



Evaluation of Surface Roughness and Optical Property in Resin-Based CAD/CAM Materials during Thermal Aging

JINGYING HU¹, XULIANG DENG², YAN LI^{3*}, YUNYANG BAI^{2*}

¹ Department of General Dentistry II, Peking University School and Hospital of Stomatology, Beijing, 100081, China

² Department of Geriatric Dentistry, Peking University School and Hospital of Stomatology, Beijing, 100081, China

³ Department of Stomatology, Affiliated Hospital of Qinghai University, Qinghai, China

Abstract: Objective: To evaluate and compare the surface roughness and optical properties in resin-based CAD/CAM materials during thermal aging. **Methods:** Lava Ultimate HT (3M ESPE, USA) and VITA Enamic HT (Vita Zahnfabrik, Germany) were selected for this study. Ten specimens for each group were prepared and polished. The surface roughness (Ra) and translucency (%) were measured by a 3D profilometer and spectrophotometer before and after the accelerated aging protocol (10,000 cycles, 5°C, and 55°C). The freeze-fracture surfaces of tested materials were observed by SEM. **Results:** Enamic HT had the lower surface roughness value of 82.56 ± 6.21 nm, while Ultimate HT owned the higher Ra of 125.89 ± 8.64 nm before thermal aging. Enamic HT had the lower transparency (%) of 55.02 ± 2.57 , while Ultimate HT owned the higher transparency (%) of 58.89 ± 1.63 before thermal aging. Ra in tested CAD/CAM materials was greater than $0.2 \mu\text{m}$ after 10,000 thermocycles of 5/55°C. **Conclusions:** The thermal aging led to a significant increase in surface roughness and a significant decrease in transparency in both CAD/CAM materials. Ultimate HT were significantly more translucent than Enamic HT before thermal aging, while Ultimate HT showed less translucent than Enamic HT after 10,000 thermocycles of 5/55°C.

Keywords: Digital dentistry, surface roughness, translucency, thermal aging, CAD/CAM

1. Introduction

Digital dentistry has a great development for indirect restorations over the past decade. The optical properties of CAD/CAM materials are pivotal in dental restorations, with the goal of accurately replicating natural tooth aesthetics and transparency are key factors important criteria in esthetic dentistry [1]. More recently, the resin nanoceramic and hybrid ceramics have become prominent research topics in dental CAD/CAM materials. In the past decade, a variety of monolithic resin-based CAD/CAM restorative materials have been developed, eliminating the need for additional laboratory processes such as firing, veneering, and glazing. Many studies stated that the mechanical properties of CAD/CAM resin-nano ceramic and hybrid ceramic are generally lower in comparison to glass-ceramic and zirconia, but they are more comparable to natural enamel and dentin [2–4]. VITA ENAMIC is a type of representative commercial polymer-infiltrated-ceramic-network composites (PICNs), which was introduced by VITA in 2013 and Lava Ultimate, launched by 3M ESPE in 2012, is essentially filled composite [5,6]. Both materials with high translucency are particularly indicated for anterior esthetic restorations. They provide a balance between aesthetics and mechanical properties, making them suitable for a wide range of restorative applications.

Translucency has been observed to be affected by filler content, filler shape, filler size and polymer matrix in relation to optical characteristics [7,8]. While several resin-based CAM/CAM materials exhibit great optical properties, it is essential to assess whether these properties are maintained over time, especially under aging conditions. The oral environment is complex, exposing dental restorative materials to mechanical, chemical, biological, and thermal changes [9,10]. These factors

*email: baiyunyang@bjmu.edu.cn; liyanerya@126.com

collectively influence the durability of dental restorations, making them a primary concern for dental practitioners. Microbial adhesion to dental restorations is closely related to their surface characteristics, such as surface roughness. Rough surfaces on dental restorations are associated with an increase in the risk of periodontal disease attributed to plaque accumulation, calculus deposition, and microbial adherence [11]. The escalation in roughness may result from inadequate polishing, wear from chewing, and the aging effects of the oral environment [8].

