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Effect of surface pretreatment on the bond strength of short fiber-reinforced CAD/CAM composite blocks

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Abstract

Objectives The aim of this laboratory research was to evaluate and compare the effect of various surface pretreatments on the shear-bond strength (SBS) of a self-adhesive resin cement to two CAD/CAM materials: a conventional particulate-composite (Cerasmart 270) and an experimental short glass fiber-reinforced composite (SFRC).

Methods Specimens were prepared from composite blocks with dimensions of 14 mm × 12 mm × 3 mm ($n = 80$ / material). The bonding surfaces were standardized by grinding with 320-grit silicon carbide papers. The specimens were then divided into two main subgroups ($n = 40$ /group) based on the surface pretreatment protocol: airborne-particle abrasion (APA) or airborne-particle abrasion plus hydrofluoric acid for 60 s (APA + HF). Following surface pretreatment, a self-adhesive resin cement was applied to the block surface using metallic cylinders. Half of the specimens were subjected to the SBS test after 48 h of water storage, while the remaining half after hydrothermal accelerated aging by 16 h boiling. Scanning electron microscopy (SEM) and three-dimensional optical profilometer were used to examine the topography of CAD/CAM composites following surface pretreatment.

Results Both CAD/CAM composite type and surface pretreatment protocol significantly influenced SBS ($p < 0.05$). For Cerasmart 270, the APA + HF protocol resulted in higher SBS values compared with airborne-particle abrasion alone. In contrast, for the SFRC CAD, airborne-particle abrasion alone produced higher SBS values than the APA + HF protocol. The effect of hydrothermal aging on shear bond strength was dependent on the surface pretreatment and material type, rather than aging alone. SEM analysis revealed distinct surface morphological differences among the tested materials and pretreatment methods.

Conclusions Airborne-particle abrasion alone was sufficient to achieve high and stable bond strength for the SFRC CAD/CAM composite. In contrast, the application of hydrofluoric acid following airborne-particle abrasion was necessary to optimize bonding of the self-adhesive resin cement to the conventional CAD/CAM composite.

Keywords CAD/CAM resin composite, Shear bond strength, Surface pretreatment, Fiber reinforced composite

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Introduction

The usage of computer-aided design and computer-aided manufacturing (CAD/CAM) technologies that enable the manufacture of minimal invasive indirect restorations has increased during the last 25 years [1]. Many advantages of CAD/CAM technology include the elimination of traditional impression and laboratory phases, restoration delivery in a single session [1, 2], speed, ease of use, material diversity, and high-quality restoration manufacturing [2]. As a result, researchers want to create restorations that look like actual teeth by improving the physical qualities of existing CAD/CAM blocks and inventing new materials [3–5].

CAD/CAM restorations can be made from feldspathic ceramics, lithium disilicate, leucite-reinforced glass ceramics, zirconia, or resin composite blocks [2, 6]. Resin composite CAD/CAM blocks have lower modulus of elasticity and therefore better stress absorption property than ceramics [7, 8]. Also due to their repairable nature, resin composite are suitable for restorative use. Because of resin composite block´s machinability, they can be milled fast with reduced milling bur wear [8, 9]. Intact marginal edges can be obtained since there is less chipping after manufacture [10]. Additionally, unlike ceramics, composite restorations do not require further finishing procedures [11] and cause less wear on the opposing tooth [12, 13]. Many factors play a role in the longevity and clinical success of the restoration. Achieving adhesion between the CAD/CAM restoration and the resin cement can often be challenging, directly affecting the treatment outcome [14].

Depending on the structure of each material used, different chemical and/or mechanical surface pretreatments can be applied to enhance adhesion [15]. Techniques such as acid etching, air-particle abrasion (airborne-particle abrasion), tribochemical silica coating, silanization, application of universal adhesives or primers, and mechanical roughening with a bur improve bonding through micromechanical interlocking [16]. The chemical composition of recently developed, highly filled particulate composite blocks is heterogeneous, consisting of a filler phase embedded within a cross-linked polymer matrix. These two phases exhibit distinct bonding characteristics, and no consensus has yet been reached regarding the optimal bonding protocol for such materials [17–21].

