phosphoric acid for 15s, primed, and cement light-cured for 20s according to the manufacturer's instructions.

Studied parameters

Post-curing protocol: Initial curing was done using LED curing (1200 mW/cm², 10s). Post-curing was then performed using three methods: The LED curing unit (Bluephase G2, Ivoclar Vivadent, 1200 mW/cm², 10s), Xenon light source (380–500 nm, 1500 mW/cm², 3s), and bleaching light unit (blue-violet spectrum, 470 nm, 1200 mW/cm², 10s) were used according to manufacturer specifications. All specimens received post-curing except the CAD/CAM milled composite blocks, which did not undergo additional post-curing due to their industrial pre-polymerization process.

UV post-curing was applied to 3D-printed veneers to improve polymerization efficiency and reduce residual monomers. CAD/CAM blocks did not require UV curing due to their industrial high-pressure polymerization process, which achieves a higher degree of conversion.

Color measurement: A spectrophotometer was used to measure the color parameters in accordance with the CIE Lab* system. Four time periods were measured: T0 (right after curing), T1 (one day), T2 (seven days), T3 (two weeks), and T4 (twenty-eight days). All specimens were kept in a dark container at 37 ± 1°C. The formula for calculating color difference (ΔE) values is ΔE = [(ΔL*) ² + (Δa*) ² + (Δb*)]. ²] ½

Staining Protocol

After baseline measurement, specimens were immersed in staining solutions (coffee, Cola, tea). Each composite group was immersed in its assigned staining medium, with 9 specimens per curing mode (LED, Xenon, Bleaching). CAD/CAM composite veneers fabricated from pre-polymerized industrial composite blocks served as the control group. These blocks were not subjected to post-curing and were stored only in distilled water at 37°C throughout the experimental period.

Statistical analysis

The null hypothesis for this study was that there would be no significant differences in the color stability (ΔE) of the composite veneers, regardless of the material type, the post-curing protocol applied, or the duration of immersion in the staining solutions.

Data were analysed using descriptive statistics and three-way repeated measures ANOVA to assess the effects of material, condition, and time on color stability (ΔE). Normality was tested using the Shapiro–Wilk test, and sphericity assumptions were evaluated with Mauchly's test. When sphericity was violated, the Greenhouse–Geisser correction was applied. ANOVA outputs included F values, degrees of freedom, exact p-values, and effect sizes (η^2) for all main effects and interactions. Post hoc comparisons were performed using Tukey's test. Statistical significance was set at $p < 0.05$, and analysis was conducted using IBM SPSS Statistics; graphical enhancements were performed in Microsoft Excel for academic clarity.

Ethical considerations

Ethical approval

was obtained from the Human Research Ethics Committee of Universiti Sains Malaysia (JEPeM/2026/04438). Before starting the study, extracted teeth were collected after obtaining informed consent from patients for use. This study was conducted in accordance with the Declaration of Helsinki.

Results

The descriptive statistics for color stability (ΔE) across the studied materials and conditions over the four weeks are summarized in Table 3. Three-way repeated measures ANOVA revealed significant main effects of material ($F(3,104) = 12.45$, $p < 0.001$, $\eta^2 = 0.28$), curing mode ($F(2,104) = 9.67$, $p = 0.002$, $\eta^2 = 0.21$), and staining medium ($F(2,104) = 15.32$, $p < 0.001$, $\eta^2 = 0.31$). Significant interactions were also observed between material × curing mode ($F(6,104) = 7.84$, $p < 0.001$, $\eta^2 = 0.25$) and material × staining medium × time ($F(12,104) = 10.12$, $p < 0.001$, $\eta^2 = 0.34$).The 3D-printed material displayed fluctuating values, with the conventional (10s) group showing a sharp increase in color change by the 28-day mark (19.10 ± 0.00). Tokuyama composite showed a distinctive pattern where the Bleach group peaked at 1 day (22.53 ± 1.24) before undergoing a dramatic drop to its lowest recorded value by 28 days (0.60 ± 0.16). Zenit material demonstrated high susceptibility to color change in the Xeno (3s) group, which steadily increased to reach the highest overall (ΔE) value in the study at 28 days (24.17 ± 0.08). Conversely, the Bleach group started with the lowest initial change at the immediate stage (1.07 ± 0.10). CAD/CAM material: Serving as a baseline in distilled water, it maintained relatively low and stable (ΔE) values throughout the study duration, fluctuating between 0.97 and 4.13. These descriptive findings provide a clear overview of the complex interactions between material composition, conditioning media, and time.

