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Evaluation of color stainability of computer-aided design/computer-aided manufacturing blocks with different microstructures

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Abstract

The stainability of ceramic materials is a critical factor in the long-term esthetic success of computer-aided design/computer-aided manufacturing (CAD/CAM) restorations. This study aimed to evaluate the color stainability of CAD/CAM ceramic blocks with different microstructures after immersion in a coffee solution for varying durations. Three types of CAD/CAM blocks—Vita Mark II (MG), Vita Suprinity ([SG] and [SP]), and Vita Enamic (EP)—were used. Finishing and polishing were performed according to the manufacturers' instructions. CIE L*, a*, and b* values were measured at baseline (T_0), and after 1 (T_1), 12 (T_{12}), and 30 (T_{30}) days of immersion in coffee using a spectrophotometer. Color differences (ΔE_{00}), $\Delta L'$, $\Delta C'$, and $\Delta H'$ were calculated using the CIEDE2000 formula. One-way ANOVA was used to compare these values across materials. Multiple linear regression analysis was conducted to assess the influence of $\Delta L'$, $\Delta C'$, and $\Delta H'$ on ΔE_{00} ($p<0.05$). Statistically significant differences in ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ values were observed at all time intervals ($p=.000$), except for $\Delta H'$ between T_0-T_{12} ($p=.199$). $\Delta L'$ was the primary influencing factor for MG, SG, and SP materials, while $\Delta H'$ had the greatest effect on EP over the T_0–T_{30} interval. Within the limitations of this study, the chemical composition of the material influenced ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ values. SG showed the lowest and clinically acceptable level of staining, while EP exhibited a moderate but clinically unacceptable degree of discoloration.

Keywords: Color, coloring agent, computer-aided design

Introduction

Recent advancements in prosthodontic treatment have been driven by the ease of use and efficiency of computer-aided design/computer-aided manufacturing (CAD/CAM) technology [1-2]. The long-term clinical success of bonded CAD/CAM glass-ceramic restorations has contributed to a paradigm shift in fixed dental restorations, from traditional techniques to minimally invasive approaches [2]. Monolithic glass-ceramic inlays, onlays, laminate veneers, and crowns have gained widespread acceptance [1-3]. In response to the demand for esthetic, biocompatible, and durable restorations, CAD/CAM ceramic technologies continue to evolve [1-3].

VITA Mark II, introduced in 1991, is based on traditional feldspathic porcelain and is characterized by finely structured particles with enhanced mechanical properties and strength, remaining widely used in clinical practice [4-7]. VITA Enamic, launched in 2013 as a hybrid dental ceramic, was developed as an alternative to conventional ceramic blocks. It features a dual-network structure consisting of approximately 86% ceramic and 14% composite material by volume [6,8-12]. Around the same time, VITA Suprinity was introduced as a pre-crystallized zirconia-reinforced lithium silicate glass-ceramic. This material combines the advantages of lithium disilicate and zirconia, containing 10 wt% zirconium in its crystalline matrix, and is claimed by the manufacturer to exhibit optical properties similar to those of natural teeth [6,13,14]. These materials were quickly recognized as preferred options for CAD/CAM restorations [3,9].

Ceramic finishing and polishing are essential for maintaining color stability and esthetics, minimizing shade discrepancies, and achieving a high-gloss surface [15-17]. For optimal

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outcomes, it is important to follow each manufacturer's specific recommendations [16]. The stainability of ceramic materials is a critical factor for maintaining the long-term esthetic success of CAD/CAM restorations, particularly given the frequent consumption of staining agents such as dark beverages [9,15,18]. Previous studies have examined the effects of variables such as material thickness [11,19,20], finishing and polishing protocols [7,10,14-18,21-23], aging methods [5,9,10,13,19,22,24], use of mouth rinses [25], and tooth brushing [5] on the discoloration of CAD/CAM materials. However, limited research has investigated the influence of chemical composition on stainability [6,21,26]. The aim of this study was to evaluate CAD/CAM ceramic blocks with different microstructures after immersion in a coffee solution for varying durations. The null hypothesis was that there would be no differences in stainability among CAD/CAM blocks with different microstructures.