Therefore, this study aimed to quantitatively assess and compare variations in translucency and surface roughness of two typical CAD/CAM resin-based materials after thermal aging. The null hypothesis was that the optical properties and surface characteristics of highly translucent CAD/CAM resin-based materials are not affected by thermal aging.

2. Materials and methods

Two representative resin-based CAD/CAM restorative materials and their high translucency blocks were selected in this study. The details regarding the manufacturers, shades, types, and chemical compositions of the materials tested are provided in Table 1.

Table 1. Characteristics of the resin-based CAD/CAM materials used in the study

Material	Shade	Manufacturers	Composition	Type
Lava Ultimate	A2-HT*	3M ESPE, USA	80 wt% nanoceramic particles embedded in 20 wt% highly cross-linked resin matrix	resin nano ceramic
Vita Enamic	2M2-HT*	Vita Zahnfabrik, Germany	Porous structure-sintered ceramic matrix infiltrated with polymer material	hybrid ceramic

Note: *HT—high translucency.

2.1. Specimen preparation and thermocycling aging

Two CAD/CAM dental materials, hybrid ceramic Vita Enamic (Vita Zahnfabrik, Säcking, Germany) and resin nanoceramic, Lava Ultimate (3M ESPE, St. Paul, MN, USA) were investigated. Detailed descriptions of these materials can be found in Table 1. The discs were cut to thicknesses of 1 mm by a precision saw. All tested surfaces underwent grinding with #600, #800, and #1200 SiC papers, followed by polishing with Sof-Lex kits (3M ESPE, USA). To mimic the hydrothermal aging experienced in the oral environment, all samples underwent thermocycling (Proto-tech, USA) for 10,000 cycles, alternating between temperatures of 5 and 55°C, with an immersion time of 30 s.

2.2. Surface roughness measurements

All samples underwent testing using a profilometer device (VK-X200, Keyence, Osaka, Japan). Surface roughness was quantified in terms of roughness average (Ra), typically measured in nanometers (nm). For each group, 10 discs were selected. The mean values were calculated before and after undergoing thermal aging. The most representative 3D profiles for each of four materials are shown.

2.3. Optical property measurements

The optical transparency of all samples was assessed using a spectrophotometer (Cary 300, Agilent Technologies, Santa Clara, CA, USA). Ten disc-shaped specimens from each group were selected for analysis. Transmittance was measured at a wavelength of 400 nm and expressed as a percentage of transparency (%). Measurements were conducted before and after thermocycling aging to assess changes in optical properties.

2.4. SEM observation

The freeze-fracture surfaces of samples were analyzed using a scanning electron microscope (SEM) (Hitachi SU8040) at $\times 20,000$ magnification, with a measured voltage set at 5 kV. Prior to SEM imaging, specimens were gold-sputtered to enhance conductivity.

2.5. Statistical analysis

The average Ra values and the mean transparency were recorded. Microsoft Excel software was used to input the data. Data were presented as mean values \pm SD (standard deviation). Shapiro-Wilk tests were conducted to assess the normality of the data. Statistical analyses were performed using the *t*-tests. In all statistical tests, *p*-values < 0.05 were considered statistically significant utilizing SPSS (Chicago, IL, USA).

3. Results and discussions

Enamic HT had the lower surface roughness value of 82.56 ± 6.21 nm before thermal aging, while Ultimate HT owned the higher Ra of 125.89 ± 8.64 nm before thermal aging. The surface roughness in both groups increased significantly after thermal aging of 10,000 cycles ($p < 0.001$). The mean surface roughness and standard deviation before and after undergoing thermal aging for the both CAD/CAM materials are shown in [Figure 1](#).

