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Air-Polishing Powders' Effect on the Color of CAD/CAM Restorative Materials

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Abstract: Air-polishing powders are used to remove stains from the enamel and various restorative materials, but their effect on the discoloration of CAD/CAM blocks remains scarce. Therefore, this study investigated the effect of various air-polishing powders on the color changes in different CAD/CAM blocks to predict the esthetic outcomes. Specimens were prepared from CAD/CAM blocks (Vita Mark II, Paradigm MZ100, Lava Ultimate, Cerasmart, Vita Enamic) and divided into five groups (n = 10) according to the air-polishing powder: sodium bicarbonate; aluminum trihydroxide; calcium carbonate; glycine; and erythritol. Color parameters were measured with a spectrophotometer before and after air-polishing. The color difference was calculated with the ΔE_{00} formula. Data were statistically evaluated with one-way ANOVA, Tukey, and two-way ANOVA tests ($\alpha = 0.05$). The CAD/CAM block type and the air-polishing powder type significantly influenced the ΔE_{00} value, whereas their interactions did not affect it significantly. Calcium carbonate and aluminum trihydroxide significantly increased the ΔE_{00} values of Lava Ultimate and Cerasmart. Although none of the groups exceeded the acceptability threshold (ΔE_{00} = 1.8), most exceeded the perceptibility threshold (ΔE_{00} = 0.8). Consequently, dentists should avoid air-polishing or should repolish with care, depending on restorative material knowledge, to maintain color stability when uncertain about the material encountered clinically.

Keywords: CAD/CAM blocks; air-polishing; color stability; resin-matrix ceramics; air-polishing powders

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1. Introduction

In recent years, patients' interest and expectations about prosthetic restorations have increased tremendously. In order to meet these expectations, the application of metal-free fixed restorations became very popular due to their superior biocompatibility, chemical stability, high color durability, lower surface roughness, and esthetical advantages [1,2]. As a result, there has been a significant advance in material development. One of these advances is CAD/CAM systems, which offer a faster and more compatible indirect prosthetic treatment [3], and another one is the diversification of tooth-colored CAD/CAM blocks to develop the ideal material. Consequently, manufacturers introduced CAD/CAM restorative materials of glass ceramics, and feldspar ceramic was the first member of this group with its good aesthetic properties, high hardness, and low thermal conductivity [1]. Then, to strengthen the physical properties of feldspar ceramics, zirconia-, leucite-, or lithium disilicate-reinforced ceramics have become prominent. However, glass ceramics have many disadvantages, including wearing the antagonist tooth, the necessity of firing for adequate strength, the difficulty of occlusal adjustment, and chipping [4,5]. Therefore, CAD/CAM blocks of resin-matrix ceramics, which overcome these disadvantages and have further advantages, are produced [2]. For instance, they are easier to process, polish, and repair, have better marginal quality, and are more elastic than dental ceramics [6–8]. Resin-matrix ceramic blocks typically consist of methacrylate-based polymer matrices with a high ceramic content, including glasses, porcelains, and ceramics, thereby being categorized as a type of ceramics by the American Dental Association [9]. They can be categorized into two primary classes related to their micro arrangement: (1) resin with scattered fillers and (2) polymer-infiltrated ceramic networks [2,10]. The first class consists of resin composite blocks, manufactured by integrating inorganic fillers, such as silica, zirconium, and barium, into an organic matrix composed of methacrylate monomers. The second class consists of blocks with polymer-infiltrated ceramic networks, which include mainly inorganic parts and the polymers infiltrated into them [2,7,10–12].

The aesthetic appearance of the restorative materials is very important for the patients, and color stability is crucial for an aesthetic smile. Most patients treated prosthodontically regularly undergo professional teeth cleaning, in which the stains and the plaque deposits are removed [13]. During this procedure, polishing is usually performed to sustain color stability and to make a more glossy and smoother surface after initial periodontal therapy [14,15]. In addition, polishing is also applied to remove the biofilm layer during supportive periodontal therapy (SPT) [16]. SPT includes all parts of a typical dental recall examination, periodontal re-evaluation, removal of bacterial plaque and calculus, and re-treatment of any parts with recurrent disease [17], and patients with high risk are advised to be recalled three to four times a year for preventive care [15,18]. During these recall appointments, apart from conventional techniques like using ultrasonic scalers and curette, air-polishing can be applied to remove bacterial plaque and stains [16,19]. Air-polishing provides a safer, faster, more compatible, and non-heat-producing option for patients [16,20–22]. Air-polishing devices work with air pressure, water, and abrasive powders [14]. When these abrasive air-polishing powders (APPs) are sprayed using the air-polishing instrument, dental plaque and stains are removed with kinetical energy [23–25].

Among the APPs, sodium bicarbonate, with a particle size of up to 250 µm, was the first to be introduced to the market [26]. However, according to the manufacturer's instructions, its use should be avoided in patients with kidney disease and those who have inconveniences with a salty diet, and its taste is not pleasant. Therefore, aluminum trihydroxide, with an 80–325 µm particle size, was introduced as an alternative for removing heavy stains and the biofilm layer [24]. However, due to their great particle sizes, both APPs were abrasive and destructive for surfaces of both the enamel and the dental restorations [27]. To overcome the negative effects of these APPs, calcium carbonate, glycine, sodium bicarbonate with reduced particle size, and erythritol-based APPs were introduced [28]. Calcium carbonate, used as an abrasive in dentifrices, exists naturally on rocks, eggshells, pearls, and seashells [24]. In addition, this APP is in the form of small spheres in clusters, while sodium bicarbonate and glycine powders are in the form of grains [29]. Glycine (aminoacetic acid) is the smallest of the non-essential amino acids found in proteins. It has two powder forms with different sizes of grains to be used, either supragingival or subgingival [24]. Furthermore, it is indicated for removing medium-light discolorations along with the APP composed of erythritol, a water-soluble sugar alcohol with very fine, dense particles [30].

There are studies about the efficiency of the APPs in removing discolorations and the staining susceptibility of restorative materials that are exposed to air-polishing and staining solutions afterward [31–33]. However, to the best of the authors' knowledge, there is no research on how these APPs themselves affect the color stability of indirect restorative materials such as resin matrix ceramics. Dentists need to know how these APPs might affect the color of restorative materials to predict aesthetic outcomes. Therefore, this study aimed to investigate the effect of five different APPs on five different CAD/CAM restorative materials regarding color change. As a result, it is hypothesized that (1) applying different APPs does not affect the color parameters of CAD/CAM restorative materials and (2) the color change after air-polishing is not affected by the type of CAD/CAM restorative material.

