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EFFECT OF MODELING LIQUID AND GLYCERIN APPLICATION PROTOCOLS ON THE SURFACE ROUGHNESS AND MICROHARDNESS OF ONE SHADE RESIN COMPOSITES

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ABSTRACT

Purpose: To evaluate the effects of different modeling liquid and glycerin application protocols on surface roughness (R_a) and Vickers microhardness (VHN) of one-shade resin composites before and after coffee staining.

Materials and Methods: Five resin composites (four one-shade and one conventional nanohybrid control) were tested using four surface protocols: modeling liquid with finishing/polishing (FP+),

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modeling liquid without polishing (FP−), glycerin over modeling liquid (GLY), and a control group. After 24-hour storage, baseline Ra and VHN values were recorded. Specimens were then immersed in coffee for 7-days, followed by repeated measurements. Data normality was assessed using the Shapiro–Wilk test. Since the data were not normally distributed, Kruskal–Wallis, Mann–Whitney U with Bonferroni correction, and Wilcoxon signed-rank tests with Benjamini–Hochberg FDR correction were used. The significance level was set at $p<0.05$.

Results: Surface protocol significantly affected all parameters ($p<0.001$), while composite type had no significant effect. The FP+ group showed the highest VHN and lowest R_a values. In contrast, the GLY group exhibited clinically unacceptable roughness ($R_a>0.2$ μm) and the lowest VHN across all materials. Coffee immersion increased Ra and decreased VHN, yet the ranking of protocols remained stable.

Conclusion: Application protocol plays a more critical role than material type. Modeling liquids are effective when followed by polishing, whereas their use with glycerin without mechanical finishing leads to significant surface deterioration and should be avoided.

Keywords: One-shade resin composites, Modeling liquid, Surface roughness, Microhardness, Glycerin

INTRODUCTION

In restorative dentistry, composite resins are widely preferred due to their excellent esthetic outcomes and their ability to achieve structural and optical harmony with natural dental tissues. Over the decades, multilayered composite systems featuring various shades and opacities were developed to meet high esthetic demands. However, the application of these multilayered systems requires precise technique and significant clinical experience, often resulting in prolonged chair

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time for the patient.[1,2] To address these challenges and enhance clinical efficiency, manufacturers have introduced simplified resin systems designed to reduce technical sensitivity. These materials, known as “one-shade,” “single-shade,” or “one-shade universal” resin composites, are claimed to match all 16 VITA classical shades using a single nominal shade, thereby streamlining the shade-matching process.[3]

Despite these advancements in optical compatibility, the inherent viscosity of organic monomers within the composite matrix can still pose challenges during handling and anatomical contouring.[4] To overcome these issues and prevent the material from adhering to instruments, clinicians often utilize specialized tools, such as titanium or aluminum-coated hand instruments and composite brushes.[5] Furthermore, low viscosity "modeling liquids" have been developed to serve as lubricants. These agents reduce the surface tension of the restorative material, facilitating smoother adaptation to cavity walls, simplifying the modeling process, and potentially minimizing air entrapment or subsequent porosity[4]. However, because modeling liquids contain low-viscosity methacrylate monomers, their application may alter the composition of the superficial resin-rich layer and potentially affect the characteristics of the oxygen-inhibited surface layer. Since OIL is an unpolymerized layer that cannot be entirely removed by standard finishing and polishing protocols, its persistence may compromise the long-term surface integrity and microhardness of the composite.[6]

Although numerous studies have examined the physical and chemical properties of modern composite resins, only a limited number of investigations have focused on the effects of modeling liquids on these materials, both in terms of their physical [7] and chemical [8,9] properties. Due to their ease of use, these liquids are frequently employed; however, their influence on the surface characteristics of one-shade composites has not yet been fully elucidated. Furthermore, to

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minimize the negative impact of the OIL, it has been suggested to cure the composite surface under a glycerin gel barrier to prevent oxygen contact during the final polymerization stage. However, the specific effects of finishing with glycerin to eliminate the OIL in conjunction with modeling liquids remain unknown. This is particularly critical for esthetic restorations using one-shade composites, where surface roughness and microhardness are vital for longevity and stain resistance. Therefore, the aim of this study was to evaluate the effect of modeling liquid and glycerin application protocols on the surface roughness and microhardness of various one-shade composites before and after coffee immersion. Two null hypotheses were tested:

$H_0$1 (No group effect): Surface roughness (R_a) and microhardness (VHN) do not differ among the application groups (Control, FP+, FP−, GLY).

$H_0$2 (No composite effect): R_a and VHN do not differ among the tested composites (Empress, Zenchroma, Omnichroma, Vittra, Topaz One).

MATERIALS AND METHODS

Sample Size Calculation

The sample size for each group was determined based on a power analysis conducted using **G*Power (version 3.1.9.7)**. The calculation was informed by mean and standard deviation values from previous literature[10] investigating similar surface properties of dental composites. To detect a large effect size (**f = 0.40**) with a significance level of **α = 0.05** and a statistical power of **1-β = 0.80**, the analysis indicated that a minimum of **6 specimens per group *(n=6)*** was required to achieve statistically significant results. This sample size is consistent with established protocols in dental biomaterial research for evaluating surface roughness and microhardness.