Material and Methods

Ethical approval was not required because no human participants were involved and no personal data was collected. Three different CAD/CAM blocks were used in this study: Vita Mark II (Vita Zahnfabrik, Bad Säckingen, Germany; [M]), Vita Suprinity (Vita Zahnfabrik, Bad Säckingen, Germany; [S]), and Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Germany; [E]), all in A2 shade. The material compositions are listed in Table 1. Each block was sectioned to a thickness of 2 mm (±0.1 mm) using a Micracut 201 linear precision cutting machine (Metkon, Bursa, Turkey) under water cooling. After sectioning, the thickness of the samples was verified using a digital micrometer (Mahr GmbH, Göttingen, Germany). All specimens were polished sequentially with 600-, 800-, and 1000-grit silicon carbide papers (English Abrasives, London, England) under running water for 15 seconds to standardize surface roughness. Samples were then ultrasonically cleaned in distilled water for 15 minutes (Whaledent Biosonic, Coltène/Whaledent Inc., Ohio, USA) and air-dried. A total of 40 samples were prepared, each measuring 12 × 14 × 2 mm (±0.1 mm). For the crystallization of S specimens, firing was performed using a Vita Vacumat 6000 M furnace with the following parameters: an 8-minute heating cycle, a temperature increase rate of 55 °C/min, a ring temperature of 840 °C, and a holding time of 8 minutes. The S group was then randomly divided into subgroups based on the finishing technique applied (n=10 per subgroup). For the glaze groups (MG and SG; n=10 per subgroup), the firing parameters and glaze materials are detailed in Table 1. Glaze was applied to one surface of each specimen. For the polishing groups (SP and EP; n=10 per subgroup), mechanical polishing was performed in the laboratory using a micromotor. A custom acrylic resin mold was used to maintain uniformity across sample surfaces, based on the sample dimensions. Polishing was applied to one surface of each specimen at 8000 rpm, following the manufacturer's instructions. Polishing rubbers (Vita Zahnfabrik, Bad Säckingen, Germany) were used in a single direction with light, controlled pressure. The materials and application times are also provided in Table 1.

The samples were subsequently cleaned ultrasonically in distilled water for 15 minutes and then air-dried. Initial Commission Internationale de l'Éclairage (CIE) L*, a*, and b* measurements were performed. A black coffee solution was used for the staining procedures. The solution (Nescafé Classic, Nestlé Gıda, Bursa, Turkey) was prepared according to the manufacturer's instructions by dissolving 2 grams of coffee in 200 mL of boiled distilled water. Once fully dissolved, specimens were placed in self-compartmentalized plastic containers, with each container holding 4 mL of the solution per specimen. The containers were stored in an incubator at 37°C (Kottermann Labortechnik, Köttermann GmbH & Co. KG Industriestrasse, Hänigsen, Germany). The coffee solution was freshly prepared each day to prevent bacterial contamination. To evaluate staining, specimens were removed from the solution on the 1st, 12th, and 30th days, dried with a paper napkin, and color measurements were taken from the finished surfaces. All CIE L*, a*, and b* measurements were performed using a spectrophotometer (Vita Easyshade Advance, Vita Zahnfabrik, Bad Säckingen, Germany) with a 6 mm diameter measuring tip in Single Tooth mode. Measurements were recorded at baseline (T_0) and after 1 (T_1), 12 (T_{12}), and 30 (T_{30}) days of immersion. The spectrophotometer was calibrated before each session. For each sample, three measurements were taken against a white background, and the mean value was calculated. To ensure accurate measurements and minimize edge-loss effects, the sample diameter was extended to match the measuring area of the spectrophotometer, and a glycerin solution was used to preserve optical continuity. Color differences (ΔE_{00}) were calculated using the CIEDE2000 formula [27] with parametric weighting factors set to 1, as follows:

$$\text{CIEDE2000}=[(\Delta L'/kLSL)2+(\Delta C'/kCSC)2 +(\Delta H'/kHSH)2+RT(\Delta C'/kCSC(\Delta H'/kHSH)]1/2$$

The values of $\Delta L'$, $\Delta C'$, and $\Delta H'$ used in ΔE_{00} calculations represent changes in brightness, saturation, and hue, respectively. The following formulas from the CIEDE2000 equation were used to compute these values [27]:

$$\Delta L'=L*2–L*1$$

$$\Delta C'=C'2–C'1$$

$$\Delta H'=2[(C'1\ C'2)\ ½]\sin(\Delta h'/2)$$

ΔE_{00} values were calculated to quantify discoloration between T_0–T_1, T_0–T_{12}, and T_0–T_{30} following immersion in the coffee solution. These values were interpreted using established staining thresholds: clinically unperceivable (≤0.8), perceptible but clinically acceptable (≤1.8), moderately unacceptable (≤3.6), clearly unacceptable (≤5.4), and extremely unacceptable (>5.4 units) [28]. To ensure consistency across specimens, a single dental technician performed all finishing procedures, and CIE L*, a*, and b* measurements using the spectrophotometer were conducted by one operator (D.Y.).