2. Materials and Methods

Five different types of CAD/CAM blocks were tested in this study. A glass–ceramic, namely, Vitablocs Mark II (VM) (feldspar ceramic; Vita Zahnfabrik H. Rauter, Bad Sackingen, Germany); resins with scattered fillers, namely, Paradigm MZ 100 (MZ) (resin composite; 3M ESPE, Seefeld, Germany), Lava Ultimate (LU) (resin nanoceramic; 3M ESPE, Seefeld, Germany), and Cerasmart (CS) (flexible hybrid ceramic; GC Corp., Alsip, IL, USA); and a polymer-infiltrated ceramic network, namely, Vita Enamic (VE) (polymer-infiltrated ceramic network; Vita Zahnfabrik H. Rauter, Bad Sackingen, Germany) were analyzed. The comprehensive information on these blocks is exhibited in Table 1. A flow chart of the study design is shown in Figure 1.

Table 1. CAD/CAM blocks used in this study.

Material and Manufacturer	Batch	Type	Shade	Composition
Vitablocs Mark II (VM); Vita Zahnfabrik	35360	Feldspar ceramic	A2	Fine-particle feldspar ceramic (4 µm).
Paradigm MZ 100 (MZ); 3M ESPE	N543696	Resin composite	A2	Bis-GMA, TEGDMA. Filler: zirconia–silica particles (0.01 to 3.5 µm), 85% by weight.
Lava Ultimate (LU); 3M ESPE	N593972	Resin nanoceramic	A2	Bis-EMA, Bis-GMA, TEGDMA, UDMA. Filler: ZrO_2 (4–11 nm) and SiO_2 (20 nm), aggregated zirconia/silica cluster filler, 80% by weight.
Cerasmart (CS); GC Corp.	1408011	Flexible hybrid ceramic	A2	Bis-MEPP, UDMA, Dimethacrylate. Filler: SiO_2 (20 nm), barium glass (300 nm), 71% by weight.
Vita Enamic (VE); Vita Zahnfabrik	42821	Polymer-infiltrated ceramic network	A2	TEGDMA, UDMA. Filler: feldspar ceramic enriched with aluminum oxide, 86% by weight.

Abbreviations: Bis-EMA, ethoxylated bisphenol A glycol dimethacrylate; Bis-GMA, bisphenol A diglycidyl methacrylate; Bis-MEPP, bisphenol A ethoxylate dimethacrylate; TEGDMA, triethylene glycol dimethacrylate; UDMA, Urethane dimethacrylate.

The sample size was calculated with power analysis using G*Power software (Version 3.1; University of Dusseldorf, Dusseldorf, Germany). The effect size (d) was taken as 0.606, and the standard deviation value for ΔE was taken as 1, so the number of samples, determined for power: 0.80 and α: 0.05, was calculated as minimum n = 6 for each group, related to a previous study [34]. Fifty samples of 1.1 mm thickness were prepared from each CAD-CAM block with diamond disks using a slow-speed precision cutter (Mecatome T180, PRESI, Eybens, France). All specimens were polished with a polishing machine (Mecatech 234 TCI-10, Presi, Eybens, France) and ground to the final thickness of 1 mm with waterproof abrasive papers from 320 to 2000 grits. Then, the samples were further polished for 180 s with the same machine, in accordance with the manufacturer's instructions, at a constant speed of 150 rpm clockwise and 30 rpm counterclockwise, with a pressure of 3.00 daN, using a blue polishing felt (PRESI, Reflex Concept Pad Mag, Eybens, France) and a 0.50 mL drop of diamond polishing solution (PRESI, Preparations Diamentees Mecaprex, Eybence, France) every 10 s. The final thicknesses of the specimens were checked with a digital micrometer (C-master; Mitutoyo, Japan). Then, the specimens were cleaned in distilled water with an ultrasonic cleaner (Eurosonic Energy; Euronda SpA, Vicenza, Italy) for 10 min and dried with oil-free air for 30 s. After the CAD/CAM blocks were randomly divided into five groups (n = 10) for air-polishing with different APPs, the color measurement of each specimen was performed.

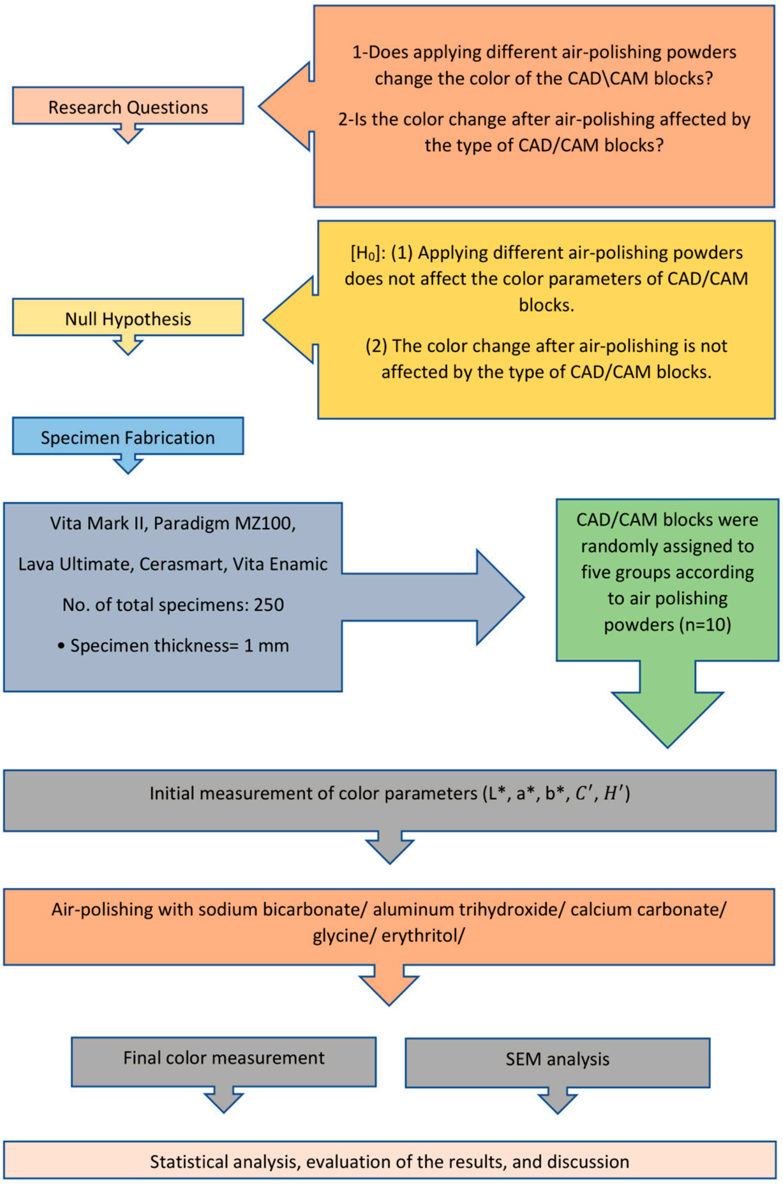

Figure 1. Study design.