Experimental Design and Materials

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In this *in vitro* study, the influence of a modeling liquid and glycerin on the surface roughness and microhardness of five different composite resins was investigated. A total of 120 specimens were fabricated and distributed among the experimental groups as illustrated in the study flowchart (Figure 1). The restorative materials consisted of four one-shade composites and one multi-shade composite, the latter serving as a control. Detailed information regarding the brand names, chemical compositions, and manufacturers of the tested composites, modeling liquid (GC Modeling Liquid, GC Corp.), and glycerin gel (Miraderm) is provided in Table 1.

Specimen Standardization and Preparation

A single experienced operator fabricated a total of 120 disc-shaped specimens (5 mm diameter × 2 mm height) using a customized Teflon mold to ensure uniformity. For each of the five composite, 24 specimens were prepared and then randomly distributed into four experimental groups (n=30 per application protocol, consisting of 6 specimens from each composite).

The uncured composite was packed into the mold, and group-specific surface treatments (modeling liquid and/or glycerin gel) were performed. To achieve a flat surface and extrude excess material, a polyester matrix strip (Mylar Strip, SS White Co.) was placed over the mold and pressed with a 1 mm thick glass microscope slide. Polymerization was performed using a wide-spectrum LED light-curing unit (Bluephase PowerCure, Ivoclar Vivadent; 390–500 nm) for 20 seconds. All specimens were subsequently stored in distilled water at 37 °C for 24 hours to allow for post-cure maturation.

Experimental Protocols

The specimens were divided into four experimental groups based on the surface treatment and polishing sequence (Figure 1):

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- **Control (C):** No modeling liquid or glycerin was applied. After light-curing through the matrix strip, specimens were polished using Sof-Lex disks (3M ESPE) in a sequence from coarse to superfine. Coarse/medium disks were used at 10,000 rpm, and fine/superfine disks at 30,000 rpm, with each step lasting 15 seconds under dry conditions.
- **Modeling Liquid + Polishing (FP+):** A modeling liquid was applied to the uncured surface. To ensure a standardized application, a single drop was dispensed onto a mixing pad; a sable brush was lightly moistened, and excess liquid was removed with a paper tissue to achieve an ultrathin, uniform film. After polymerization, the polishing protocol described for the Control group was followed.
- **Modeling Liquid (FP−):** Modeling liquid was applied as described in the FP+ group; however, no finishing or polishing procedures were performed after curing.
- **Modeling Liquid + Glycerin (GLY):** Following modeling liquid application, a layer of glycerin gel was applied to the uncured surface using a separate brush. After light-curing, the glycerin residue was rinsed off with distilled water, and no polishing was performed.

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Coffee Immersion Protocol

To simulate clinical staining, all specimens were immersed in a standardized coffee solution (Nescafé Classic, Nestlé) for 7-days at 37 °C. The solution was prepared by dissolving 2 g of coffee powder in 200 mL of boiling water and filtering it after 10 minutes. The staining medium was refreshed daily. Upon completion of the cycle, specimens were rinsed with distilled water and cleaned with a cotton pellet to remove surface debris before final measurements.

Surface Roughness and Microhardness Assessment

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Surface roughness and microhardness measurements were performed both at baseline (after storage in distilled water for 24 h) and after the 7-day coffee immersion protocol.

To determine the average surface roughness (R_a), specimens were individually analyzed using a profilometer (Surftest 410; Mitutoyo, Kawasaki, Japan). Measurements were conducted over an evaluation length of 4 mm at a traverse speed of 0.5 mm/s, with a 0.8 mm cut-off value. Five measurements were recorded for each specimen, and the average R_a value was calculated.

Subsequently, Vickers microhardness (VHN) was measured on the top surfaces of the specimens using a digital microhardness tester (Falcon 400, Innovatest, Maastricht, Netherlands) equipped with a Vickers diamond indenter. A load of 100 g was applied for 10 seconds, and indentations were analyzed under a 20× magnification microscope. Three indentations were made on each specimen to determine the mean microhardness value.

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Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, Version 25.0 (IBM Corp., Armonk, NY, USA) and the stats models library (version 0.10.0) for Python. The normality of the data was assessed using the Shapiro-Wilk test. As the data exhibited a non-normal distribution, non-parametric tests were employed.

The Kruskal-Wallis test was used to determine the overall effect of the application protocols (group effect) and the composite types (material effect) on surface roughness (R_a) and microhardness (VHN). When the Kruskal-Wallis test indicated significant differences across the four application protocols, pairwise intergroup comparisons were performed using the Mann-Whitney U test with Bonferroni correction.