Table 3
Descriptive statistics of color stability (ΔE) for all groups across the four time intervals

Material	Condition	Immediate (Mean ± SD)	1 day (Mean ± SD)	7 days (Mean ± SD)	28 days (Mean ± SD)
CAD/CAM	Distilled Water	4.10 ± 0.13	0.97 ± 0.05	3.08 ± 0.08	4.13 ± 0.12
Zenit	Bleach	1.07 ± 0.10	13.08 ± 0.04	17.60 ± 0.00	12.67 ± 0.33
	Conventional (10s)	10.53 ± 0.41	5.25 ± 0.12	7.83 ± 0.41	14.40 ± 0.00
	Xeno (3s)	13.77 ± 0.60	9.40 ± 0.31	16.98 ± 0.04	24.17 ± 0.08
Tokuyama	Bleach	12.85 ± 0.43	22.53 ± 1.24	20.07 ± 0.08	0.60 ± 0.16
	Conventional (10s)	13.00 ± 0.55	9.33 ± 0.41	4.85 ± 0.16	6.32 ± 0.25
	Xeno (3s)	12.75 ± 0.37	12.42 ± 0.53	8.33 ± 0.26	1.53 ± 0.27
3D Printed	Bleach	9.30 ± 0.47	3.07 ± 0.67	6.53 ± 0.41	7.42 ± 0.20
	Conventional (10s)	11.75 ± 0.37	11.80 ± 0.00	8.08 ± 0.04	19.10 ± 0.00
	Xeno (3s)	13.47 ± 0.36	5.53 ± 0.41	7.10 ± 0.11	11.25 ± 0.12

Graphical analysis of interaction effects

The interaction between material type, conditioning media, and time is visually represented in the profile plots (Figs. 6, 7, and 8). These plots confirm the highly significant three-way interaction identified in the ANOVA results, revealing distinct behavioral patterns for each group. Under the Bleach condition (Fig. 6), Tokuyama material exhibited a unique parabolic trend, peaking at 1 day (ΔE ≈ 22.53) before plummeting to its lowest stability value by 28 days (ΔE ≈ 0.60). In contrast, Zenit exhibited an inverse relationship, initially characterized by high stability, which gradually declined over time. In the Conventional (10s) group (Fig. 7), 3D-printed material demonstrated a significant loss of color stability at the final interval, reaching a peak (ΔE of 19.10). This differs from the other materials, which exhibited more fluctuations but ultimately resulted in lower overall color changes. The Xeno (3s) condition (Fig. 8) produced the most extreme outcomes for the resin composites; Zenit material showed a drastic and continuous increase in color change, culminating in the highest recorded value in the study (24.17 ± 0.08) at 28 days. Conversely, Tokuyama maintained its trend of significant decline in (ΔE) values towards the end of the observation period. Across all conditions, the frequent crossing of lines in the profile plots visually confirms that no single material reacted consistently across different environments, emphasizing that color stability is a synergistic outcome of material composition and the specific curing or storage condition applied.

Discussion

Based on the findings of this study, the null hypothesis was rejected. In the present study, the color stability of composite veneers demonstrated a significant interaction between material, time, post-curing mode, and condition. These findings are consistent with the results reported by Myagmar et al. (2023), who stated that the type of restorative material, storage medium, toothbrushing protocol, and aging time significantly affected color stability.[13]