The color parameters, L* (lightness), a* (green-red coordinates), and b* (yellow-red coordinates) of each specimen were measured on a white background (L* = 98.20, a* = −3.52, b* = 4.65) using a spectrophotometer (CM-3600d, Konica Minolta, Tokyo, Japan), with 360–740 nm wavelength interval, specular component included, standard D65 (daylight) light source, and 2° observer [35], double-ray UV-100% visible reflection feature with 10 nm intervals, by an experienced operator who had been trained to use the spectrophotometer. Each specimen was measured three times; the mean value was the sample's color. The device was calibrated before the measurement of each group, according to the manufacturer's instructions, using computer software (Spectra-Magic NX, Version 3.61, Konica Minolta Sensing, Inc., Tokyo, Japan).

After initial color measurements, five different APPs, namely, sodium bicarbonate, aluminum trihydroxide, calcium carbonate, glycine, and erythritol, were applied to each group with an air-polishing device (Air-Flow S1, EMS, Nyon, Switzerland). The brands, manufacturers, lot numbers, particle sizes, Mohs hardness numbers, and densities of the tested APPs are presented in Table 2.

Table 2. Air-polishing powders used in this study.

Composition	Brand Name	Manufacturer	Mean Particle Size	Mohs No.	Density (g/cm^3)	Lot No.
Sodium bicarbonate	Air-Flow Classic	EMS	65 µm	2.5	2.22	1403132
Aluminum trihydroxide	Cavitron Jet-Fresh Powder	Dentsply	80–325 µm	4	2.42	110527
Calcium carbonate	Prophypearls	KAVO	45–55 µm	3	2.93	0265936
Glycine	Air-Flow Soft	EMS	65 µm	2	1.59	1202101
Erythritol	Air-Flow Plus	EMS	14 µm	<2	1.45	1302262

The APPs were applied on the surface of the specimens with a 60° angle and 4–5 mm distance at a medium setting (water pressure: 3 bar, air pressure: 5.75 bar) always by the same trained operator [24,36,37]. In addition, the powder chamber of the device was filled to the maximum level after each application to ensure constant powder flow. A previous study reported that the application period of APP during a recall appointment should be 1–2 s for a tooth's anatomical crown, and more than 10 s would be harmful to the patient [38]. In a dental arch without any loss of interdental papilla and ideally aligned, an average upper central incisor's surface area that can be air-polished is approximately 150 mm^2 [39]. Therefore, if air polishing can be applied for 1 s to a 150 mm^2 area in a recall appointment, then it should be applied for 1/150 s to an area of 1 mm^2 in one recall appointment. Consequently, to simulate ten years of 3 monthly recall appointments [15,18,40–42], air-polishing should be applied for a period of 40 times longer, equivalent to 40/150 s for a 1 mm^2 area [43]. Since the surface areas of the CAD/CAM blocks were different from each other, the duration of air-polishing was calculated for the area of each CAD/CAM block separately.

After surface treatment with the APPs, each specimen's L*, a*, and b* values were measured in the same way. The quantitative color difference (ΔE_{00}) values between the initial and final measurements of the specimens were calculated using the CIEDE2000 color difference formula [44].

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_c}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_c}\frac{\Delta H'}{k_H S_H}}$$

In this formula, $\Delta L'$, $\Delta C'$, and $\Delta H'$ indicate the differences in lightness, chroma, and hue, respectively; S_L, S_C, and S_H are weighting functions that provide a better correspondence with visual evaluation; and R_T is the rotation function. The parametric weighting factors k_L, k_C, and k_H are correction terms for experimental conditions, and they were determined as 1 [45,46].

Microscopic morphologies and particle sizes of the APPs were analyzed under scanning electron microscopy (SEM) (Zeiss EVO LS 10, Oberkochen, Germany). The APPs were sputter-coated with gold/palladium (Quorum SC7620, West Sussex, England) and then analyzed at 10 kV, with 100×, 200×, and 15,000× magnifications. In addition, ten specimens from each CAD/CAM block were processed, with two samples for each APP. The CAD/CAM block was then split into two halves. One half was sprayed with APP, while the other half was covered and left untreated, serving as control. Then, these specimens were also sputter-coated with gold/palladium (Quorum SC7620, West Sussex, England), and the surface topography was analyzed under SEM with 10 kV at 200× magnification.

Mean ± standard deviation values were calculated according to the raw data in Table S1 and subjected to the Shapiro–Wilk test to analyze the convenience of quantitative data for a normal distribution; a one-way ANOVA analysis to compare three or more groups that showed a normal distribution; and the Tukey HSD test to determine which group made the difference. A two-way ANOVA analysis was used to evaluate the effect of both the APP and the restorative material type on quantitative variables. Significance was evaluated at $p < 0.01$ and $p < 0.05$ levels.

3. Results

The results of the colorimetric analysis revealed that applying APPs affects the final color of CAD/CAM restorative material ($p < 0.05$, $p < 0.001$). In accordance with the two-way ANOVA test results in Table 3, the type of CAD/CAM restorative material had a significant effect on the ΔL^* (F: 21.121; $p < 0.001$), Δa^* (F: 18.063; $p < 0.001$), Δb^* (F: 49.923; $p < 0.001$), $\Delta C'$ (F: 43.939; $p < 0.001$), $\Delta H'$ (F: 19.243; $p < 0.001$), and ΔE_{00} (F: 6.205; $p < 0.001$) values. In addition, the type of APP had a significant effect on the Δa^* (F: 28.589; $p < 0.001$), $\Delta \mathrm{H}$ (F: 27.578; $p < 0.001$), and ΔE_{00} (F: 5.505; $p < 0.001$) values, but did not have a significant effect on ΔL^* (F: 2.399; p: 0.051), Δb^* (F: 1.805; p: 0.129), or $\Delta C'$ (F: 2.062; p: 0.087) values. The interaction terms were not significant for the ΔL^* (F: 1.095; p: 0.361), Δa^* (F: 1.552; p: 0.084), Δb^* (F: 0.854; p: 0.623), $\Delta C'$ (F: 0.948; p: 0.515), $\Delta H'$ (F: 1.669; p: 0.054), or ΔE_{00} (F: 0.996; p: 0.462) values.

Table 3. Influence of CAD/CAM block type and air-polishing powder on the change in color parameters according to two-way ANOVA.