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To evaluate the changes in R_a and VHN within each specific group before and after the 7-day coffee immersion protocol (intra-group/longitudinal comparisons), the Wilcoxon rank-sum test was utilized. To control the inflation of Type I error rates during these multiple pairwise comparisons at the cell level, the Benjamini-Hochberg False Discovery Rate (FDR) correction was applied. For all statistical evaluations, the significance level was set at $\alpha = 0.05$.

Although a full factorial design was employed, data non-normality and the subgroup sample size (n=6 per cell) rendered non-parametric main-effect evaluations (Kruskal-Wallis followed by Mann-Whitney U with Bonferroni correction) more methodologically robust to avoid underpowered interaction models. Consequently, the statistical evaluation focused on independent main effects, and findings regarding composite type reflect strictly pooled analyses rather than the absence of localized, material-specific protocol responses.

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RESULTS

Across composites, the GLY group exhibited substantially higher surface roughness than the other groups both before and after coffee immersion ($p<0.001$). Within each group, the relative ordering of composites was consistent with the letter codes in the tables; importantly, when all groups were pooled, no overall difference among composites was detected (p=0.811 pre; p=0.317 post). (Table 2)

Before and after coffee immersion, roughness differed markedly across wetting-resin groups ($p<0.001$), with GLY showing substantially higher values than the other groups in both phases. When all groups were pooled, there was no overall difference among composites (p=0.811 pre; p=0.317 post). After coffee immersion, surface roughness generally increased across the experimental groups, while the overall ranking of the application protocols remained unchanged.

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The GLY group consistently showed the highest Ra values, whereas the FP+ and Control groups maintained the lowest roughness values. Multiple-comparison corrections were applied as described in the Statistical Analysis section. (Table 3, Figure 2)

Group effects were also pronounced for microhardness in both phases (p<0.001): FP+ showed the highest values, followed by Control**,** then FP−, and the lowest values in GLY. In contrast, when composites were pooled across groups there was no overall composite effect (p=0.187 pre; p=0.086 post), reflected by identical lower-case letters across the row. (Table 4 and Table 5)

Following coffee immersion, microhardness values generally decreased in most group–composite combinations. However, the overall protocol ranking remained stable, with FP+ showing the highest VHN values and GLY showing the lowest values. Multiple-comparison corrections were applied as described in the Statistical Analysis section. (Figure 3)

DISCUSSION

The results of this study led to the rejection of the first null hypothesis (**$H_0$1**), as the application protocols significantly influenced both surface roughness and microhardness, regardless of the composite type. Notably, the GLY group exhibited markedly higher R_a values than the other groups, while microhardness values followed a descending order of FP+ > Control > FP− > GLY. Conversely, the second null hypothesis (**$H_0$2**) was accepted, as no significant differences were observed among the five tested resin composites when the application protocols were pooled. These patterns remained consistent both before and after the coffee immersion protocol, indicating that the impact of surface modeling techniques outweighs the intrinsic differences in composite formulations.

Surface roughness is a critical parameter influencing plaque accumulation, staining susceptibility, and the overall longevity of restorations. It is widely accepted that R_a values exceeding 0.2 μm

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create a favorable environment for bacterial adhesion and increase the risk of secondary caries. [11] In the present study, the GLY group (modeling liquid + glycerin) exhibited R_a values that far exceeded this clinical threshold. This finding suggests that the combined application of these agents without subsequent polishing creates a structurally unstable, resin-rich superficial layer. Similar outcomes have been reported in studies indicating that unpolished wetting agents can lead to surface degradation and increased susceptibility to environmental factors [12]

The application of modeling liquids is primarily intended to promote a more homogeneous surface by enhancing the flowability of the composite and reducing the formation of surface voids [13]. While the results for the FP+ group align with this objective—showing roughness values comparable to the control group—the substantial increase in roughness observed in the GLY group highlights a significant clinical risk. It is likely that when glycerin is applied over a modeling liquid, it interferes with the uniform distribution of the low-viscosity monomers or creates an irregular interface during the polymerization process. Consequently, these findings reinforce the principle that while modeling liquids may facilitate clinical handling, they must be used in conjunction with standard finishing and polishing protocols to maintain surface integrity [14,15]

When focusing on surface microhardness, a clear distinction emerged among the groups: FP+ consistently yielded the highest values, whereas a significant drop was observed in the GLY group across all composite brands. While current literature[16] often highlights glycerin as a tool to enhance surface curing by blocking oxygen, our data suggests this benefit is not universal and depends heavily on the application sequence. In our experimental setup, light had to pass through a 1 mm glass slide and a matrix strip before reaching the composite. We hypothesize that this setup, combined with the presence of a viscous glycerin gel over the modeling liquid, may have contributed to a cumulative light-shading effect. This possible attenuation of light transmission

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may have reduced the effective energy delivered to the composite surface, potentially resulting in lower microhardness values in the superficial layer.