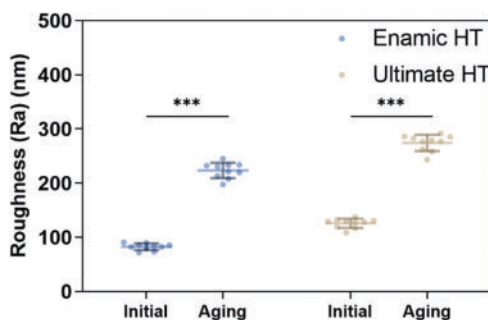


Figure 1. Surface roughness (Ra) values, by material tested, are presented as mean \pm standard deviation (***) $p < 0.001$. $N = 10$

The 3D profilometry images in [Figure 2](#) illustrate the tested materials before and after thermal aging. The red regions indicate the surface areas with the highest elevation (peaks), while the green regions indicate the surface areas with the lowest elevation (valleys). The Enamic HT and Ultimate HT after thermal aging showed a much rougher surface than those before undergoing aging.

The mean transparency(%) and standard deviations before and after thermal aging for the two CAD/CAM Materials were shown in [Figure 3](#). Enamic HT had the lower transparency(%) of 55.02 ± 2.57 before thermal aging, while Ultimate HT owned the higher transparency(%) of 58.89 ± 1.63 before thermal aging. Transparency in both group decreased significantly after aging. Transparency of Ultimate HT is significantly higher than that of Enamic HT before thermal aging ($p < 0.01$), while transparency of Ultimate HT showed significantly lower than that of Enamic HT after thermal aging ($p < 0.001$).

Furthermore, SEM images shown in [Figure 4](#) presented freeze-fracture surface under liquid nitrogen and some internal structure of tested CAD/CAM materials could be observed. Ultimate had micro cracks (red arrow in [Figure 4](#)) inside, while Enamic had internal relative integrity and continuity after thermal aging.

This study investigated the impact of thermal aging on the optical properties and surface characteristics of highly translucent CAD/CAM resin-based materials. The null hypothesis was rejected, as both translucency and surface roughness were influenced by thermal aging, with statistically significant changes.

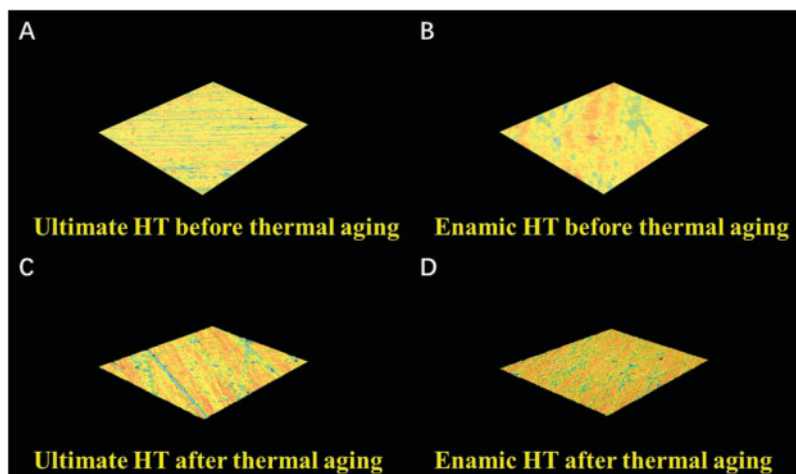


Figure 2. 3D profilometry of the tested CAD/CAM materials before and after thermal aging

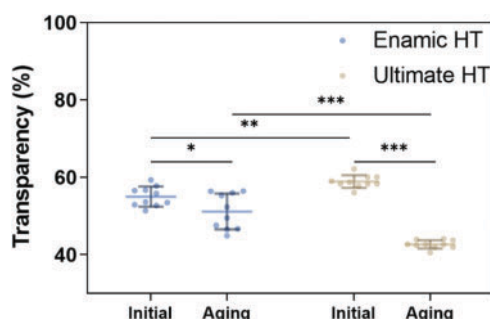


Figure 3. Transparency values, by material tested, are presented as mean \pm standard deviation (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). N = 10