Airborne-particle abrasion and silanization significantly strengthen the bond between CAD/CAM composite blocks and resin cement, although the composite block surface is not uniformly modified after airborne-particle abrasion [22]. Etching with hydrofluoric acid increases adhesion by interacting with the glass phase in the material's structure [18, 19]. Unlike glass ceramics, composite blocks contain limited silica, which can interact with hydrofluoric acid [4].

New experimental short glass fiber–reinforced composite (SFRC) CAD/CAM blocks have recently been developed. These aesthetic monolithic composites contain filler particles and short, multidirectional glass fibers within a resin matrix [23, 24]. The main purpose of adding fibers is to improve the fracture toughness compared to conventional particulate-filled CAD/CAM composites. Early studies on their optical, mechanical, and surface properties have shown encouraging results [25–27]. However, there is still a lack of investigation into the bonding capabilities of this novel SFRC composite, particularly regarding the optimal surface pretreatment needed to maximize its bond with resin cement.

This laboratory study compares the effects of various surface pretreatments on the shear bond strength (SBS) of a self-adhesive resin cement to both conventional and SFRC composite CAD/CAM materials under different surface and aging conditions. The null hypothesis states that material type, surface pretreatment, and aging protocol will not significantly influence the SBS of the CAD/CAM composite blocks.

Materials and methods

Table 1 details the materials and their specific compositions used in this investigation. The experimental SFRC CAD/CAM block was custom fabricated from a monomer matrix (23 wt%), which was itself a blend of 70% UDMA and 30% TEGDMA. This matrix contained 25 wt% silinated short glass fibers (200–300 & Ø6 µm) and 52 wt% silinated barium glass fillers (Ø 0.7 µm). The manufacturing process began by blending the photoinitiators,

Table 1 CAD/CAM composites and luting resin used in the study

Material	Manufacturer	Composition according to manufacturer
Cerasmart 270	GC Corp, Tokyo, Japan	Bis-MEPP, UDMA, dimethacrylate, Silica (20 nm), barium glass (300 nm) 71 wt%
SFRC	Experimental	UDMA, TEGDMA, Short glassfiber (200–300 µm & Ø6 µm), Barium glass 77 wt%
G-CEM ONE (Universal self-adhesive resin)	GC Corp,	Paste A: Fluoroaluminosilicate glass, titanium dioxide, UDMA, 2-Hydroxy-1,3 dimethacryloxypropane, initiators Paste B: Silica filler, UDMA, 10-MDP, dimethylbenzyl hydroperoxide.

TEGDMA triethylene glycol dimethacrylate, *UDMA* urethane dimethacrylate, *Bis-MEPP* Bis (p-methacryloxy (ethoxy) 1–2 phenyl)-propane, *10-MDP* 10-methacryloyloxydecyl dihydrogenphosphate, *wt%* weight%

fillers, fibers, and monomers into a uniform mixture using a Thinky Mixer ARV-310 (TM, Tokyo, Japan). This resulting compound was subsequently loaded into rectangular molds and subjected to compression in a pressure chamber to increase density and prevent the formation of internal voids. Finally, the material underwent optimal monomer conversion through polymerization under precise controls, involving temperatures up to 170 °C and high pressure.

Specimen preparation

Specimens were prepared from Cerasmart 270 (GC Corp, Tokyo, Japan) and experimental SFRC composite blocks by sectioning the blocks under water cooling with a low-speed diamond saw (Secotom-50, Struers, Denmark). Sections measuring 14 mm × 12 mm × 3 mm were obtained from each CAD/CAM block ($n = 80$ for each material). The specimens were mounted in a cylindrical mold filled with auto-polymerizing acrylic resin (Palapress Vario, Heraeus Kulzer). The surfaces were ground with 180- and 320-grit silicon carbide papers to create a standardized surface for bonding, using an automatic grinding machine (Rotopol-1; Struers). After polishing, the surfaces were cleaned under running water (Fig. 1). Specimens were then randomly allocated to the different experimental groups according to surface pretreatment.

Surface pretreatments

Specimens form each CAD/CAM composite were divided into two surface pretreatment groups ($n = 40$ per group):

- Group APA (Airborne-particle abrasion): Specimens were subjected to airborne-particle abrasion only.
- Group APA + HF (Airborne-particle abrasion + Acid Etching): Specimens were subjected to airborne-particle abrasion followed by hydrofluoric acid etching.