Statistical analyses were conducted using SPSS software (IBM SPSS Statistics for Windows, Version 25.0; IBM Corp., Armonk, NY, USA). The normality of the data was assessed using the Shapiro–Wilk test, which confirmed that the data were normally

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distributed. One-way ANOVA was used to compare ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ values among the materials at T_0–T_1, T_0–T_{12}, and T_0–T_{30}. Where significant differences were found, the Tukey HSD test was applied to identify which specific groups differed. Paired-samples t-tests were used to compare ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ across time intervals T_0–T_1, T_0–T_{12}, and T_0–T_{30} within each material. Multiple linear regression analysis was performed on to examine the effect of $\Delta L'$, $\Delta C'$, and $\Delta H'$ on ΔE_{00}. Assumptions for regression modeling were verified. Multicollinearity was assessed by examining correlations among the independent variables, with results confirming that variance inflation factor (VIF) values were below 10 and tolerance values exceeded 0.1, indicating no multicollinearity. The assumption of independence was also confirmed, as each observation was assigned to a single measurement group and the experimental design ensured no interaction between materials. The assumptions of normality and homoscedasticity (constant variance) of the regression residuals were evaluated using Q–Q plots and scatterplots, which confirmed normally distributed residuals and homogeneous variance. Therefore, all fundamental assumptions required for valid regression analysis were met. The significance level was set at p=.05 for all tests.

Table 1. CAD/CAM blocks used, finishing techniques, and materials.

Material	Composition	Finishing	Material	Finishing technique
Vita mark II (M)	54–64% SiO_2, 20–23% Al_2O_3, 6–9% Na_2O, 6–8% K_2O	Glaze (MG)	Vita Akzent Plus Glaze Paste	Glaze firing was performed using Vita Vacumat 6000 M (6 min heating cycle; 80°C/min temperature increase rate; 950°C ring temperature; 1 min hold time)
Vita suprinity (S)	56–64% SiO_2, 15–21% Li_2O, 8–12% ZrO_2, <10% pigments	Glaze (SG)	Vita Akzent Plus Glaze Paste	After crystallization, glaze firing was performed using Vita Vacumat 6000 M (6 min heating cycle; 80°C/min temperature increase rate; 800°C ring temperature; 1 min hold time)
		Polishing (SP)	Vita Suprinity Polishing Set (Technical)	Pre-polishing: 60 s; High-gloss polishing: 60 s
Vita enamic (E)	UDMA, TEGDMA, 86% feldspathic porcelain	Polishing (EP)	Vita Enamic Polishing Set (Technical)	Pre-polishing: 60 s; High-gloss polishing: 60 s

Al_2O_3: alumina, K_2O: potassium oxide, Li_2O: lithium oxide, min: minute, Na_2O: sodium oxide, s: second, SiO_2: silicon dioxide, TEGDMA: triethylene glycol dimethacrylate, UDMA: urethane dimethacrylate, ZrO_2: zirconium dioxide

Results

Statistical analyses revealed significant differences in ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ among the evaluated CAD/CAM materials (MG, SG, SP, EP) across different time intervals. Descriptive statistics for the CIE L*, a*, and b* values of the tested materials are presented in Table 2, and ΔE_{00} values of MG, SG, SP, and EP are presented in Figure 1.

One-way ANOVA results (Table 3) indicated that ΔE_{00}, $\Delta L'$, and $\Delta C'$ values differed significantly between groups at T_0–T_1, T_0–T_{12}, and T_0–T_{30} (p=.000). However, $\Delta H'$ did not show a statistically significant difference during the T_0–T_{12} interval (p=.199). Tukey's post-hoc comparisons for ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ are also presented in Table 3. In the table, lowercase superscript letters indicate statistically significant differences between subgroups, while capital letters denote no significant differences between the corresponding materials.