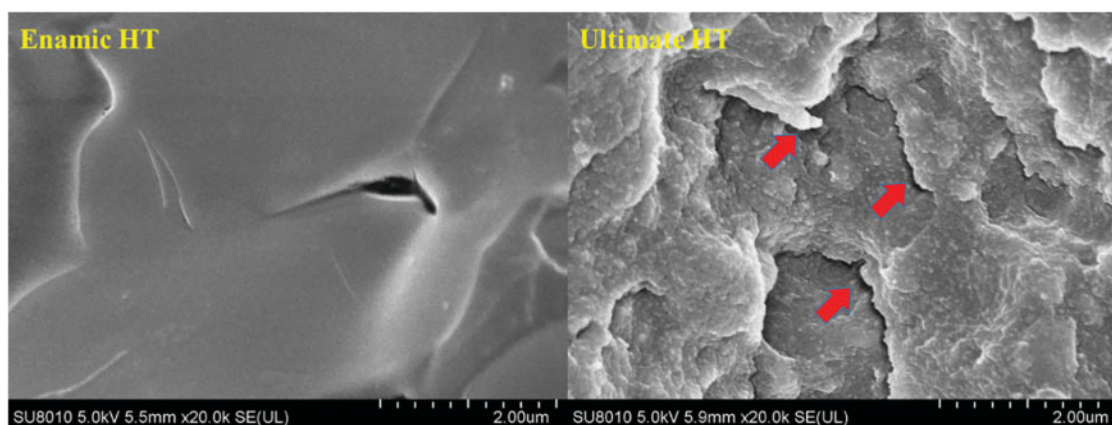


Figure 4. SEM pictures of freeze-fracture surface under liquid nitrogen

Thermocycling simulates temperature variations in the oral cavity caused by daily diet and breathing, hence mimicking the natural aging process of dental restorations [12]. 10,000 cycles represented approximately one year of *in vivo* exposure [13]. In this study, we evaluated and compared the surface roughness and optical properties of two representative CAD/CAM materials during thermal aging. The results revealed a significant increase in surface roughness and a decrease in transparency after thermocycling. Polishing dental restorations plays a crucial role in aesthetics and longevity, particularly

for anterior teeth [14]. In dental practice, the polishability and polish retention of restorative materials should be focused on because higher surface roughness could lead to increased bacterial adhesion or plaque formation [15,16]. The *streptococcus mutants*, for instance, exhibited accelerated growth on resin composites *in vitro* [17], which might result from surface roughness and the higher affinity of salivary proteins to polymeric materials [18]. Many scholars held the view that the surface roughness of restoration is no more than 0.2 μm . Deposition of bacterial biofilm on the restoration surface could increase the incidence of secondary caries and periodontitis. Additionally, increased surface roughness might result in more wear of dental restorations [19,20]. Ra in tested CAD/CAM materials were greater than 0.2 μm and less than 0.3 μm after 10,000 thermal cycles. Previous studies showed surface roughness in Enamic HT and Ultimate HT was lower than 0.2 μm after 5000 thermocycles (5/55°C) [3]. Therefore, it is important to emphasize that resin-based CAD/CAM restoration might require fine polishing after approximately one year of clinical use.

Thermocycling is a combination of hydrolytic and thermal degradation. In the presence of water, ester linkages in the methacrylate groups undergo hydrolysis, producing alcohols and carboxylic acids. This degradation reduces the molecular weight of the polymer, making the resin more vulnerable to mechanical stress and further degradation over time [21]. It had been reported that thermocycling could negatively affect the mechanical properties of CAD/CAM resin-based materials (i.e., flexural strength, hardness, and elastic modulus) [22–25]. However, there was little research on translucency change after more than 10,000 thermocycles. In this study, we focused on the effect of thermal aging on translucency and explored the possible mechanisms underlying these changes. Our findings demonstrate that thermal aging significantly affects the optical properties of CAD/CAM resin-based ceramic.

Before aging, Ultimate HT exhibited higher transparency than Enamic HT, which can be attributed to several factors. Resin nanoceramics were manufactured by mixing the polymer matrix with high transparency in the continuous phase, which was favorable for light penetration. Hence, Ultimate HT owned better translucency than Enamic HT before thermal aging, which was consistent with the findings of Al Amri et al. and Kurtulmus-Yilmaz et al. [26,27]. Transparency in both Enamic HT and Ultimate HT decreased significantly after 10,000 thermal cycles, which might also be related to the increase Ra. The influence of surface characteristics on the translucency of restorative materials has been previously studied, showing that roughness alterations impair light transmittance [1,28]. Mie scattering dominates when defects are comparable in size to the wavelength, while Rayleigh scattering is more significant when defects are much smaller than the wavelength [29]. In this study, both surface roughness and micro-defects contributed to increased light scattering, which consequently affected the transparency of the materials.