Moreover, the chemical and physical interactions between these layers cannot be ignored. When focusing on surface characteristics, a clear distinction emerged among the groups: the FP+ group consistently yielded the highest microhardness values, whereas markedly lower VHN and exceptionally high Ra values were observed in the GLY group across all composite brands.[12] These findings indicate that the combined use of a modeling liquid and glycerin gel prior to curing compromised the surface mechanical integrity and roughness of the tested composites. A plausible explanation for this phenomenon is that the direct application of the viscous glycerin gel over the modeling liquid may have induced a dilution effect, localized pooling, or interfacial instability within the nascent, resin-rich superficial layer. Such a disruption is highly relevant clinically, given that polymerization continues even after the initial light exposure. [17] However, since the degree of conversion was not directly measured in the present study, the lower VHN values in the GLY group cannot be definitively attributed to impaired polymerization efficiency; such a contribution remains strictly hypothetical. Instead, these outcomes should be interpreted with caution and related to surface-level disruptions. Although all specimens were prepared using a standardized mold, matrix strip, glass slide pressure, and rinsing protocol, the simultaneous occurrence of high roughness and low hardness may reflect a non-uniform superficial layer, incomplete removal of surface residues, or small preparation-related surface irregularities. Consequently, the high Ra and low VHN values in the GLY group may stem from both material-related surface alteration and methodological artifacts. Future studies incorporating direct measurements—such as light irradiance, monomer elution, FTIR or Raman spectroscopy for degree of conversion, and SEM or

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AFM for surface morphology analysis—are warranted to clarify whether these changes are related to altered polymerization, residual resin-rich layers, or specific morphological surface defects.

The 7-day coffee immersion protocol resulted in a general increase in surface roughness and a reduction in microhardness for the majority of the groups. This trend is consistent with previous studies demonstrating that coffee, as a complex staining solution, can promote hydrolytic degradation of the resin matrix and plasticize the polymer network [18,19]. However, it is noteworthy that the relative ranking of the groups remained unchanged after the staining period; for instance, the GLY group maintained the highest R_a and lowest VHN values. This stability in rankings suggests that the initial surface quality, determined by the modeling liquid application and subsequent polishing, is the primary driver of long-term surface performance. Even though all composites underwent significant pre-to-post changes at the cell level, the modeling liquid's impact was more dominant than the degradative effect of the staining solution itself.

Interestingly, when composites were pooled across groups, no significant differences were detected among the tested one-shade materials and the conventional control for either surface roughness or microhardness. This suggests that, despite variations in filler type (e.g., the supra-nanospherical fillers in Omnichroma vs. nanohybrid structures in others), filler loading, and resin matrix composition, these materials respond similarly to surface manipulation protocols when viewed globally. This observation aligns with previous studies indicating that clinical variables, such as polishing technique and surface treatment, may outweigh intrinsic material-related factors in determining final surface performance [20,21]. It appears that the use of a wetting resin creates a common 'surface skin' that dictates the interaction with the environment, regardless of the underlying composite's specific technology. Nevertheless, readers should interpret this general observation of comparable material behaviors with caution; conclusions regarding the absence of

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significant material effects apply strictly to our pooled analyses and do not preclude possible protocol-specific or localized responses exhibited by individual resin matrices under specific surface conditions.

The 7-day coffee immersion protocol used in the present study should be interpreted as an accelerated in vitro staining model rather than a direct simulation of continuous clinical exposure.[22] In the oral environment, restorations are exposed to coffee intermittently and are simultaneously affected by saliva, oral clearance, toothbrushing, dietary habits, and thermal or pH fluctuations. Nevertheless, prolonged immersion protocols are commonly used in dental materials research to intensify pigment exposure within a standardized period and to compare the relative susceptibility of restorative materials or surface treatments to discoloration and surface degradation. Therefore, the 7-day coffee immersion period was selected to provide a controlled and reproducible aging challenge, allowing comparison of the effects of different surface manipulation protocols under clinically relevant staining conditions. However, the absence of dynamic oral factors should be considered a limitation, and future studies including thermocycling, brushing simulation, and intermittent staining cycles would better reflect real-life exposure conditions.

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Despite the standardized conditions provided by this *in vitro* design, several limitations warrant cautious interpretation of the results. First, the specimens were subjected to static immersion in a staining solution, which fails to account for the dynamic and complex nature of the oral cavity. In a clinical setting, salivary flow, enzymatic activity, and pH fluctuations can significantly modulate the degradation of the resin matrix and the intensity of pigment adsorption. Furthermore, the absence of mechanical challenges, such as toothbrushing abrasion and functional loading, limits our understanding of the long-term wear resistance of the modeling liquid-enriched surface layer.

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Another limitation is related to the statistical design. Although the experimental design included both application protocol and composite type, the statistical analysis focused on the independent main effects of these factors rather than formally testing the protocol × composite interaction due to subgroup sample size constraints. Therefore, possible interaction effects between surface manipulation protocols and specific composite formulations should be interpreted cautiously and require confirmation in future studies using factorial or interaction-based statistical models.