The surface pretreatment protocols were as follows:

Airborne-particle abrasion was performed uniformly for all groups using 50 µm alumina particles (Korox, Bego, Germany) with an intraoral airborne-particle abrasion device (CoJet System, 3 M ESPE, USA). The pretreatment was conducted at a distance of 10 mm under 2 bar pressure for 10 s, with the nozzle held perpendicular to the specimen surface.

For groups designated APA + HF, after airborne-particle abrasion, the specimens were rinsed with a water spray and then treated with a 4.5% hydrofluoric acid gel (IPS Ceramic Etching Gel, Ivoclar Vivadent AG, Liechtenstein) for 60 s. Following their respective treatments, all specimens were thoroughly rinsed with a water spray and air-dried.

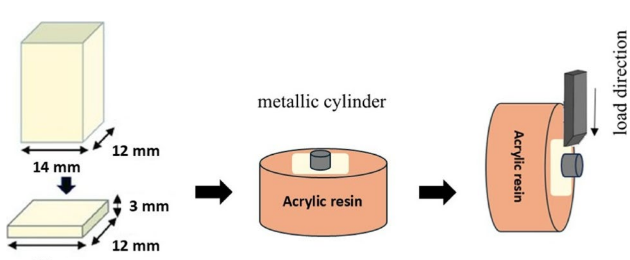

Fig. 1 Schematic figure of the specimen designs and shear bond test setup

Surface characterization

The surface topography was characterized using scanning electron microscopy (SEM) (LEO, Oberkochen, Germany) and a three-dimensional (3D) non-contact optical profilometer (Bruker Nano GmbH, Berlin, Germany) operated with Vision64 software. For this analysis, three specimens from each group were prepared separately. The specimens were sputter-coated with a thin gold layer (BAL-TEC SCD 050 Sputter Coater, Balzers, Liechtenstein) prior to imaging.

Cement application and shear bond strength testing

The self-adhesive resin cement (G-CEM One, GC Corp, Tokyo, Japan) was selected from the same manufacturer as the CAD/CAM composite blocks to ensure material compatibility and to follow the manufacturer's recommended restorative system. The cement was mixed for 10 s in accordance with the manufacturer's instructions. To standardize the cement thickness, the cement was applied to the block surface through a metallic cylinder mold (3 mm in diameter and height) (Fig. 1).

The specimens were then divided into two surface condition groups ($n = 20$ per group): slightly humid and completely dry (Fig. 2). For the completely dry surface condition, specimens were air-dried using oil- and water-free compressed air from a dental unit air syringe for 10 s at 10 cm, ensuring complete removal of visible surface moisture. For the slightly humid surface condition, specimens were rinsed with distilled water and gently blot-dried using standardized absorbent paper (Whatman No.1, Kent, UK) without air-drying. This procedure resulted in a visibly moist surface with no pooling water, ensuring consistent surface humidity among specimens.

After cement application, excess cement was removed with a dental explorer. The cement was then light-cured through the mold for 20 s per side using an LED light-curing unit (Elipar S10, 3 M ESPE, Germany). The light output (1598.4 mW/cm2) was monitored at the beginning of each group using a calibrated radiometer (BlueLight Analytics, MARC system).

Following cementation, the specimens were assigned to either a non-aged group (storage in distilled water