Interestingly, the transparency in Ultimate HT was much lower than that in Enamic HT after 10,000 thermocycles of 5/55°C. SEM micrographs of the freeze-fracture surfaces revealed microcracks in Ultimate HT, while Enamic HT maintained relative internal integrity and continuity. This difference may be attributed to the curing process under high pressure during the manufacturing of Enamic [30]. Andreas Koenig et al. also reported defects (pores and blowholes) in CAD/CAM Resin nano ceramic [31]. Once the micro defects formed, water or saliva might seep into the pores, which could increase light scattering and reduce transparency.

The limitations of this study are that it cannot reproduce various environmental factors in the oral cavity, such as Mastication and saliva. Additional studies are needed to clarify chemical factors (pH, color drinks, and alcohol) on the optical properties and roughness of dental CAD/CAM materials.

4. Conclusions

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

1. The thermal aging led to a significant increase in surface roughness in both CAD/CAM materials.



2. Ra in tested CAD/CAM materials were greater than 0.2 μm and less than 0.3 μm after 10,000 thermal cycles. Enamic HT and Ultimate HT restoration might require fine polishing during the 1-year follow-up in dental practice.
3. Transparency in the Enamic HT and Ultimate HT decreased significantly after thermal aging. Ultimate HT were significantly more translucent than Enamic HT before aging, while Ultimate HT showed less translucent than Enamic HT after 10,000 thermocycles of 5/55°C.

Acknowledgement: This work was supported by Clinical Research Foundation of Peking University School and Hospital of Stomatology (PKUSS-2023CRF101) and Key Research and Translational Project by Qinghai Province (2023-QY-201).

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

References

1. WU, Z., TIAN, J., WEI, D., ZHANG, Y., LIN, Y. et al., Effects of thickness and polishing treatment on the translucency and opalescence of six dental CAD-CAM monolithic restorative materials: an *in vitro* study. *BMC Oral Health*, 23(1), 2023, 579. <https://doi.org/10.1186/s12903-023-03299-y>.
2. HAMPE, R., LÜMKEMANN, N., SENNER, B., STAWARCZYK, B., The effect of artificial aging on Martens hardness and indentation modulus of different dental CAD/CAM restorative materials. *J. Mech. Behav. Biomed. Mater.*, 86(1), 2018, 191–198. <https://doi.org/10.1016/j.jmbbm.2018.06.028>.
3. BAI, Y., YUAN, S., WU, J., Evaluation of surface roughness and elastic modulus in ceramic and resin composite cad/cam materials during ageing. *Ceram. Silikaty*, 65(1), 2020, 24–29. <https://doi.org/10.13168/cs.2020.0038>.
4. ALAMOUSH, R. A., SILIKAS, N., SALIM, N. A., AL-NASRAWI, S., SATTERTHWAITTE, J. D., Effect of the composition of CAD/CAM composite blocks on mechanical properties. *Biomed. Res. Int.*, 2018(3), 2018, 4893143. <https://doi.org/10.1155/2018/4893143>.
5. CUI, B., LI, J., WANG, H., LIN, Y., SHEN, Y., et al., Mechanical properties of polymer-infiltrated-ceramic (sodium aluminum silicate) composites for dental restoration. *J. Dent.*, 62, 2017, 91–97. <https://doi.org/10.1016/j.jdent.2017.05.009>.
6. WANG, H., CUI, B., LI, J., LI, S., LIN, Y., et al., Mechanical properties and biocompatibility of polymer infiltrated sodium aluminum silicate restorative composites. *J. Adv Ceram.*, 6(1), 2017, 73–79. <https://doi.org/10.1007/s40145-016-0214-0>.
7. KOIZUMI, H., OKAMURA, K., HIRABA, H., KODAIRA, A., YONEYAMA, T., et al., Radiopacity of computer-aided design/computer-aided manufacturing composite resin blocks. *Eur. J. Oral Sci.*, 128(3), 2020, 241–245. <https://doi.org/10.1111/eos.12692>.
8. CUI, B., SUN, F., DING, Q., WANG, H., LIN, Y., et al., Preparation and characterization of sodium aluminum silicate-polymer composites and effects of surface roughness and scratch directions on their flexural strengths. *Front. Mater.*, 8, 2021, 655156. <https://doi.org/10.3389/fmats.2021.655156>.
9. ZHOU, X., WANG, S., PENG, X., HU, Y., REN, B., et al., Effects of water and microbial-based aging on the performance of three dental restorative materials. *J. Mech. Behav. Biomed. Mater.*, 80(4), 2018, 42–50. <https://doi.org/10.1016/j.jmbbm.2018.01.023>.
10. SZCZESIO-WLODARCZYK, A., SOKOLOWSKI, J., KLECZEWSKA, J., BOCIONG, K., Ageing of dental composites based on methacrylate resins-a critical review of the causes and method of assessment. *Polymers*, 12(4), 2020, 882. <https://doi.org/10.3390/polym12040882>.
11. CHECKETTS, M. R., TURKYILMAZ, I., ASAR, N. V., An investigation of the effect of scaling-induced surface roughness on bacterial adhesion in common fixed dental restorative materials. *J. Prosthet. Dent.*, 112(5), 2014, 1265–1270. <https://doi.org/10.1016/j.prosdent.2014.04.005>.