V Variation Factor	df		Type III Sum of Squares	Mean Square	F	p
Corrected model	24	ΔE_{00}	20.789	0.866	2.615	<0.001 **
		ΔL^*	80.765	3.365	4.650	<0.001 **
		Δa^*	9.202	0.383	8.810	<0.001 **
		Δb^*	37.621	1.568	9.190	<0.001 **
		$\Delta C'$	34.267	1.428	8.299	<0.001 **
		$\Delta H'$	8.909	0.371	8.916	<0.001 **
Intercept	1	ΔE_{00}	167.265	167.265	505.055	<0.001 **
		ΔL^*	5.791	5.791	8.002	0.005 **
		Δa^*	18.857	18.857	433.297	<0.001 **
		Δb^*	1.246	1.246	7.306	0.007 **
		$\Delta C'$	0.476	0.476	2.767	0.098
		ΔH	23.409	23.409	562.262	<0.001 **
CAD/CAM block	4	ΔE_{00}	8.220	2.055	6.205	<0.001 **
		ΔL^*	61.143	15.286	21.121	<0.001 **
		Δa^*	3.144	0.786	18.063	<0.001 **
		Δb^*	34.060	8.515	49.923	<0.001 **
		$\Delta C'$	0.476	0.098	43.939	<0.001 **
		$\Delta H'$	3.205	0.801	19.243	<0.001 **
Air-polishing powder	4	ΔE_{00}	7.292	1.823	5.505	<0.001 **
		ΔL^*	6.946	1.737	2.399	0.051
		Δa^*	4.977	1.244	28.589	<0.001 **
		Δb^*	1.231	0.308	1.805	0.129
		$\Delta C'$	1.419	0.355	2.062	0.087
		$\Delta H'$	4.593	1.148	27.578	<0.001 **
CAD/CAM block × air-polishing powder	16	ΔE_{00}	5.276	0.330	0.996	0.462
		ΔL^*	12.676	0.792	1.095	0.361
		Δa^*	1.081	0.068	1.552	0.084
		Δb^*	2.330	0.146	0.854	0.623
		$\Delta C'$	2.610	0.163	0.948	0.515
		$\Delta H'$	1.112	0.069	1.669	0.054

** $p < 0.01$.

As illustrated in Tables 4–8, in the MZ groups, the samples' ΔL^*, Δa^*, Δb^*, and $\Delta C'$ values decreased, while the $\Delta H'$ values increased, regardless of the APP used. The APP of aluminum trihydroxide increased the Δb^* and $\Delta C'$ values of LU significantly compared with the APP of glycine. In addition, calcium carbonate increased the Δa^* and $\Delta H'$ values of LU significantly, compared with the other APPs. Furthermore, aluminum trihydroxide and calcium carbonate changed the Δa^* and $\Delta H'$ values of CS significantly, compared with the rest of the APPs.

Table 4. Mean ± standard deviation values of the ΔL^* value and post hoc analysis for pairwise comparisons.

	^{1} **Sodium Bicarbonate**	^{2} **Aluminum Trihydroxide**	^{3} **Calcium Carbonate**	^{4} **Glycine**	^{5} **Erythritol**	^{b} ***p***	^{c} **Post Hoc**
^{A} **VM**	−0.28 ± 0.48	0.08 ± 0.39	−0.07 ± 0.23	−0.11 ± 0.42	1.02 ± 2.36	0.090	
^{B} **MZ**	−0.66 ± 0.82	−0.94 ± 1.04	−1.19 ± 0.47	−0.78 ± 0.62	−0.57 ± 0.80	0.411	
^{C} **LU**	0.01 ± 0.56	0.23 ± 1.02	−0.13 ± 0.57	−0.16 ± 0.40	−0.02 ± 0.27	0.654	
^{D} **CS**	−0.66 ± 0.82	−0.56 ± 0.87	−1.14 ± 0.69	−0.14 ± 0.65	−0.43 ± 0.94	0.096	
^{E} **VE**	0.52 ± 0.43	0.51 ± 0.35	0.58 ± 0.75	0.45 ± 0.43	0.63 ± 1.65	0.992	
^{b} ***p***	0.001 **	0.001 **	<0.001 **	<0.001 **	0.066		
^{c} **Post Hoc**	B, D < E	B < A, C, E D < E	B, D < A, C, E	B < A, E	–		

^{b} One-way ANOVA, ^{c} Tukey HSD, ** $p < 0.01$. Different superscript upper-case letters imply the CAD/CAM block they refer, and different superscript numbers imply the air-polishing powder they refer. Abbreviations: VM, Vita Mark II; MZ, Paradigm MZ 100; LU, Lava Ultimate; CS, Cerasmart; VE, Vita Enamic.

Table 5. Mean ± standard deviation values of the Δa^* value and post hoc analysis for pairwise comparisons.

	^{1} **Sodium Bicarbonate**	^{2} **Aluminum Trihydroxide**	^{3} **Calcium Carbonate**	^{4} **Glycine**	^{5} **Erythritol**	^{b} ***p***	^{c} **Post Hoc**
^{A} **VM**	−0.34 ± 0.15	−0.59 ± 0.34	−0.41 ± 0.15	−0.24 ± 0.10	−0.32 ± 0.09	0.002 **	1, 4, 5 > 2
^{B} **MZ**	−0.13 ± 0.10	−0.49 ± 0.16	−0.49 ± 0.10	−0.27 ± 0.16	−0.16 ± 0.09	<0.001 **	1, 4, 5 > 2, 3
^{C} **LU**	−0.11 ± 0.08	−0.24 ± 0.15	−0.52 ± 0.26	−0.15 ± 0.10	−0.18 ± 0.29	<0.001 **	1, 2, 4, 5 > 3
^{D} **CS**	−0.25 ± 0.13	−0.58 ± 0.22	−0.55 ± 0.18	−0.19 ± 0.09	−0.28 ± 0.11	<0.001 **	1, 4, 5 > 2, 3
^{E} **VE**	0.16 ± 0.12	−0.28 ± 0.26	−0.30 ± 0.57	0.00 ± 0.10	0.05 ± 0.31	0.007 **	1 > 2, 3
^{b} ***p***	<0.001 **	0.002 **	0.370	<0.001 **	0.003 **		
^{c} **Post Hoc**	A, B, C, D < E A < B, C	A, D < C, E	–	A, B, C, D < E	A, D < E		

^{b} One-way ANOVA, ^{c} Tukey HSD, **$p < 0.01$. Different superscript upper-case letters imply the CAD/CAM block they refer, and different superscript numbers imply the air-polishing powder they refer. Abbreviations: VM, Vita Mark II; MZ, Paradigm MZ 100; LU, Lava Ultimate; CS, Cerasmart; VE, Vita Enamic.

Table 6. Mean ± standard deviation values of the Δb^* value and post hoc analysis for pairwise comparisons.