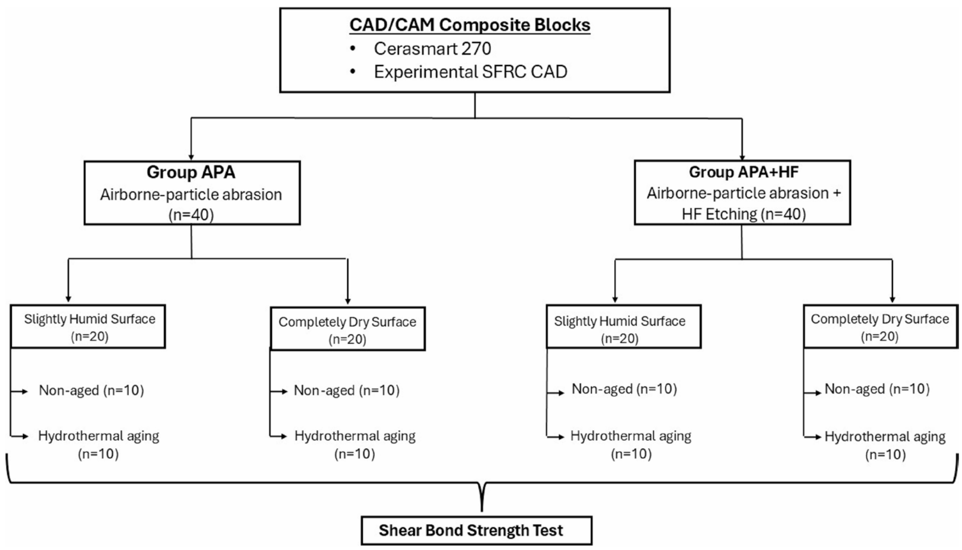

Fig. 2 Flow chart illustrates specimen preparation, surface pretreatment protocols, surface conditions, aging procedures, and group allocation

at 37 °C for 48 h; $n = 10$) or an aged group (hydrothermal aging by boiling in water for 16 h; $n = 10$). Boiling in water for 16 h was used as an accelerated hydrothermal aging protocol to challenge the resin matrix and the fiber–matrix interface of both Cerasmart 270 and SFRC CAD materials. This approach promotes water sorption and interfacial degradation, thereby enabling the evaluation of aging sensitivity and bond durability of fiber-reinforced and non–fiber-reinforced CAD/CAM composites.

SBS was measured before and after aging using a universal testing machine (Lloyd LR30K Plus, Lloyd Instruments, UK) at a crosshead speed of 1.0 mm/min until failure.

Failure modes analysis

After SBS tests, the failure modes of the specimens were visually evaluated using a stereomicroscope (Wild M3Z; Wild Heerbrugg). The evaluations were performed by three independent and previously calibrated examiners who were trained using standardized failure mode definitions to ensure consistency among evaluators. Failure modes were classified as adhesive (A), occurring at the interface between the composite and resin cement; cohesive (C), occurring within the composite or resin cement; or mixed (M), involving a combination of adhesive and cohesive failures.

Statistical analysis

A priori power analysis was performed using G*Power software (version 3.1.9.7, Heinrich Heine University, Düsseldorf, Germany). Based on previously published shear bond strength data, an effect size (f) of 0.40, a significance level of $\alpha = 0.05$, and a statistical power of 80% were assumed. The analysis indicated that a minimum of 8 specimens per group was required. Therefore, 10 specimens were included in each subgroup to compensate for potential data loss.

Statistical analyses were performed using SPSS software (version 23.0; IBM Corp., Armonk, NY, USA). A three-way analysis of variance (three-way ANOVA) was applied with material type, surface pretreatment, and aging condition as independent variables and shear bond strength as the dependent variable. The level of statistical significance was set at $p < 0.05$. When significant interaction effects were detected, group-wise comparisons were interpreted based on the estimated marginal means. The assumption of homogeneity of variances was assessed using Levene's test.

Results

The SBS results are presented in Fig. 3, and the distribution of failure modes is detailed in Table 2. Levene's test confirmed homogeneity of variances for SBS values ($p = 0.384$). The three-way ANOVA demonstrated a significant main effect of material type on shear bond strength ($p < 0.001$), while surface pretreatment and aging did not show significant main effects ($p > 0.05$). However, significant interaction effects were observed between surface pretreatment and aging ($p = 0.004$) and between surface pretreatment and material type ($p < 0.001$).

The SFRC CAD/CAM composite exhibited higher SBS values than Cerasmart 270 across all experimental conditions. The highest SBS was observed in the SFRC specimens treated with airborne-particle abrasion under dry conditions (21.7 ± 4.39 MPa). For SFRC CAD, airborne-particle abrasion alone resulted in significantly higher SBS values than the APA + HF protocol under both dry and humid conditions ($p < 0.05$). No statistically significant differences were detected between non-aged and