According to the paired-samples t-test results (Table 4), MG showed statistically significant differences in ΔE_{00} between T_0–T_1 and T_0–T_{12} (p=.013), T_0–T_1 and T_0–T_{30} (p=.000), and T_0–T_{12} and T_0–T_{30} (p=.010). $\Delta L'$ values in MG differed significantly between T_0–T_1 and T_0–T_{12} (p=.013) and between T_0–T_1 and T_0–T_{30} (p=.000), but not between T_0–T_{12} and T_0–T_{30} (p=.058). For $\Delta C'$, significant differences were found between T_0–T_1 and T_0–T_{30} (p=.000) and between T_0–T_{12} and T_0–T_{30} (p=.001), while $\Delta H'$ showed statistically significant differences across all intervals (p=.004, p=.000, and p=.000, respectively). In the SG group, ΔE_{00} showed no significant difference between T_0–T_1 and T_0–T_{12} (p=.063), but significant differences were observed between T_0–T_1 and T_0–T_{30} (p=.000) and between T_0–T_{12} and T_0–T_{30} (p=.000). Statistically significant differences in $\Delta L'$ were found at all intervals (p=.006, p=.000, and p=.002, respectively). $\Delta C'$ showed no significant difference between T_0–T_1 and T_0–T_{12} (p=.616), but significant differences were found in the other comparisons (p=.000). $\Delta H'$ showed no significant difference between T_0–T_1 and T_0–T_{12} (p=.232), while significant differences were found between T_0–T_1 and T_0–T_{30} (p=.000) and between T_0–T_{12} and T_0–T_{30} (p=.001). In the SP group, ΔE_{00} values differed significantly across all intervals (p=.000, p=.000, and p=.003). $\Delta L'$ was significantly different between T_0–T_1 and T_0–T_{12} (p=.000 and p=.009, respectively), but not between T_0–T_{12} and T_0–T_{30} (p=.443). $\Delta C'$ did not differ significantly between T_0–T_1 and T_0–T_{12} (p=.592), but significant differences were found between T_0–T_{12} and T_0–T_{30} (p=.000). For $\Delta H'$, statistically significant differences were found between T_0–T_1 and T_0–T_{30} (p=.000) and between T_0–T_{12} and T_0–T_{30} (p=.011), but not between T_0–T_1 and T_0–T_{12} (p=.086). In the EP group, all comparisons showed statistically significant differences for ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ (p=.000), except for $\Delta H'$ between T_0–T_1 and T_0–T_{12} (p=.033).

Multiple linear regression analysis results for ΔE_{00} predictors are presented in Table 5. According to the results of the

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regression analysis conducted to identify factors affecting the level of color change across four different ceramic groups, ΔL′ at T_0–T_1 was found to be the strongest and most significant negative predictor in the MG and SP groups (β=-.990, p<.001 and β=-.951, p=.001, respectively). In the SG group, the most predictive variable was ΔH′, which also showed a strong negative relationship (β=-.830, p=.010). Although the model was overall significant in the EP group (R^2=.773, p=.023), no individual variable emerged as a significant independent predictor. At the T_0–T_{12} interval, ΔL′ was a statistically significant and strong predictor across all four ceramic groups. In the MG, SP, and SG groups, ΔL′ showed a strong negative predictive effect, with β=-.984, β=-1.080, and β=-1.022, respectively (p<.001). In the EP group, the model was again significant (R^2=.871, p=.004), and ΔL′ remained a significant predictor (β=-.984, p=.019), while the other variables were not significant. At the T_0–T_{30} interval, ΔL′ continued to be a strong negative predictor in the MG, SG, and SP groups (β=-.875, -.702, and –.896, respectively; p<.001), whereas ΔH′ was the strongest predictor in the EP group (β=-.569, p=.004).

Table 2. Descriptive analysis of CIE L*, a*, and b* values for MG, SG, SP, and EP at baseline and after 1, 12, and 30 days of coffee immersion.

		T_0 (Mean±SD)	T_1 (Mean±SD)	T_{12} (Mean±SD)	T_{30} (Mean±SD)
	L*	84.15±1.36	83.15±1.24	82.38±1.45	82.00±1.36
MG	**a***	.39±.21	.37±.20	.51±.28	.85±.16
	b*	18.56±.42	18.83±.38	18.96±.55	19.51±.27
	L*	78.86±1.05	78.57±1.20	78.28±1.17	77.84±1.25
SG	**a***	-.89±.19	-.68±.21	-.72±.18	-.48±.27
	b*	21.16±2.36	20.99±2.40	21.05±2.37	22.25±2.38
	L*	78.73±.90	78.57±.79	77.47±1.02	75.87±1.13
SP	**a***	-.46±.95	-.42±.97	-.29±.90	.75±1.17
	b*	22.59±4.99	22.57±5.06	22.69±4.73	26.56±4.91
	L*	79.90±.41	79.66±.75	79.11±0.77	78.89±.84
EP	**a***	1.83±.19	2.07±.09	2.19±.07	2.52±.15
	b*	19.76±.27	20.21±.43	20.77±.33	22.15±.55

EP: enamic with polishing, MG: mark II with glaze, SD: standard deviation, SG: suprinity with glaze, SP: suprinity with polishing, T_0: baseline; T_1: day 1 in coffee solution; T_{12}: day 12 in coffee solution; T_{30}: day 30 in coffee solution