12. AKIN, H., OZDEMIR, A. K., Effect of corrosive environments and thermocycling on the attractive force of four types of dental magnetic attachments. *J. Dent. Sci.*, 8(2), 2013, 184–188. <https://doi.org/10.1016/j.jds.2012.09.011>.
13. DE MUNCK, J., VAN LANDUYT, K., COUTINHO, E., POITEVIN, A., PEUMANS, M., et al., Micro-tensile bond strength of adhesives bonded to Class-I cavity-bottom dentin after thermocycling. *Dent. Mater.*, 21(11), 2005, 999–1007. <https://doi.org/10.1016/j.dental.2004.11.005>.
14. KUMARI, C. M., BHAT, K. M., BANSAL, R., Evaluation of surface roughness of different restorative composites after polishing using atomic force microscopy. *J. Conserv. Dent.*, 19(1), 2016, 56–62. <https://doi.org/10.4103/0972-0707.173200>.
15. MITRA, S. B., WU, D., HOLMES, B. N., An application of nanotechnology in advanced dental materials. *J. Am. Dent. Assoc.*, 134(10), 2003, 1382–1390. <https://doi.org/10.14219/jada.archive.2003.0054>.
16. MEI, L., BUSSCHER, H. J., VAN DER MEI, H. C., REN, Y., Influence of surface roughness on streptococcal adhesion forces to composite resins. *Dent. Mater.*, 27(8), 2011, 770–778. <https://doi.org/10.1016/j.dental.2011.03.017>.
17. BEYTH, N., BAHIR, R., MATALON, S., DOMB, A. J., WEISS, E. I., *Streptococcus mutans* biofilm changes surface-topography of resin composites. *Dent. Mater.*, 24(6), 2008, 732–736. <https://doi.org/10.1016/j.dental.2007.08.003>.
18. SINGH, J., KHALICHI, P., CVITKOVITCH, D. G., SANTERRE, J. P., Composite resin degradation products from BisGMA monomer modulate the expression of genes associated with biofilm formation and other virulence factors in *Streptococcus mutans*. *J. Biomed. Mater. Res. A*, 88(2), 2009, 551–560. <https://doi.org/10.1002/jbm.a.31879>.
19. BAI, Y., ZHAO, J., SI, W., WANG, X., Two-body wear performance of dental colored zirconia after different surface treatments. *J. Prosthet. Dent.*, 116(4), 2016, 584–590. <https://doi.org/10.1016/j.prosdent.2016.02.006>.
20. GRYPMAK, A., AARTS, J. M., CAMERON, A. B., CHOI, J. J. E., Evaluation of wear resistance and surface properties of additively manufactured restorative dental materials. *J. Dent.*, 147(4), 2024, 105120. <https://doi.org/10.1016/j.jdent.2024.105120>.
21. KUMAR, D., GHOSE, D., MUTREJA, I., BOLSKAR, R. D., APARICIO, C., et al., Utilizing a degradation prediction pathway system to understand how a novel methacrylate derivative polymer with flipped external ester groups retains physico-mechanical properties following esterase exposure. *Dent. Mater.*, 38(2), 2022, 251–265. <https://doi.org/10.1016/j.dental.2021.12.008>.
22. SOUZA, R. O. A., OZCAN, M., MICHIDA, S. M. A., DE MELO, R. M. PAVANELLI, C. A., et al., Conversion degree of indirect resin composites and effect of thermocycling on their physical properties. *J. Prosthodont.*, 19(3), 2010, 218–225. <https://doi.org/10.1111/j.1532-849X.2009.00551.x>.
23. PIENIAK, D., PRZYSTUPA, K., WALCZAK, A., NIEWCZAS, A. M., KRZYZAK, A., et al., Hydro-thermal fatigue of polymer matrix composite biomaterials. *Materials*, 12(22), 2019, 3650. <https://doi.org/10.3390/ma12223650>.
24. DRUMMOND, J. L., Degradation, fatigue, and failure of resin dental composite materials. *J. Dent. Res.*, 87(8), 2008, 710–719. <https://doi.org/10.1177/154405910808700802>.
25. PALA, K., TEKÇE, N., TUNCER, S., DEMIRCI, M., ÖZNURHAN, F., et al., Flexural strength and microhardness of anterior composites after accelerated aging. *J. Clin. Exp. Dent.*, 9(3), 2017, e424–e430. <https://doi.org/10.4317/jced.53463>.
26. AL AMRI, M. D., LABBAN, N., ALHIJJI, S., ALAMRI, H., ISKANDAR, M., et al., *In vitro* evaluation of translucency and color stability of CAD/CAM polymer-infiltrated ceramic materials after accelerated aging. *J. Prosthodont.*, 30(4), 2021, 318–328. <https://doi.org/10.1111/jopr.13239>.