	^{1} **Sodium Bicarbonate**	^{2} **Aluminum Trihydroxide**	^{3} **Calcium Carbonate**	^{4} **Glycine**	^{5} **Erythritol**	^{b} ***p***	^{c} **Post Hoc**
^{A} **VM**	−0.05 ± 0.18	0.15 ± 0.20	0.05 ± 0.20	0.06 ± 0.15	0.12 ± 0.31	0.305	-
^{B} **MZ**	−0.74 ± 0.35	0.14 ± 0.43	−0.62 ± 0.25	−0.63 ± 0.22	−0.69 ± 0.34	0.495	-
^{C} **LU**	−0.20 ± 0.32	0.23 ± 1.02	0.02 ± 0.37	−0.32 ± 0.23	−0.08 ± 0.27	0.030 *	4 < 2
^{D} **CS**	−0.30 ± 0.27	−0.02 ± 0.77	−0.47 ± 0.39	−0.12 ± 0.28	−0.05 ± 0.53	0.204	-
^{E} **VE**	0.48 ± 0.34	0.42 ± 0.36	0.58 ± 0.55	0.44 ± 0.37	0.59 ± 1.08	0.957	-
^{b} ***p***	<0.001 **	0.001 **	<0.001 **	<0.001 **	0.001 **		
^{c} **Post Hoc**	B < A, C, D < E	B < A, C, E	B, D < A, C < E	B < A, D, E A, C, D < E C < A	B < A, E		

^{b} One-way ANOVA, ^{c} Tukey HSD, * $p < 0.05$, ** $p < 0.01$. Different superscript upper-case letters imply the CAD/CAM block they refer, and different superscript numbers imply the air-polishing powder they refer. Abbreviations: VM, Vita Mark II; MZ, Paradigm MZ 100; LU, Lava Ultimate; CS, Cerasmart; VE, Vita Enamic.

Table 7. Mean ± standard deviation values of the $\Delta C'$ value and post hoc analysis for pairwise comparisons.

	^{1} Sodium Bicarbonate	^{2} Aluminum Trihydroxide	^{3} Calcium Carbonate	^{4} Glycine	^{5} Erythritol	[b] p	[c] Post Hoc
^{A} VM	−0.04 ± 0.18	0.18 ± 0.20	0.07 ± 0.19	0.06 ± 0.15	0.13 ± 0.31	0.217	
^{B} MZ	−0.71 ± 0.35	−0.41 ± 0.34	−0.52 ± 0.24	−0.58 ± 0.21	−0.65 ± 0.33	0.216	
^{C} LU	−0.18 ± 0.31	0.17 ± 0.42	0.10 ± 0.34	−0.30 ± 0.22	−0.05 ± 0.31	0.014 *	4 < 2
^{D} CS	−0.29 ± 0.26	0.02 ± 0.77	−0.43 ± 0.38	−0.11 ± 0.28	−0.03 ± 0.53	0.208	
^{E} VE	0.50 ± 0.35	0.40 ± 0.37	0.57 ± 0.56	0.44 ± 0.37	0.59 ± 1.10	0.951	
[b] p	0.001 **	0.001 **	<0.001 **	<0.001 **	0.066		
[c] Post Hoc	B < A, C, D < E	B < A, C, E	D, B < A, C < E	A, B, C, D < E B < A, D C < A	B < A, E		

[b] One-way ANOVA, [c] Tukey HSD, * $p < 0.05$, ** $p < 0.01$. Different superscript upper-case letters imply the CAD/CAM block they refer, and different superscript numbers imply the air-polishing powder they refer. Abbreviations: VM, Vita Mark II; MZ, Paradigm MZ 100; LU, Lava Ultimate; CS, Cerasmart; VE, Vita Enamic.

Table 8. Mean ± standard deviation values of the $\Delta H'$ value and post hoc analysis for pairwise comparisons.

	^{1} Sodium Bicarbonate	^{2} Aluminum Trihydroxide	^{3} Calcium Carbonate	^{4} Glycine	^{5} Erythritol	[b] p	[c] Post Hoc
^{A} VM	0.34 ± 0.15	0.59 ± 0.33	0.41 ± 0.15	0.24 ± 0.10	0.32 ± 0.08	0.002 **	1, 2, 3 < 5
^{B} MZ	0.26 ± 0.11	0.57 ± 0.17	0.60 ± 0.12	0.37 ± 0.18	0.27 ± 0.09	<0.001 **	1, 2, 3 < 4, 5
^{C} LU	0.14 ± 0.12	0.22 ± 0.16	0.52 ± 0.29	0.19 ± 0.12	0.18 ± 0.25	0.001 **	1, 2, 3, 5 < 4
^{D} CS	0.27 ± 0.14	0.58 ± 0.22	0.59 ± 0.21	0.20 ± 0.09	0.28 ± 0.11	<0.001 **	1, 2, 3 < 4, 5
^{E} VE	−0.13 ± 0.11	0.31 ± 0.25	0.34 ± 0.55	0.04 ± 0.08	0.00 ± 0.23	0.003 **	2 < 4, 5
[b] p	0.001 **	0.001 **	<0.001 **	<0.001 **	0.066		
[c] Post Hoc	E < A, B, C, D C < A	C < A, B, D	-	E < A, B, C, D C, D < B	E < A, B, D		

[b] One-way ANOVA, [c] Tukey HSD. ** $p < 0.01$. Different superscript upper-case letters imply the CAD/CAM block they refer, and different superscript numbers imply the air-polishing powder they refer. Abbreviations: VM, Vita Mark II; MZ, Paradigm MZ 100; LU, Lava Ultimate; CS, Cerasmart; VE, Vita Enamic.

As shown in Table 9, there were significant differences in terms of the ΔE_{00} values related to the type of APP only in the LU and CS groups (p: 0.004). According to the pairwise comparison, it was found that the ΔE_{00} values of the samples that were exposed to erythritol in the LU group and glycine in the CS group were significantly lower than those exposed to calcium carbonate (p: 0.012; p: 0.003); and aluminum trihydroxide (p: 0.047; p: 0.008), respectively. There was no significant difference in terms of the ΔE_{00} values in the VM, MZ, and VE groups according to different APPs ($p > 0.05$).

Table 9. Mean ± standard deviation values of the ΔE_{00}^{*} value and post hoc analysis for pairwise comparisons.

	^{1} Sodium Bicarbonate	^{2} Aluminum Trihydroxide	^{3} Calcium Carbonate	^{4} Glycine	^{5} Erythritol	[b] p	[c] Post Hoc
^{A} VM	−0.62 ± 0.23	0.90 ± 0.44	0.62 ± 0.21	0.44 ± 0.24	1.14 ± 1.75	0.352	-
^{B} MZ	1.03 ± 0.33	1.34 ± 0.45	1.32 ± 0.38	0.99 ± 0.41	0.93 ± 0.42	0.072	-
^{C} LU	0.49 ± 0.22	0.79 ± 0.43	0.87 ± 0.35	0.45 ± 0.24	0.37 ± 0.39	0.004 **	5 < 2, 3
^{D} CS	−0.66 ± 0.82	1.19 ± 0.34	1.26 ± 0.56	0.48 ± 0.36	0.83 ± 0.46	0.002 **	4 < 2, 3
^{E} VE	0.58 ± 0.33	0.71 ± 0.25	1.03 ± 0.58	0.46 ± 0.39	0.85 ± 1.36	0.423	-
[b] p	0.005 **	0.003 **	0.005 **	0.002 **	0.570		
[c] Post Hoc	C, E < B	C, E < B	A < B, D	A, C, D, E < B	-		

[b] One-way ANOVA, [c] Tukey HSD, ** $p < 0.01$. Different superscript upper-case letters imply the CAD/CAM block they refer, and different superscript numbers imply the air-polishing powder they refer. Abbreviations: VM, Vita Mark II; MZ, Paradigm MZ 100; LU, Lava Ultimate; CS, Cerasmart; VE, Vita Enamic.