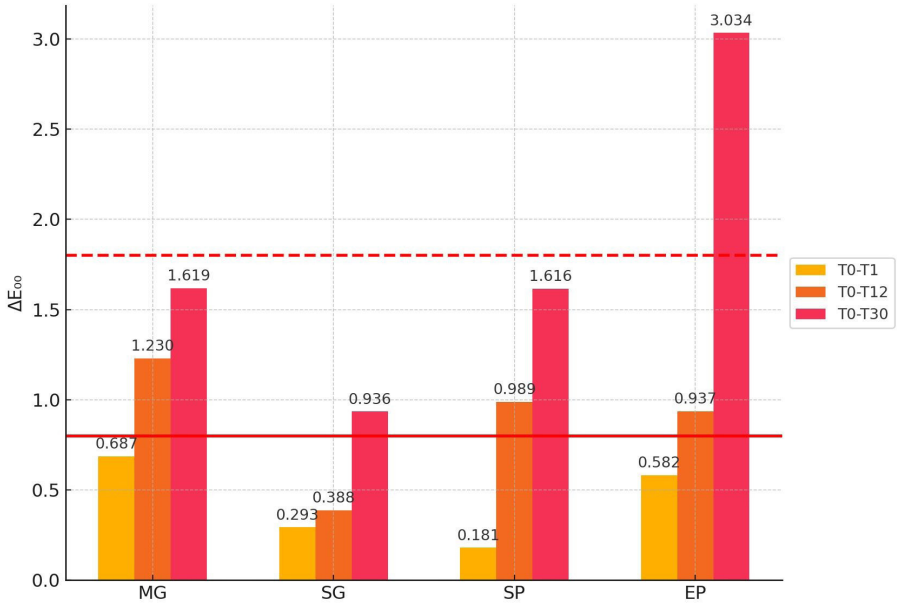

Figure 1. ΔE_{00} values of materials. The red line represents the perceptibility threshold of 0.8 units, while the discontinuous red line represents the acceptability threshold of 1.8 units; T_0: baseline, T_1: day 1 in coffee solution, T_{12}: day 12 in coffee solution, T_{30}: day 30 in coffee solution, MG: mark II with glaze, SG: suprinity with glaze, SP: suprinity with polishing, EP: enamic with polishing

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Table 3. Statistical comparison of ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ in MG, SG, SP, and EP materials across coffee-immersion time intervals (baseline, 1, 12, and 30 days)**

	Time	Group	n	Mean	SD	p-value
ΔE_{00}	T_0-T_1	MG^{abA}	10	.68	.10	.000*
		SG^{aBc}	10	.29	.08	
		SP^{bBd}	10	.18	.12	
		EP^{Acd}	10	.58	.35	
	T_0-T_{12}	MG^{aAB}	10	1.23	.48	.000*
		SG^{abc}	10	.38	.15	
		SP^{Abd}	10	.98	.30	
		EP^{Bcd}	10	.93	.39	
	T_0-T_{30}	MG^{aAb}	10	1.61	.36	.000*
		SG^{acd}	10	.93	.25	
		SP^{Ace}	10	1.61	.40	
		EP^{bde}	10	3.03	.63	
$\Delta L'$	T_0-T_1	MG^{abc}	10	–.99	.17	.000*
		SG^{aAB}	10	–.11	.21	
		SP^{bAC}	10	–.15	.23	
		EP^{cBC}	10	–.24	.73	
	T_0-T_{12}	MG^{aAb}	10	–1.77	.72	.000*
		SG^{acB}	10	–.40	.25	
		SP^{AcC}	10	–1.26	.50	
		EP^{bBC}	10	–.78	.77	
	T_0-T_{30}	MG^{abA}	10	–2.14	.54	.000*
		SG^{aBc}	10	–.84	.33	
		SP^{bBd}	10	–1.01	.83	
		EP^{Acd}	10	–2.86	.58	
$\Delta C'$	T_0-T_1	MG^{aAB}	10	.26	.12	.000*
		SG^{aCb}	10	–.18	.13	
		SP^{ACc}	10	–.02	.15	
		EP^{Bbc}	10	.49	.45	
	T_0-T_{12}	MG^{aAb}	10	.40	.32	.000*
		SG^{aBc}	10	–.12	.31	
		SP^{ABd}	10	.08	.55	
		EP^{bcd}	10	1.06	.38	
	T_0-T_{30}	MG^{Aab}	10	.97	.27	.000*
		SG^{Acd}	10	1.06	.19	
		SP^{ace}	10	2.48	.58	
		EP^{bde}	10	3.96	.96	