27. KURTULMUS-YILMAZ, S., CENGIZ, E., ONGUN, S., KARAKAYA, I., The effect of surface treatments on the mechanical and optical behaviors of CAD/CAM restorative materials. *J. Prosthodont.*, 28(2), 2019, e496–503. <https://doi.org/10.1111/jopr.12749>.
28. BRESCANSIN, F. N., PROCHNOW, C., GUILARDI, L. F., KLEVERLAAN, C. J., BACCHI, A., et al., Effect of different surface treatments on optical, colorimetric, and surface characteristics of a lithium disilicate glass-ceramic. *J. Esthet. Restor. Dent.*, 33(7), 2021, 1017–1028. <https://doi.org/10.1111/jerd.12793>.
29. ZHAO, M., SUN, Y., ZHANG, J., ZHANG, Y., Novel translucent and strong sub-micron alumina ceramics for dental restorations. *J. Dent. Res.*, 97(3), 2018, 289–295. <https://doi.org/10.1177/0022034517733742>.
30. LABORIE, M., NAVEAU, A., MENARD, A., CAD-CAM resin-ceramic material wear: a systematic review. *J. Prosthet. Dent.*, 131(5), 2024, 812–818. <https://doi.org/10.1016/j.prosdent.2022.01.027>.
31. KOENIG, A., SCHMIDTKE, J., SCHMOHL, L., SCHNEIDER-FEYRER, S., ROSENTRITT, M. et al., Characterisation of the filler fraction in CAD/CAM resin-based composites. *Materials*, 14(8), 2021, 1986. <https://doi.org/10.3390/ma14081986>.

Received: 08 April 2024; Accepted: 02 July 2025; Published: 18 July 2025