When comparing the effect of the APPs on the ΔE_{00} values of the CAD/CAM blocks, as presented in Table 9, in the sodium bicarbonate, aluminum trihydroxide, calcium carbonate, or glycine-treated groups, there were significant differences in terms of the ΔE_{00} values according to the type of CAD/CAM restorative material (p: 0.005; p: 0.003; p: 0.005; and p: 0.002), respectively, whereas in the erythritol group, there was no significant difference ($p > 0.05$). According to the pairwise comparisons, it was found that among the sodium bicarbonate-treated groups, the ΔE_{00} values of the MZ samples were significantly higher than LU (p: 0.005) and VE (p: 0.027); among the aluminum trihydroxide-treated groups, the ΔE_{00} values of MZ were significantly higher than the LU (p: 0.026) and VE (p: 0.006) CAD/CAM blocks. Among the calcium carbonate-treated groups, the ΔE_{00} values of the VM samples were significantly lower than CS (p: 0.017) and MZ (p: 0.007); among the glycine-treated groups, the ΔE_{00} values of MZ samples were significantly higher than the VM (p: 0.005), LU (p: 0.007), CS (p: 0.013) and VE (p: 0.008) samples.

Figure 2 presents the SEM micrographs showing different microscopic morphologies and particle sizes of the APPs tested. As seen in Figure 2, with 100× and 200× magnifications, the particles of sodium bicarbonate and glycine are not evenly distributed; their sizes are in a wide range, with a large variety of fragment forms with sharp edges and corners. On the other hand, the particles of the calcium carbonate powder are in the form of large and small spherical clusters, and the aluminum trihydroxide particles are again spherical but in a more irregular form. Furthermore, erythritol particles have a homogenous distribution. They seem denser than the rest of the powders in terms of particle per unit area, and their particle sizes are similar to each other with an irregular microstructure. In addition, at 15,000× magnification, the particles of the powders are analyzed in detail, and their sizes are measured. It is observed that sodium bicarbonate powder resembles a rocky shape, whereas glycine powder seems to have smoother, rounder borders. In addition, aluminum trihydroxide powder seems to have interlockings with sharp edges; calcium carbonate powder appears as a cluster of small particles; and erythritol powder has an amorphous microstructure with an irregular surface. Furthermore, according to the SEM measurements of this study, particle sizes of sodium bicarbonate range between 10 and 258 µm; aluminum trihydroxide range between 110 and 227 µm; calcium carbonate range between 4 and 94 µm; glycine range between 7 and 211 µm; and erythritol range between 4 and 75 µm.

The SEM micrographs in Figures 3–7 show the differences between the air-polished and non-air-polished parts for each CAD/CAM restorative material and the APPs. As seen in these SEM images, calcium carbonate caused a significant roughness on all CAD/CAM restorative materials. In addition, aluminum trihydroxide caused a distinct roughness in CAD/CAM restorative materials, especially in MZ, LU, and CS blocks belonging to the resin with scattered fillers group (Figures 4–6). No significant difference was observed between CAD/CAM blocks consisting of resin with scattered fillers air-polished with sodium bicarbonate, glycine, and erythritol (Figures 4–6).

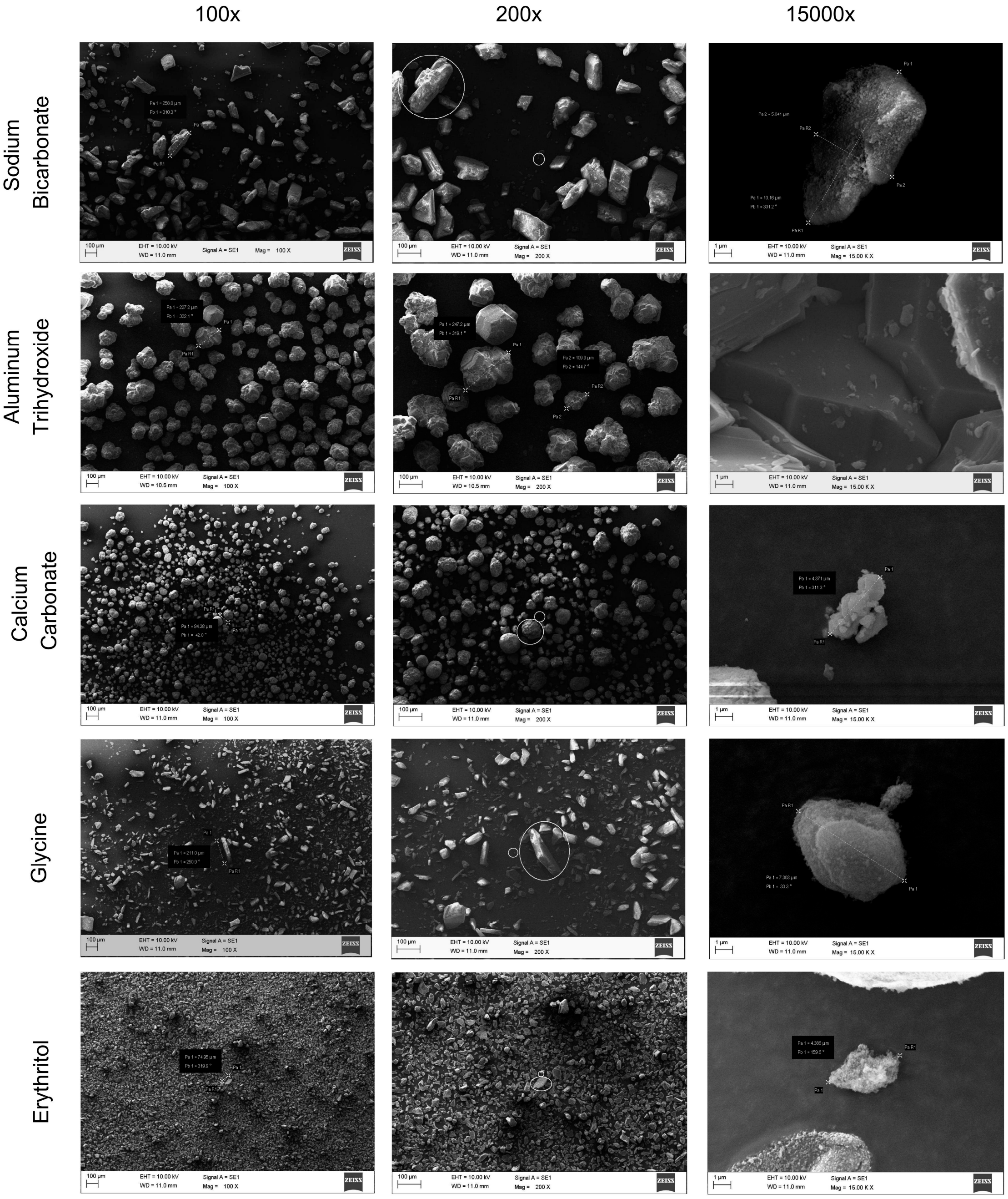

Figure 2. SEM micrographs of the air polishing powders at 100×, 200×, 15,000× magnifications. In the 100× images, the size of a big particle is measured. In the 200× images, a big particle and a small particle to be measured are marked, and the small particle of aluminum trihydroxide is measured at this magnification since its particle size is too large to measure at 15,000× magnification. In the 15,000× images, the size of a small particle is measured.