Another limitation concerns the aging protocol; while a 7-day immersion in coffee provides a controlled simulation of pigment exposure, it does not encompass the cumulative effect of thermal cycling, which is known to induce interfacial stresses between the filler and the matrix. In addition, direct analyses of polymerization efficiency and surface morphology, such as degree of conversion, monomer release, SEM, or AFM, were not performed. Therefore, the proposed explanations for the GLY group, including a possible light-shading effect, dilution-like effect, or interfacial instability, should be interpreted as hypotheses rather than definitive mechanisms. Lastly, although this study evaluated five distinct composite systems, the interaction between modeling liquids and other emerging material categories—such as fiber-reinforced or bulk-fill composites—remains to be explored.

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From a practical perspective, the findings of this study carry critical messages for daily restorative workflows. One-shade resin composites are widely adopted to streamline chairside time and simplify shade matching. However, clinicians frequently utilize modeling liquids to ease handling and instrument adaptation. Our results demonstrate that regardless of the commercial brand or filler technology chosen, omitting finishing and polishing—especially when combining wetting resins with oxygen-inhibiting glycerin barriers—leads to severe surface degradation, with roughness values drastically exceeding the critical 0.2 μm plaque-retention threshold. Therefore,

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practitioners must recognize that material choice cannot compensate for improper surface manipulation protocols; achieving long-term clinical success necessitates a rigorous finishing and polishing sequence (FP+) whenever modeling liquids are employed.

CONCLUSION

Within the limitations of this *in vitro* study, it can be concluded that the surface characteristics of one-shade resin composites are heavily dependent on the application protocol of modeling liquids, emphasizing that proper finishing and polishing are essential regardless of the composite material used. The most favorable surface integrity was achieved through the FP+ protocol, which demonstrated that following modeling liquid application with a rigorous finishing and polishing sequence is essential for maintaining high microhardness and clinically acceptable surface roughness. Conversely, the combined use of modeling liquid and glycerin gel without subsequent polishing (the GLY group) resulted in a compromised surface layer characterized by catastrophic roughness levels and inferior mechanical strength. Furthermore, while a 7-day coffee staining protocol induced general degradative changes across all groups, it did not alter the performance hierarchy established by the initial surface manipulation techniques. These findings underscore the critical importance of adhering to conventional polishing protocols when using wetting resins to ensure the long-term clinical success of one-shade restorations.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

REFERENCES

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1. Lucena, C., Ruiz-López, J., Pulgar, R., Della Bona, A. & Pérez, M. M. Optical behavior of one-shaded resin-based composites. *Dent. Mater.* **37**, 840–848 (2021).

2. Dietschi, D., Shahidi, C. & Krejci, I. Clinical performance of direct anterior composite restorations: a systematic literature review and critical appraisal. *Int. J. Esthet. Dent.* **14**, 252–270 (2019).

3. Iyer, R. S., Babani, V. R., Yaman, P. & Dennison, J. Color match using instrumental and visual methods for single, group, and multi-shade composite resins. *J. Esthet. Restor. Dent.* **33**, 394–400 (2021).

4. Pisano, M. *et al.* Effects of different curing methods on the color stability of composite resins. *Restor. Dent. Endod.* **49**, (2024).

5. Li, X. *et al.* Resin Composites Reinforced by Nanoscaled Fibers or Tubes for Dental Regeneration. *Biomed Res. Int.* **2014**, 1–13 (2014).

6. Borges, M. G. *et al.* Oxygen Inhibition of Surface Composites and Its Correlation with Degree of Conversion and Color Stability. *Braz. Dent. J.* **32**, 91–97 (2021).

7. Graf, N. & Ilie, N. Long-term mechanical stability and light transmission characteristics of one shade resin-based composites. *J. Dent.* **116**, 103915 (2022).

8. Bayraktar, E. T. *et al.* Effect of Modeling Resins on Microhardness of Resin Composites. *Eur. J. Dent.* **15**, 481–487 (2021).

9. Abdelraouf, R. M. & Habib, N. A. Color-Matching and Blending-Effect of Universal Shade Bulk-Fill-Resin-Composite in Resin-Composite-Models and Natural Teeth. *Biomed Res. Int.* **2016**, 1–8 (2016).

10. Çakmak, G. *et al.* Surface roughness, optical properties, and microhardness of additively and subtractively manufactured CAD-CAM materials after brushing and coffee thermal cycling. *J. Prosthodont.* **34**, 68–77 (2025).

11. Bollenl, C. M. L., Lambrechts, P. & Quirynen, M. Comparison of surface roughness of oral hard materials to the threshold surface roughness for bacterial plaque retention: A review of the literature. *Dent. Mater.* **13**, 258–269 (1997).

12. SEDREZ-PORTO, J. A., MÜNCHOW, E. A., BRONDANI, L. P., CENCI, M. S. & PEREIRA-CENCI, T. Effects of modeling liquid/resin and polishing on the color change of resin composite. *Braz. Oral Res.* **30**, (2016).