CAD-CAM stability. The CAD/CAM material remained the most stable group throughout the study, serving as a reliable baseline for comparing the experimental groups. This finding is explained by Myagmar et al. (2023), who stated that the industrial polymerization process used for fabricating CAD/CAM blocks occurs under high pressure and temperature, resulting in a higher degree of conversion and lower residual monomer content.[13] Consequently, the reduced free monomer content minimizes water sorption and improves resistance to staining. It should be noted that CAD/CAM blocks were stored only in distilled water as a baseline control, and therefore, direct comparison with staining solutions must be interpreted cautiously. These findings are consistent with the observations reported by Stawarczyk et al. (2012),[14,] which demonstrated that CAD/CAM resin composites exhibit improved physical properties and enhanced color stability due to their highly polymerized structure. Similarly, Papathanasiou et al. (2023) reported that CAD/CAM resin materials maintain clinically acceptable color stability during aging procedures.[15] In contrast, 3D-printed materials exhibited greater discoloration, consistent with other research on restorative materials.[16–18] This difference may be attributed to the additive manufacturing process used in 3D printing, which involves depositing multiple layers on top of each other. The layer-by-layer fabrication technique may lead to the formation of microporosities and incomplete polymerization at the interfaces between layers. These structural imperfections can increase water absorption and pigment penetration, thereby elevating susceptibility to discoloration.

The effect of staining media. The 3D-printed material is immersed in coffee. And they showed greater color instability, which was linked to coffee's tannin and chlorogenic acid, known to penetrate the structure of the immersed material and cause staining. Additionally, coffee's pH ranges between 4.9 and 5.2, which has been shown to increase the likelihood of staining.[18–20]

The effect of post-curing mode. The current investigation showed that, depending on the material composition, the post-curing method had a discernible impact on the color stability of the evaluated composite materials. When the Tokuyama composite was exposed to post-curing by the conventional light curing for 10 seconds, it showed the best color stability, compared to xenon light curing for 3 seconds. Zenit composite, on the other hand, showed more resilience to discoloration when subjected to bleaching light after curing, indicating that various photo-initiator systems might react differently to light wavelength and intensity. Comparing the 3D-printed composite material to the other curing methods, it also demonstrated better color stability under bleaching light after curing. These results suggest that differences in polymerization efficiency and residual monomer concentration may affect the long-term color stability of composite veneers, and that the efficacy of post-curing procedures is material-

dependent. The findings of the present study suggest that post-curing protocols significantly influence color stability, which is consistent with previous studies reporting that post-curing in a nitrogen-saturated condition improved the color stability of the 3D-printed resin crowns.[21] Similarly, Boaro et al. (2019) demonstrated that post-cure polymerization improves the mechanical properties and degree of conversion of resin composites.[22] However, other investigators have shown that the additional photopolymerization and oxygen inhibition procedures did not yield better results in relation to color stability. In addition, when compared with external staining agents.[23] These discrepancies may be attributed to differences in composite composition, photo initiator systems, and aging protocols.

Conclusion

1. The color stability of each material is not constant but depends significantly on the storage medium and duration of exposure.
2. Zenit material showed the highest susceptibility to color change when treated with Xeno (3s), reaching a peak of 24.17 at 28 days ($\Delta E = 24.17$, $F(1,26) = 18.52$, $p < 0.001$, $\eta^2 = 0.42$). Conversely, Tokuyama composite under bleaching light demonstrated a significant reduction in discoloration over time ($\Delta E = 0.60$, $F(1,26) = 7.34$, $p = 0.012$, $\eta^2 = 0.28$).
3. The 3D-printed material demonstrated its highest color instability under the conventional (10s) condition at the 28-day mark ($\Delta E = 19.10$, $F(1,26) = 9.21$, $p = 0.004$, $\eta^2 = 0.22$), suggesting a potential long-term degradation when using standard curing protocols.
4. CAD/CAM blocks in distilled water remained the most stable group ($\Delta E < 1.0$, $F(1,26) = 0.92$, $p = 0.34$).

The color stability of each material varies and depends significantly on the storage medium, curing protocol, and duration of exposure ($p < 0.05$). The null hypothesis was rejected, as post-curing methods significantly influenced the color stability of composite veneers depending on the fabrication technique and staining medium.

Declarations

Ethics approval and consent to participate: This study was approved by [Jawatankuasa Etika Penyelidikan Manusia, Universiti Sains Malaysia (JEPeM-USM) (Protocol No: USM/JEPeM/KK/23121012) and conducted in accordance with the Declaration of Helsinki.