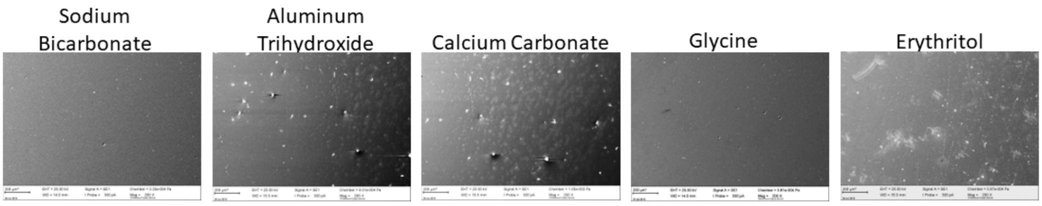

Figure 3. SEM micrographs of Vita Mark II specimens with a half-air-polished, half-non-polished surface at 200×.

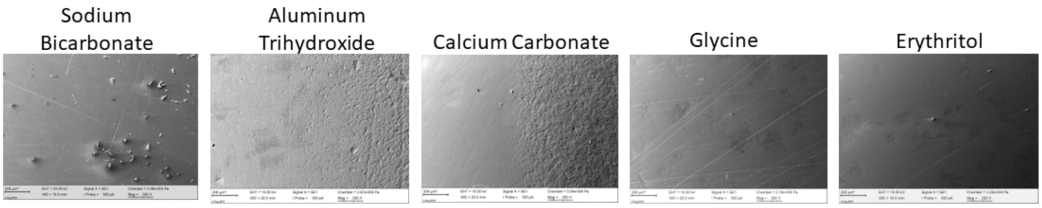

Figure 4. SEM micrographs of Paradigm MZ 100 specimens with a half-air-polished, half-non-polished surface at 200×.

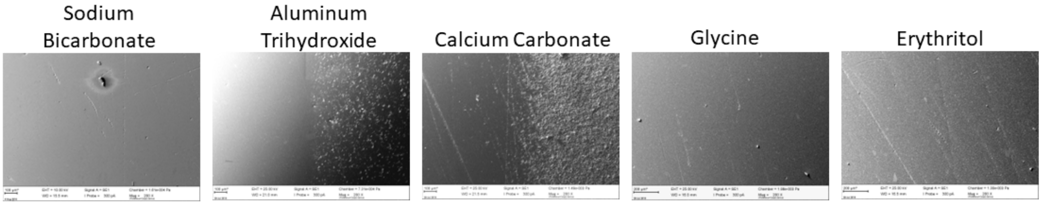

Figure 5. SEM micrographs of Lava Ultimate specimens with a half-air-polished, half-non-polished surface at 200×.

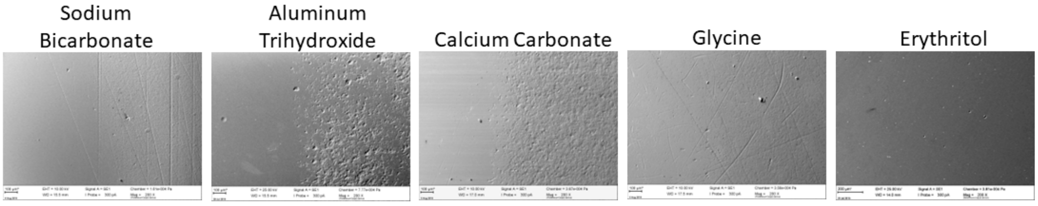

Figure 6. SEM micrographs of Cerasmart specimens with a half-air-polished, half-non-polished surface at 200×.

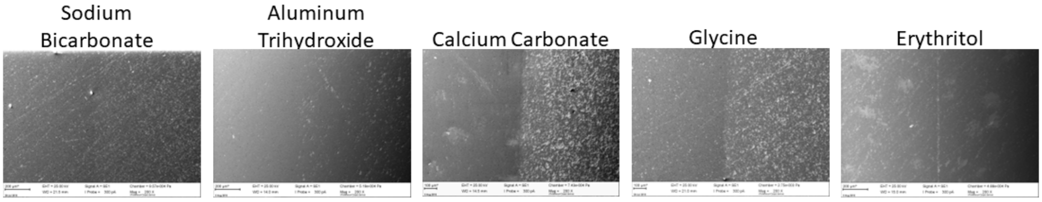

Figure 7. SEM micrographs of Vita Enamic specimens with a half-air-polished, half-non-polished surface at 200×.

4. Discussion

In this in vitro study, the effect of five different APPs on the color change in five different CAD/CAM restorative materials was evaluated, and statistically significant differences were found ($p < 0.05$, $p < 0.001$). According to the results, both the first and second parts of the null hypothesis were rejected since the color of CAD/CAM restorative materials changed in different amounts after applying different APPs.

Based on the results, the ΔE_{00} values of the LU samples that were exposed to erythritol and the CS samples that were exposed to glycine were significantly lower than those exposed to calcium carbonate and aluminum trihydroxide. Considering the APPs, calcium carbonate has the highest density, and aluminum trihydroxide has the highest hardness value (Table 2) and the largest average particle size, as seen in the SEM images in Figure 2. On the other hand, erythritol has the lowest density, the lowest hardness value, and the smallest average particle size, and glycine follows subsequently. Previous studies reported that the APP becomes more abrasive as the mean particle size, hardness, and density increase [21,23,26]. In addition, as surface roughness increases, gloss decreases, affecting color perception [13,19,34,45,47]. Therefore, the color changes in the restorative materials can be attributed to the surface roughness that air-polishing causes, as can be seen in the SEM images of the CAD/CAM restorative materials (Figures 3–7). For instance, the LU (Figure 5) and CS (Figure 6) samples treated with calcium carbonate and aluminum trihydroxide show apparent porosity in the SEM images compared with the other APPs, and this can explain the significant color change. Furthermore, Pelka et al. and Barnes et al. reported that in terms of abrasiveness, glycine < sodium bicarbonate < calcium carbonate < aluminum trihydroxide [24,29]. This result corresponds to the amount of color change caused by the APPs that are used in the present study.