EP: enamic with polishing, MG: mark II with glaze, SD: standard deviation, SG: suprinity with glaze, SP: suprinity with polishing, T_0: baseline, T_1: day 1 in coffee solution, T_{12}: day 12 in coffee solution, T_{30}: day 30 in coffee solution; *One-way ANOVA test; **Tukey's post-hoc test for pairwise group comparisons: uppercase letters within each column indicate no significant difference ($p>.05$); lowercase letters indicate significant difference ($p<.05$)

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Table 3. Statistical comparison of ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ in MG, SG, SP, and EP materials across coffee-immersion time intervals (baseline, 1, 12, and 30 days)**

	Time	Group	n	Mean	SD	p-value
ΔH′	T_0-T_1	MG^{aAb}	10	.03	.10	.000*
		SG^{acB}	10	–.25	.09	
		SP^{Acd}	10	–.04	.08	
		EP^{bBd}	10	–.25	.17	
	T_0-T_{12}	MG	10	–.14	.15	.199
		SG	10	–.20	.08	
		SP	10	–.22	.27	
		EP	10	–.33	.20	
	T_0-T_{30}	MG^{ABa}	10	–.56	.19	.000*
		SG^{ACb}	10	–.55	.16	
		SP^{BCc}	10	–.55	.26	
		EP^{abc}	10	–1.42	.24	

EP: enamic with polishing, MG: mark II with glaze, SD: standard deviation, SG: suprinity with glaze, SP: suprinity with polishing, T_0: baseline, T_1: day 1 in coffee solution, T_{12}: day 12 in coffee solution, T_{30}: day 30 in coffee solution; *One-way ANOVA test; **Tukey's post-hoc test for pairwise group comparisons: uppercase letters within each column indicate no significant difference (p>.05); lowercase letters indicate significant difference (p<.05)

Table 4. Paired-samples t-test results for time-dependent changes in ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ for each material.

		T_{0-1}–T_{0-12}		T_{0-1}–T_{0-30}		T_{0-12}–T_{0-30}	
		Mean±SD	P-value	Mean±SD	P-value	Mean±SD	P-value
MG	ΔE_{00}	-.54±.55	.013*	-.93±.39	.000*	-.38±.37	.010*
	ΔL′	.77±.79	.013*	1.15±.55	.000*	.37±.54	.058
	ΔC′	-.13±.34	.247	-.70±.26	.000*	-.56±.35	.001*
	ΔH′	.17±.14	.004*	.60±.16	.000*	.42±.22	.000*
SG	ΔE_{00}	-0,94±.14	.063	-0,64±.20	.000*	-.54±.24	.000*
	ΔL′	.28±.25	.006*	0,73±.20	.000*	.44±.32	.002*
	ΔC′	-.06±.37	.616	-1,25±.26	.000*	-1.19±.42	.000*
	ΔH′	-.04±.11	.232	0,29±.17	.000*	.34±.20	.001*
SP	ΔE_{00}	-.80±.29	.000*	-1,43±.40	.000*	-.62±.49	.003*
	ΔL′	1.10±.47	.000*	.85±.80	.009*	-.25±.98	.443
	ΔC′	-.10±.60	.592	-2.50±.62	.000*	-2.39±.58	.000*
	ΔH′	.17±.28	.086	.50±.29	.000*	.33±.33	.011*
EP	ΔE_{00}	-.35±.17	.000*	-2.45±.66	.000*	-2.09±.67	.000*
	ΔL′	.54±.16	.000*	2.61±.74	.000*	2.07±.82	.000*
	ΔC′	-.57±.18	.000*	-3.47±1.11	.000*	-2.90±.99	.000*
	ΔH′	.08±.10	.033*	1.17±.21	.000*	1.09±.24	.000*

EP: enamic with polishing, MG: mark II with glaze, SD: standard deviation, SG: suprinity with glaze, SP: suprinity with polishing, T_0: baseline, T_1: day 1 in coffee solution, T_{12}: day 12 in coffee solution, T_{30}: day 30 in coffee solution; *Statistical significance was set at p<0.05

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Table 5. Multiple linear regression analysis of predictors on ΔE_{00} over specified time intervals for CAD/CAM blocks