13. Peutzfeldt, A. & Asmussen, E. Determinants of in vitro gap formation of resin composites. *J. Dent.* **32**, 109–115 (2004).

14. Ergücü, Z. & Türkün, L. S. Surface Roughness of Novel Resin Composites Polished with One-step Systems. *Oper. Dent.* **32**, 185–192 (2007).

15. Turssi, C. P., Ferracane, J. L. & Serra, M. C. Abrasive wear of resin composites as related to finishing and polishing procedures. *Dent. Mater.* **21**, 641–648 (2005).

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16. Marigo, L. *et al.* Influences of Different Air-Inhibition Coatings on Monomer Release, Microhardness, and Color Stability of Two Composite Materials. *Biomed Res. Int.* **2019**, 1–8 (2019).

17. Helvatjoglou-Antoniadi, M., Papadogianis, Y., Koliniotou-Kubia, E. & Kubias, S. Surface hardness of light-cured and self-cured composite resins. *J. Prosthet. Dent.* **65**, 215–220 (1991).

18. Bagheri, R., Burrow, M. F. & Tyas, M. Influence of food-simulating solutions and surface finish on susceptibility to staining of aesthetic restorative materials. *J. Dent.* **33**, 389–398 (2005).

19. ERTAS, E., GÜLER, A. U., YÜCEL, A. Ç., KÖPRÜLÜ, H. & GÜLER, E. Color Stability of Resin Composites after Immersion in Different Drinks. *Dent. Mater. J.* **25**, 371–376 (2006).

20. Ferracane, J. L. Resin-based composite performance: Are there some things we can't predict? *Dent. Mater.* **29**, 51–58 (2013).

21. Ilie, N. *et al.* Academy of Dental Materials guidance—Resin composites: Part I—Mechanical properties. *Dent. Mater.* **33**, 880–894 (2017).

22. Guler, A. U., Yilmaz, F., Kulunk, T., Guler, E. & Kurt, S. Effects of different drinks on stainability of resin composite provisional restorative materials. *J. Prosthet. Dent.* **94**, 118–124 (2005).

Tables Legends

Table 1. Tested Resin Composites, Modeling Agent, and Glycerin Gel

Materials	Organic Matrix	Inorganic Matrix	Resin Type	Manufacturer	Lot Number
IPS Empress Direct	UDMA, Bis-GMA, TEGDMA	Barium glass, ytterbium trifluoride, mixed oxides, silicon dioxide, copolymer (52–59 vol%)	Nanohybrid	Ivoclar Vivadent AG, Schaan, Liechtenstein.	M26421
Zenchroma Universal	Bis-GMA, UDMA, TEMDMA	Glass powder, silicon dioxide (53 vol%)	Microhybrid	President Dental, Allershausen, Germany	2022003395

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Omnichroma	TEGDMA, UDMA, Mequinol, Dibutyl hydroxyl toluene, UV absorber	Silica-zirconia filler (0.2–0.4 μm) (68 vol%)	Nanofill	Tokuyama Dental Corp., Tokyo, Japan	041M1
Vittra APS Unique	Methacrylate monomers, APS initiator system, co-initiators, stabilizers, silane	Boron-aluminum-silicate glass (52–60 vol%)	Nanohybrid	FGM, Joinville, Santa Catarina, Brazil	230921
Charisma Topaz ONE	TCD-Urethaneacrylate, TEGDMA, UDMA	Barium aluminum boro-fluorosilicate glass, silica, TiO2 (58 vol%)	Nanohybrid	Kulzer, GmbH, Germany	K010202
Modeling Liquid	UDMA, 2-Hydroxy-1,3dimethacryloxypropane,2-hydroxyethyl methacrylate	–	–	GC Corp., Tokyo, Japan	2022003395
Glycerin Gel	–	–	–	Miraderm Pharma, Istanbul, Turkey	ESG112021

Note: All information has been provided by the manufacturers; Bis-GMA, Bisphenol A Glycidyl Methacrylate; TEGDMA, triethyleneglycol dimethacrylate; TCD, Tricyclodecane; TEMDMA, Triethylene Glycol Mono Dimethacrylate; UDMA, urethane dimethacrylate.