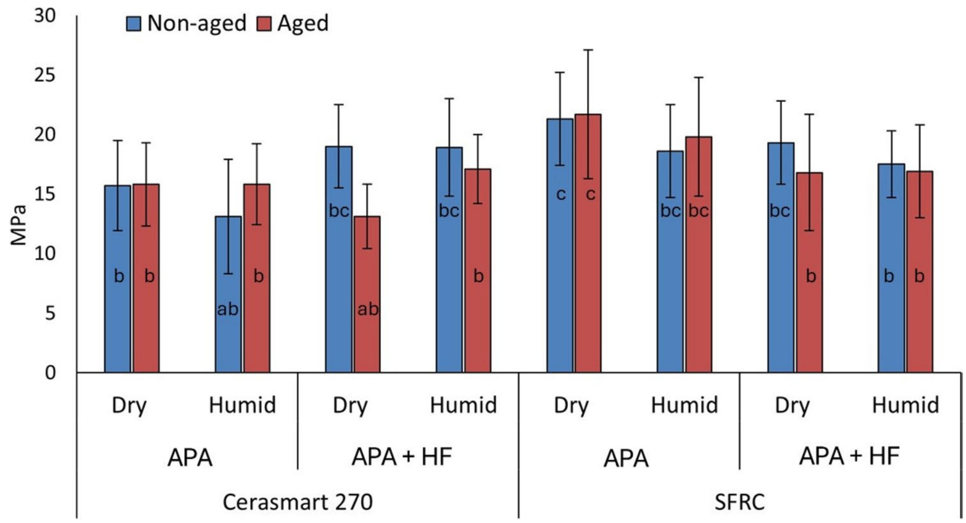

Fig. 3 Shear bond strength (mean values and standard deviations; MPa) of the tested groups ($n=10$). Same letters indicate no statistically significant differences between groups

Table 2 Failure behavior distribution of different surface pretreatments after shear bond strength test between CAD/CAM composite and self-adhesive resin cement

			Non-aged			Aged		
			Adhesive	**Cohesive**	**Mix**	**Adhesive**	**Cohesive**	**Mix**
Cerasmart	APA	Dry	2	6	2	0	6	4
		Humid	5	3	2	2	4	4
	APA + HF	Dry	4	4	2	5	3	2
		Humid	3	5	2	1	6	3
SFRC	APA	Dry	10	0	0	10	0	0
		Humid	10	0	0	10	0	0
	APA + HF	Dry	10	0	0	10	0	0
		Humid	10	0	0	10	0	0

aged SFRC specimens within the same surface pretreatment and surface condition groups ($p > 0.05$).

In contrast, the bond strength of Cerasmart 270 was significantly influenced by the surface pretreatment protocol. Under dry conditions, APA + HF pretreatment resulted in significantly higher SBS values than airborne-particle abrasion alone in the non-aged group (19.2 ± 3.95 MPa vs. APA; $p < 0.05$). Following hydrothermal aging, a significant reduction in SBS was observed in the APA + HF-treated Cerasmart 270 specimens, particularly under dry conditions (13.1 ± 2.7 MPa; $p < 0.05$). No significant aging-related changes were observed in the APA-only Cerasmart 270 groups ($p > 0.05$).

When surface condition was considered, specimens prepared under dry conditions tended to show slightly higher SBS values than those prepared under humid conditions for both materials; however, this difference did not reach statistical significance as a main effect ($p > 0.05$).

The effect of aging on SBS was dependent on the surface pretreatment protocol rather than aging alone, with APA-treated groups showing more stable bond strength values compared with APA + HF-treated groups.

The failure mode analysis (Table 2) revealed that SFRC specimens consistently failed adhesively at the resin cement–composite interface, even when achieving high bond strength. In contrast, Cerasmart 270 showed a higher incidence of cohesive failures within the composite material. The absence of cohesive failure within the SFRC material suggests that its bulk structure remained intact under the applied loading conditions, indicating that the adhesive interface, rather than the composite substrate, represented the primary site of failure for SFRC.

Representative scanning electron micrographs of the surface topography for both CAD/CAM composites following different surface pretreatments are presented in Fig. 4. For Cerasmart 270, distinct morphological changes were induced by the pretreatments. The surfaces that APA treated (Fig. 4A) exhibited a characteristic irregular roughness with undercuts. Subsequent hydrofluoric acid etching (APA + HF) (Fig. 4B) altered this topography, resulting in a more pronounced pattern