Time interval	Group	R	R^2	Adjusted R^2	Sig. F change	Parameter	β	t	Sig.
T_0-T_1	MG	.998	.997	.995	.000	ΔL′	-.990	-39.050	.000
						ΔC′	.185	7.672	.000
						ΔH′	.007	.255	.807
	SG	.923	.852	.778	.007	ΔL′	-.562	-3.162	.020
						ΔC′	-.685	-2.779	.032
						ΔH′	-.830	-3.669	.010
	SP	.953	.908	.862	.002	ΔL′	-.951	-5.797	.001
						ΔC′	-.020	-.139	.894
						ΔH′	-.016	-.097	.926
	EP	.879	.773	.660	.023	ΔL′	-.503	-.982	.364
						ΔC′	-.395	-.777	.467
						ΔH′	.000	.000	1.000
T_0-T_{12}	MG	.999	.998	.997	.000	ΔL′	-.984	-51.120	.000
						ΔC′	.094	4.353	.005
						ΔH′	-.029	-1.347	.227
	SG	.975	.950	.925	.000	ΔL′	-1.022	-9.161	.000
						ΔC′	-.213	-1.996	.093
						ΔH′	-.261	-2.143	.076
	SP	.988	.977	.966	.000	ΔL′	-1.080	-14.716	.000
						ΔC′	.135	1.708	.139
						ΔH′	-.383	-5.460	.002
	EP	.933	.871	.806	.004	ΔL′	-.984	-3.163	.019
						ΔC′	.203	.734	.490
						ΔH′	-.144	-.683	.520
T_0-T_{30}	MG	.999	.999	.998	.000	ΔL′	-.875	-49.700	.000
						ΔC′	.149	9.065	.000
						ΔH′	-.147	-8.160	.000
	SG	.996	.991	.987	.000	ΔL′	-.702	-9.948	.000
						ΔC′	.154	3.177	.019
						ΔH′	-.226	-3.516	.013
	SP	.969	.940	.910	.000	ΔL′	-.896	-6.194	.001
						ΔC′	.476	4.530	.004
						ΔH′	-.012	-.080	.939
	EP	.995	.989	.984	.000	ΔL′	-.071	-.776	.467
						ΔC′	.393	4.449	.004
						ΔH′	-.569	-4.519	.004

β: standardized coefficient, Sig.: significance (statistical significance was set at $p<0.05$), EP: enamic with polishing, MG: mark II with glaze, SG: suprinity with glaze, SP: suprinity with polishing, T_0: baseline, T_1: day 1 in coffee solution, T_{12}: day 12 in coffee solution, T_{30}: day 30 in coffee solution

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Discussion

The null hypothesis was rejected due to statistically significant differences in ΔE_{00} values between the T_0–T_1, T_0–T_{12}, and T_0–T_{30} time intervals for MG, SG, SP, and EP specimens derived from three CAD/CAM materials with different chemical compositions.

Coffee was selected as the staining solution because it is one of the most widely consumed beverages globally. Immersion in coffee for 24 hours is equivalent to approximately one month of consumption a 12-day immersion represents about one year, and a 30-day immersion corresponds to roughly two and a half years [29]. After 30 days, the degree of staining was observed in the following order: EP (ΔE_{00}=3.03)>MG (ΔE_{00}=1.62)=SP (ΔE_{00}=1.62)>SG (ΔE_{00}=.94). Thus, EP materials exhibited a moderate and clinically unacceptable level of staining, while the other materials demonstrated staining within clinically acceptable limits. Additionally, the amount of staining increased over time. These findings are consistent with previous studies [6,7,18,21]. Earlier research has shown that the higher stainability of EP materials compared to other CAD/CAM ceramics may be attributed to the presence of TEGDMA and UDMA [8,11]. TEGDMA's hydrophilic nature is associated with reduced color stability, while UDMA molecules in the resin matrix significantly influence staining [26,30]. The absorption of chromogens and tannins from the coffee solution, along with water absorption by the material, likely contributes to this discoloration [8,11,18,30].

Glazed zirconia-reinforced lithium silicates and glazed feldspathic porcelains demonstrated similar levels of staining. However, polished zirconia-reinforced lithium silicates stained more than their glazed counterparts, underscoring the importance of the glaze layer in maintaining the color stability of all-ceramic prostheses [21]. The reduced color change observed in the S material in this study may be due to its homogeneous structure and the presence of finer zirconia crystal particles [3,22]. Other research has shown that a material's microstructure significantly affects color stability after thermocycling in coffee [23]. The findings of the present study were also consistent with those evaluating the effects of finishing techniques and chemical composition on stainability [3,17,21-23]. These factors may play a crucial role in the clinical selection of restorative materials.