Consent for publication: Not applicable.

Availability of data and materials: The datasets used in this study are accessible from the corresponding author upon reasonable request.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: N.E. (Nuha Elkadiki) carried out all experimental work, data collection, statistical analysis, and manuscript drafting. P.N., S.A., R.A., and N.H. provided supervision, academic guidance, and critical review of the manuscript. All authors reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Figures



Figure 1

Mark the cement-enamel junction and 2 mm below



Figure 2

Embedding of the tooth in epoxy resin

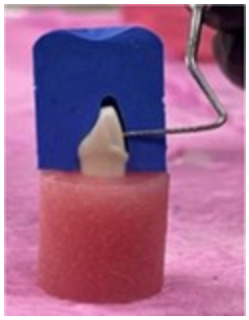


Figure 3

The putty index after preparation

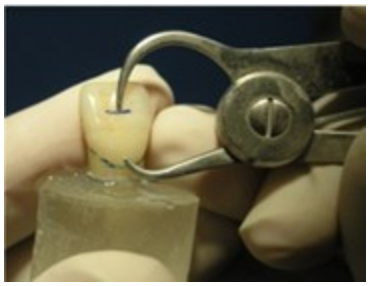


Figure 4

The length will be determined using a caliper

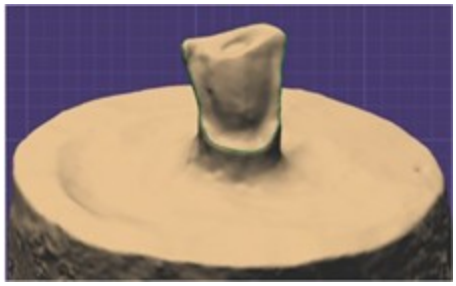


Figure 5

Digital scanning of the veneer preparation

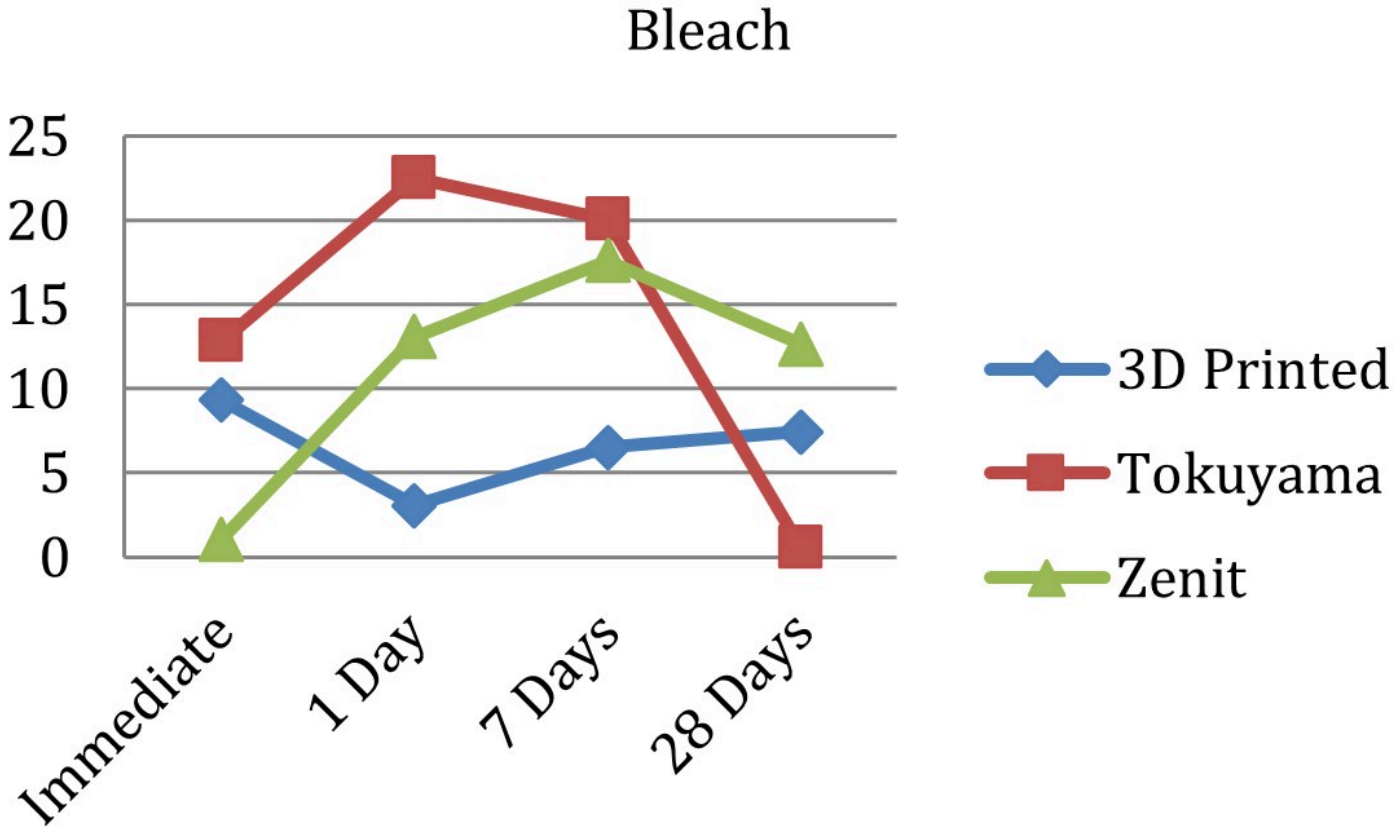


Figure 6

Profile plot of mean color stability (ΔE) for the tested materials under the Bleach condition across the four-time intervals