Table 2. Surface roughness before coffee immersion (pre)

Group	Empress	Zen	Omnichroma	Vittra	One	TOTAL

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Control	0.049 ± 0.010^{aA}	0.058 ± 0.013^{aA}	0.047 ± 0.015^{aA}	0.054 ± 0.017^{aA}	0.089 ± 0.030^{bB}	0.060 ± 0.023^{A}
FP+	0.051 ± 0.014^{aA}	0.101 ± 0.121^{aB}	0.058 ± 0.016^{aA}	0.063 ± 0.006^{aA}	0.074 ± 0.007^{bA}	0.069 ± 0.054^{A}
FP−	0.066 ± 0.010^{aA}	0.078 ± 0.064^{aB}	0.114 ± 0.015^{bC}	0.058 ± 0.004^{aA}	0.057 ± 0.008^{aA}	0.075 ± 0.035^{A}
GLY	2.258 ± 0.243^{bD}	1.171 ± 0.866^{bB}	0.229 ± 0.048^{cA}	1.552 ± 0.548^{bC}	0.256 ± 0.097^{aA}	1.093 ± 0.904^{B}
TOTAL	0.606 ± 0.98 ^{a}	0.352 ± 0.633^{a}	0.112 ± 0.078^{a}	0.432 ± 0.708^{a}	0.119 ± 0.095^{a}	0.324 ± 0.632

KW p (across groups, by composite): Empress <0.001 (~0.0002); Zen <0.001 (~0.0008); Omnichroma <0.001 (~0.0002); Vittra <0.001 (~0.0006); One <0.001 (~0.0002).

KW p for TOTAL column (groups pooled across composites): <0.001 (~0.0002).

KW p for TOTAL row (composites pooled across groups): 0.811 (ns) → TOTAL row letters all a.

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Table 3. Surface roughness after coffee immersion (post)

Group	Empress	Zen	Omnichroma	Vittra	One	TOTAL
Control	0.054 ± 0.007^{aA}	0.065 ± 0.017^{abAB}	0.071 ± 0.022 ^{aAB}	0.058 ± 0.014^{aA}	0.102 ± 0.028^{bB}	0.070 ± 0.025^{A}
FP+	0.058 ± 0.014^{aA}	0.061 ± 0.012^{aA}	0.063 ± 0.015 ^{aA}	0.066 ± 0.006^{abAB}	0.080 ± 0.006^{bB}	0.065 ± 0.013^{A}
FP−	0.071 ± 0.01^{abA}	0.054 ± 0.006^{aA}	0.148 ± 0.029 ^{bB}	0.064 ± 0.005^{aA}	0.061 ± 0.008^{aA}	0.079 ± 0.038^{A}

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GLY	1.784 ± 0.267^{cD}	0.922 ± 0.575^{bB}	0.246 ± 0.047 ^{cA}	1.277 ± 0.426^{bC}	0.203 ± 0.041^{cA}	0.886 ± 0.694^{B}
TOTAL	0.491 ± 0.772^{a}	0.276 ± 0.466^{a}	0.132 ± 0.081 ^{a}	0.366 ± 0.573^{a}	0.113 ± 0.062^{a}	0.277 ± 0.495
KW p (across groups, by composite): Empress <0.001 (~0.0002); Zen <0.001 (~0.0006); Omnichroma <0.001 (~0.0002); Vittra <0.001 (~0.0006); One <0.001 (~0.0002). KW p for TOTAL column (groups pooled across composites): <0.001 (~0.0002). KW p for TOTAL row (composites pooled across groups): 0.317 (ns) → TOTAL row letters all a.						

Table 4. Microhardness before coffee immersion (pre) (mean ± SD)

Group	Empress	Zen	Omnichroma	Vittra	One	TOTAL
Control	72.564 ± 7.088^{aA}	68.907 ± 5.593^{aA}	71.443 ± 4.386^{aA}	80.581 ± 3.361^{aA}	66.743 ± 5.652^{aA}	72.048 ± 6.920^{A}
FP+	80.422 ± 3.162^{aA}	82.733 ± 5.190^{bA}	68.367 ± 4.406^{aA}	83.342 ± 4.355^{aA}	77.727 ± 6.762^{aA}	78.518 ± 7.181^{B}
FP−	33.301 ± 6.706^{bA}	47.419 ± 10.538^{cA}	33.546 ± 5.503^{bA}	44.021 ± 11.156^{bA}	42.741 ± 6.383^{bA}	40.205 ± 9.734^{C}
GLY	23.182 ± 8.488^{bA}	28.960 ± 6.738^{cA}	19.044 ± 5.740^{cA}	33.052 ± 4.837^{bA}	22.261 ± 3.313^{cA}	25.300 ± 7.616^{D}
TOTAL	52.367 ± 25.832^{a}	57.005 ± 22.033^{a}	48.100 ± 23.387^{a}	60.249 ± 23.395^{a}	52.368 ± 22.593^{a}	54.018 ± 23.468
KW p (across groups, by composite): Empress <0.001; Zen <0.001; Omnichroma <0.001; Vittra <0.001; One <0.001. KW p for TOTAL column (groups pooled across composites): <0.001. KW p for TOTAL row (composites pooled across groups): 0.187 (ns) → TOTAL-row letters all a.						