In terms of color change according to the type of CAD/CAM restorative material, the ΔE_{00} values of the MZ samples were significantly higher than the LU and VE samples treated with sodium bicarbonate or aluminum trihydroxide. Previous research reported that air-polishing with sodium bicarbonate or aluminum trihydroxide increases the roughness of resin composites, and the higher ΔE_{00} values of the MZ samples could be partially attributed to this [25,32]. In addition, Guler et al. revealed that an increase in filler size and replacement of the fillers in restorative materials after air-polishing might increase roughness [31]. The filler size of LU is much smaller than MZ, which probably caused less roughness of LU and, thereby, less color change. Among the calcium carbonate-treated groups in this study, the ΔE_{00} values of the VM samples were found to be significantly lower than those of CS and MZ, which is parallel with the results of a recent study reporting that glass–ceramic materials have significantly better color stability than resin composites [48]. In addition, among the glycine-treated groups, the color change in the MZ samples was significantly higher than the other restorative materials, which is due to the differences in composition and microstructure of the restorative materials [13,48]. However, when the SEM images of the CAD/CAM blocks were analyzed, the glycine-treated VE samples (Figure 7) seemed more porous than the glycine-treated MZ samples (Figure 4). There might be two reasons why the MZ samples do not appear significantly rougher than the other blocks in SEM images (Figures 3–7) but their ΔE_{00} values are significantly higher: 1—when the glycine powder is sprayed on VE, it might have roughened the surface and splashed, but may have partially penetrated into the MZ sample owing to MZ's lower hardness value compared with the other blocks in this study, and glycine's tiny size, thereby changed the color and 2—the SEM images' magnification is 200×, and this might not be enough to show the exact surface topography that the small-sized APPs created [49].

In this study, to determine the color difference, the CIEDE2000 system, which is the most recent formula that CIE officially suggests, is used because the CIELAB system is not sufficient for determining especially small color differences [35,44]. The ΔE_{00} values of this study were interpreted according to the literature reports on visual thresholds, which provide guidance on the clinical relevance of the results [35]. According to the 50:50% CIEDE2000 acceptability thresholds for $\Delta E_{00} = 1.8$ [44], $\Delta L' = 2.92$, $\Delta C' = 2.52$, and $\Delta H' = 1.90$ [35], all groups had acceptable color changes. However, according to the 50:50% perceptibility threshold ($\Delta E_{00} = 0.8$) [44], the VM samples air-polished with aluminum trihydroxide or erythritol; the MZ samples treated with any of the APPs; the LU samples exposed to calcium carbonate; the CS samples air-polished with any of the APPs, except glycine; and the VE samples treated with calcium carbonate or erythritol demonstrated ΔE_{00} values above the perceptibility threshold. Regarding these results, glycine seems safe to use on restorative materials, except MZ, a resin composite. Cobb CM et al. also reported that glycine is the most efficient in removing biofilm from natural teeth and restorative materials, and it causes the least surface damage compared with the other powders [15]. Another study revealed that glycine and erythritol have a similar surface-damaging potential [22]. However, despite its small particle size, as seen in the SEM image (Figure 2), and its low density and hardness, though statistically insignificant, erythritol caused a sufficient color change to exceed the perceptibility threshold of all restorative materials except LU. This effect of erythritol might be because more particles may have struck the sample per unit of time owing to its small and uniform particle size (Figure 2) [37]. In addition, LU seems to be discolored the least among the other CAD/CAM blocks, which is probably due to its small filler size, which sustains better resistance to abrasion due to the quality of the interfacial bonding between the small fillers and the resin matrix [21]. It is reported that large and insufficiently embedded filler particles usually result in a greater loss of volume. In contrast, small filler particles demonstrate higher resistance to air-polishing abrasion and a more regular microstructure, which also leads to better chemical and optical properties [21]. Furthermore, LU is composed of aggregated nanoclusters, and owing to that, polishing causes drifting of the nanofillers instead of turning out of the whole cluster, which provides better resistance to wear [28]. Moreover, Barnes et al. revealed that sodium bicarbonate and glycine are safe for resin composites, whereas aluminum trihydroxide and calcium carbonate are not [24]. However, in this study, it was found that in terms of color stability, sodium bicarbonate and glycine are also not safe to use on MZ resin composite blocks. In addition, the ΔE_{00} values of the MZ samples were above the perceptibility threshold in all the APP groups, probably due to their organic components and relatively big filler particles [21].

In this in vitro study, it was observed that the APPs, which are used to remove stains, themselves cause discolorations on the restorative materials. Although they changed the color of the restorative materials within 50:50% acceptable limits, the majority of them exceeded the 50:50% perceptible limits, which means that 50% of the observers could notice the color difference [35]. Therefore, considering the findings of this study and the previous studies, regardless of the APP used, clinicians should consider avoiding or reducing the use of APPs on CAD/CAM restorative materials during supportive periodontal therapy, since they may have doubts about which restorative material they are facing intraorally. Another feasible method is to repolish the restorations after air-polishing, either with the finest polishing pastes and rubber cups or according to the manufacturer′s instructions, if the restorative material is known, to smoothen the surface as much as possible and thereby sustain color stability [13,28,31].

There are some limitations to this study. Primarily, in vitro studies do not demonstrate the intra-oral environment completely in terms of coloring beverages, the washing effect of saliva, habits like smoking, brushing the teeth, thermal alterations, etc., which may affect the color change. In addition, the samples were not subjected to artificial aging because this study aimed to evaluate the effect of APP, not aging. Secondly, intra-oral feldspathic ceramic restorations are glazed, but most restorative materials used in this study did not require glaze as the manufacturers instructed, and in order not to add another variable to this study and to standardize the study protocol, the specimens were not glazed, but they were all mechanically polished with a diamond polishing solution.

Further laboratory and clinical studies, without such limitations, should be executed to confirm the findings of this study. Although combining variables will not provide information on the effect of any single variable, aging and glaze can be added as variables to simulate the intraoral conditions better. In addition, this study analyzed only the color change and the SEM micrographs for surface analysis, but the surface roughness and gloss should also be investigated with a combination of repolishing procedures. Moreover, the influence of different APPs to CAD/CAM blocks stored in staining solutions such as coffee, coke, and black tea can also be researched in future studies in terms of optical and surface properties.

5. Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

- Both the type of CAD/CAM restorative material type and the APP had a significant effect on color difference, but their interaction terms were not significant.
- The color changes in all groups were clinically acceptable, but most of the groups presented perceptible color changes.
- Among the APPs, glycine seems the safest to use on restorative materials, but even glycine caused a perceptible color change for MZ.
- Dentists who are uncertain about the specific restorative material should limit prolonged air-polishing or avoid it altogether.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app132011573/s1, Table S1: Raw Data of Color Parameters.

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