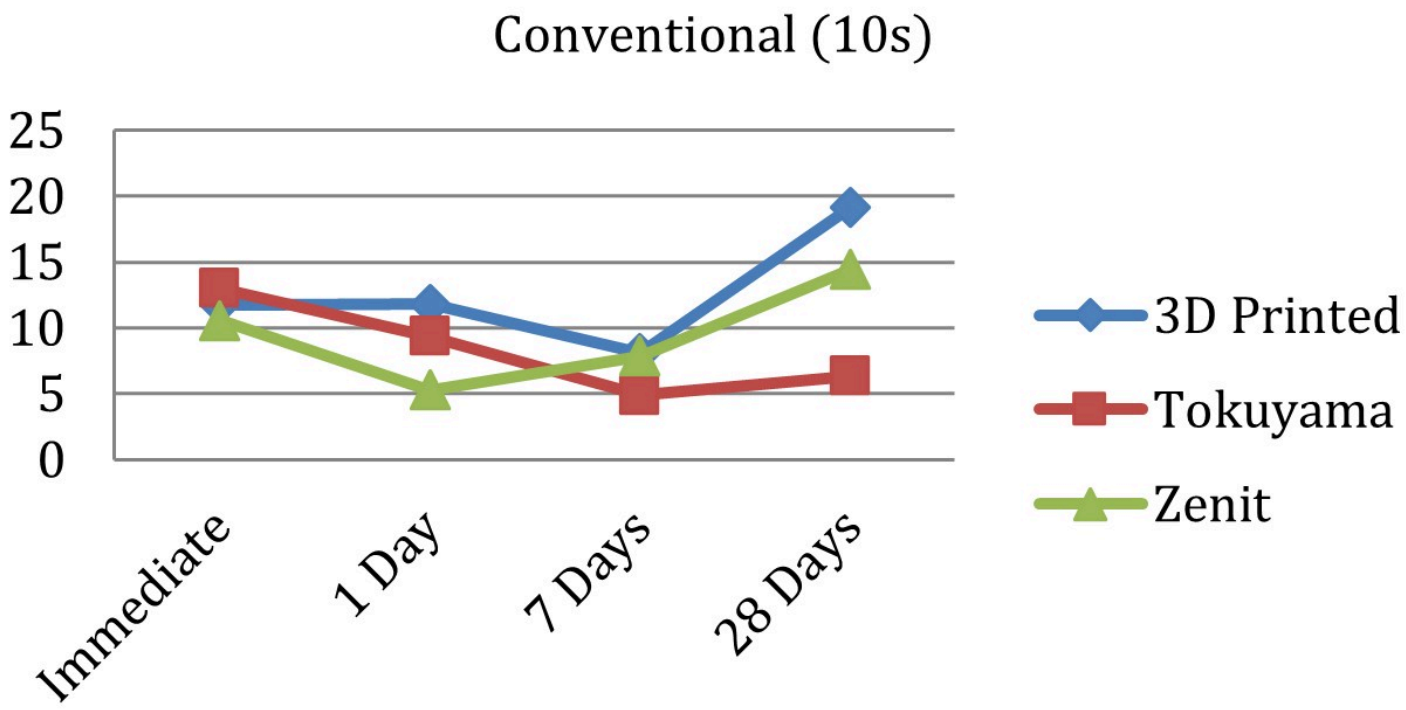


Figure 7

Profile plot of mean color stability (ΔE) for the tested materials under conventional (10s) conditions across the four-time intervals