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Table 5. Microhardness after coffee immersion (post) (mean ± SD)

Group	Empress	Zen	Omnichroma	Vittra	One	TOTAL
Control	71.816 ± 5.104^{aA}	66.515 ± 6.984^{aA}	70.029 ± 6.365^{aA}	75.171 ± 2.590^{aA}	62.868 ± 4.495^{aA}	68.066 ± 6.531^{A}
FP+	74.889 ± 5.478^{aA}	75.335 ± 5.522^{aA}	65.933 ± 5.038^{aA}	79.444 ± 2.889^{aA}	73.672 ± 4.868^{aA}	74.343 ± 6.155^{B}
FP−	31.165 ± 7.332^{bA}	43.736 ± 10.714^{bA}	31.506 ± 6.441^{bA}	39.882 ± 9.681^{bA}	42.328 ± 6.630^{bA}	37.161 ± 9.364^{C}
GLY	20.504 ± 6.746^{bA}	27.253 ± 6.611^{cA}	17.161 ± 3.000^{cA}	31.087 ± 4.682^{bA}	21.418 ± 3.187^{cA}	23.485 ± 6.954^{D}
TOTAL	49.188 ± 24.998^{a}	54.093 ± 21.718^{a}	44.069 ± 21.756^{a}	56.396 ± 22.297^{a}	50.071 ± 20.956^{a}	50.763 ± 22.420

KW p (across groups, by composite): Empress <0.001; Zen <0.001; Omnichroma <0.001; Vittra <0.001; One <0.001.

KW p for TOTAL column (groups pooled across composites): <0.001.

KW p for TOTAL row (composites pooled across groups): 0.086 (ns) → TOTAL-row letters all a.

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Figures Legends

Figure 1. Study protocol

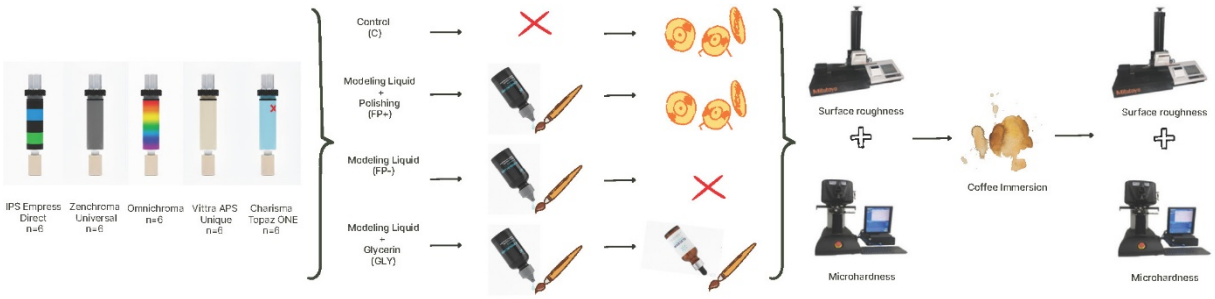

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Figure 2. Comparison of surface roughness before and after coffee immersion across different groups and composite materials (Mean ± SD).

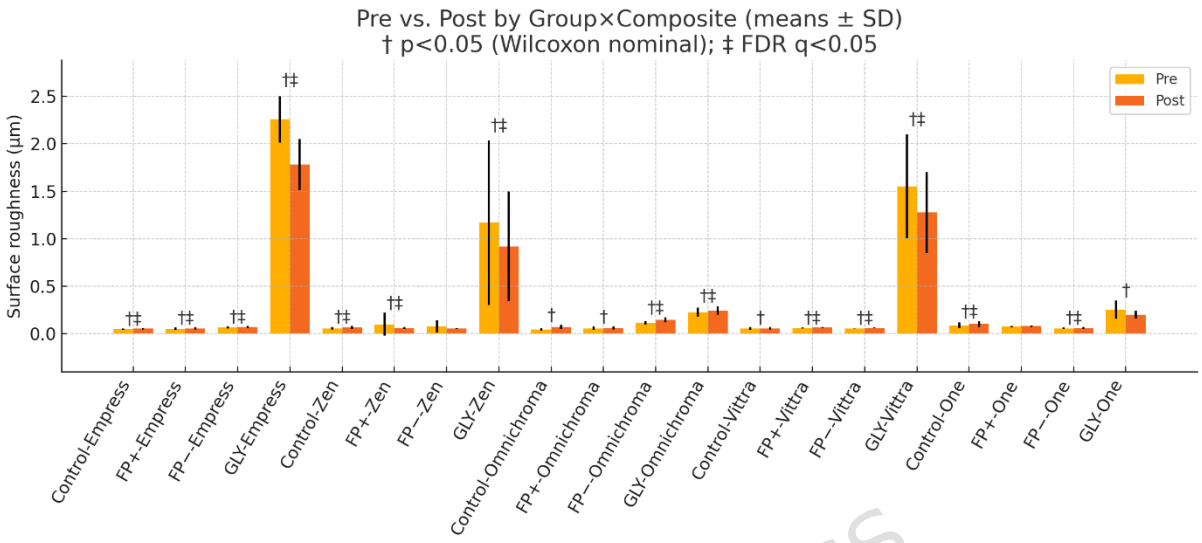

Figure 3. Comparison of microhardness before and after coffee immersion across different groups and composite materials (Mean ± SD).