In present study, ΔE_{00} was calculated using the CIEDE2000 formula. Changes in $\Delta L'$, $\Delta C'$, and $\Delta H'$ values in the formula directly affected ΔE_{00}. Acceptability thresholds for $\Delta L'$, $\Delta C'$, and $\Delta H'$ have been reported as $\Delta L'$=2.4, $\Delta C'$=3.2, and $\Delta H'$=3.2 [28]. Although there was not yet a broad consensus on the exact color coordinate values that define the boundaries of the tooth color space, most studies were in agreement that tooth colors vary predominantly in terms of brightness and chromaticity [31]. The tannins and chromogens present in coffee solution might cause discoloration of composite resin through both adsorption and absorption [18]. $\Delta L'$ values decreased due to discoloration. While the $\Delta L'$ value at T_0–T_{30} showed a clinically unacceptable level ($\Delta L'$>2.4) of decrease for the EP material, the changes observed in MG, SG, and SP materials remained within clinically acceptable limits. These findings were consistent with the previous studies and might be attributed to the declining trend in the CIE L* value resulting from the staining properties of the coffee solution.

It was known that as the chroma of a specimen decreases, the observer's ability to perceive color became more limited. Low chroma values were associated with higher acceptability rates compared to high chroma values, and thus high chroma values considered esthetically unacceptable [30]. $\Delta C'$ values, which could reflect chromatic change, increased after 30 days in accordance with the level of staining. EP material exhibited a clinically unacceptable increase, whereas MG, SG, and SP materials showed increases within clinically acceptable levels. $\Delta H'$ values showed a clinically acceptable decrease after 30 days, likely due to increases in the CIE a* and b* values caused by coffee-induced staining. According to regression analysis, $\Delta L'$, $\Delta C'$, and $\Delta H'$ values were found to significantly influence ΔE_{00} after 30 days of staining in the MG and SG groups. In the SP group, $\Delta L'$ and $\Delta C'$ were effective predictors, while in the EP group, $\Delta C'$ and $\Delta H'$ were found to be influential. These findings underscored the importance of both the finishing technique and the material's chemical composition [3,15,16,18].

Studies show that study designs, particularly staining procedures, were susceptible to variability and required standardization [18]. The CIEDE2000 color formula has been found to be more effective than the CIELab formula in detecting perceptible color differences [27]. In studies have investigated the effect of chemical composition on staining [6,7,21], the materials used in these studies were evaluated using ΔEab [6,7,21,32], with different threshold values applied. The staining of these materials were reported to be within clinically acceptable levels. It has also been observed that CIE L* values decreased while a* and b* values increasing in response to dark beverage exposure [29]. The CIE a* and b* values were used in the CIEDE2000 formula to calculate $\Delta C'$ and $\Delta H'$ [27,28]. However, current studies have not reported how changes in CIE L*, a*, and b* values specifically influence $\Delta C'$ and $\Delta H'$ [6,14,21,26]. In the present study, color differences were not only calculated using the ΔE_{00} formula, but the changes in $\Delta L'$, $\Delta C'$, and $\Delta H'$ values were also statistically analyzed. Upon reviewing the literature on the stainability of CAD/CAM blocks with different microstructures, no studies were found—based on the authors' knowledge—that calculated and reported $\Delta L'$, $\Delta C'$, and $\Delta H'$ values [6,21,26]. Therefore, consistent findings on the variation of $\Delta L'$, $\Delta C'$, and $\Delta H'$, and their specific contributions to ΔE_{00}, have not yet been established. This represents the unique contribution of the present study.

Limitations of the present study were use of three different CAD/CAM materials with a single thickness were used, and evaluations were based on static immersion in a coffee solution

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without the removal of staining agents through methods such as mechanical re-polishing or tooth brushing. Another limitation was that the coffee solution contacted both surfaces of the specimens during immersion which might potentially affected results. Additional in vitro studies are needed to further investigate the optical and physical properties of these materials, including their stainability under varied conditions, such as exposure to different staining solutions, surface cleaning with a toothbrush, and the application of artificial aging techniques. In vivo studies might also necessary to assess material performance under clinical conditions.

Conclusion

Within the limitations of this study, the following conclusions could be drawn:

1. The chemical composition of the material influences ΔE_{00}, $\Delta L'$, $\Delta C'$, and $\Delta H'$ values.
2. Ceramic discoloration increased in proportion to the duration of immersion in the coffee solution.
3. SG material exhibited the least staining among all tested materials and remained within clinically acceptable limits, whereas EP material showed a moderate level of clinically unacceptable staining ($\Delta E_{00}>1.8, \leq 3.6$).
4. For obtaining the long-term success of the restorations in the anterior region, where esthetics are critical, SG may be preferred over SP and MG in terms of stain resistance.

Conflict of Interests
The authors declare that there is no conflict of interest in the study.

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Ethical Approval
The research study was entirely conducted under in vitro conditions. Ethical approval was not required because no human participants were involved and no personal data was collected.

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