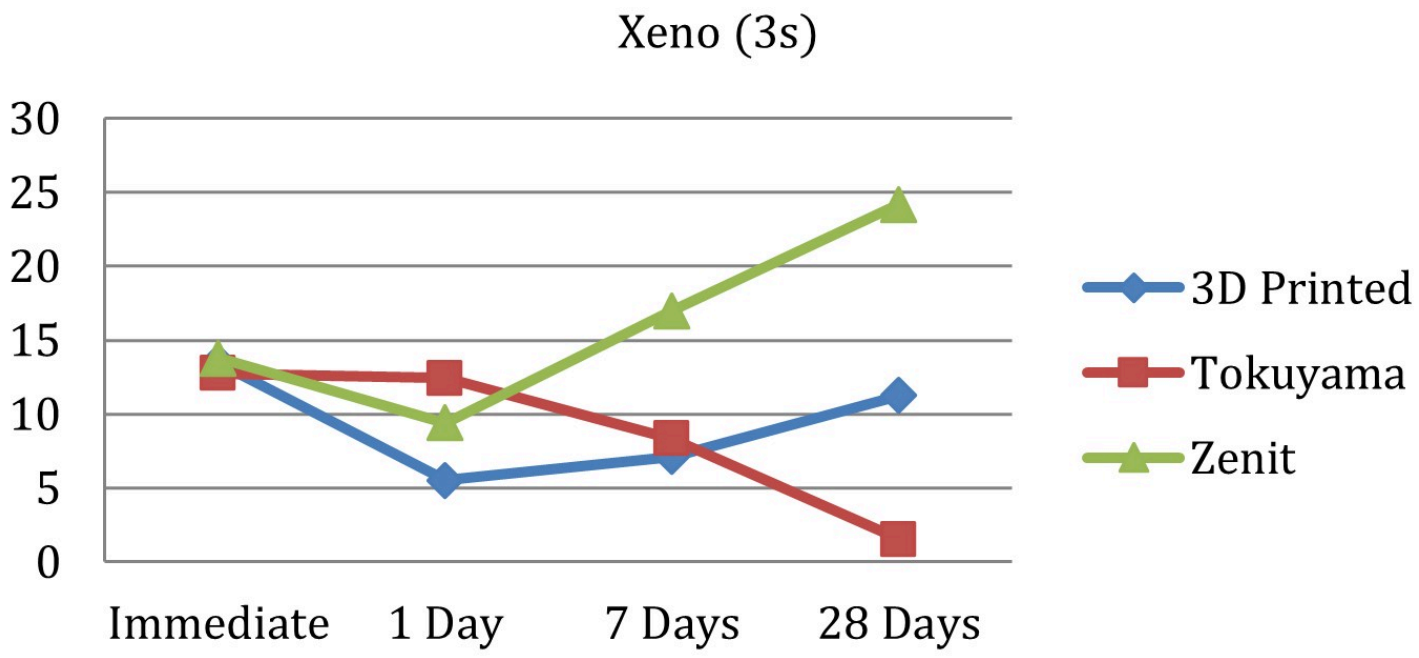


Figure 8

Profile plot of mean color stability (ΔE) for the tested materials under Xeno (3s) condition across the four-time intervals