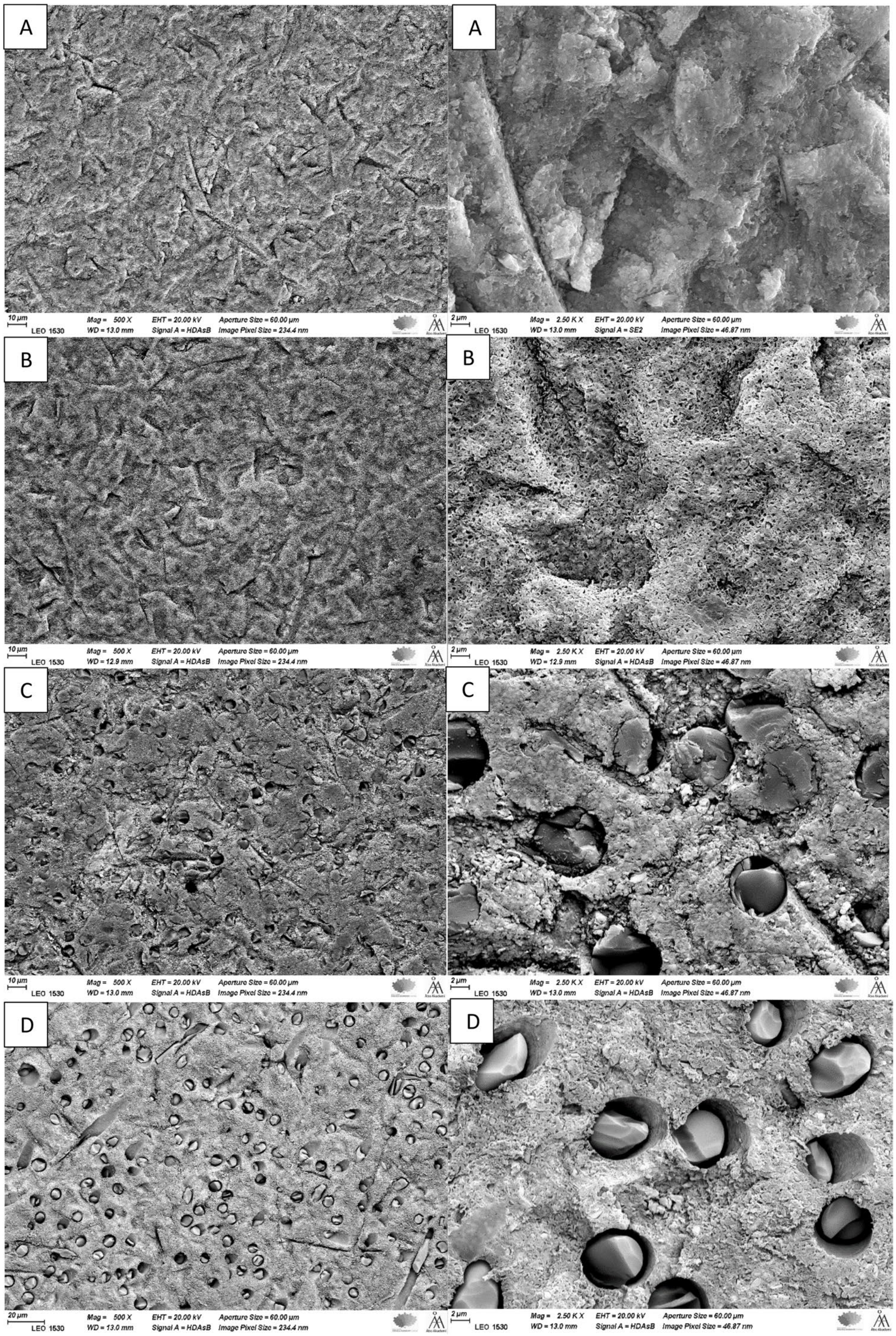

Fig. 4 Scanning electron micrographs of Cerasmart 270 and SFRC composite surfaces after surface pretreatments. Surfaces were treated with either airborne-particle abrasion (APA) or airborne-particle abrasion followed by hydrofluoric acid etching (APA + HF). Images are shown at two magnifications (500× and 2500×). **A** Cerasmart 270, APA. **B** Cerasmart 270, APA + HF. **C** SFRC, APA. **D** SFRC, APA + HF

where the acid treatment dissolved the glassy filler particles, creating porosities and a honeycomb-like structure. In contrast, the SFRC demonstrated a markedly different response. The APA surfaces (Fig. 4C) showed a textured surface with exposed, largely intact short fibers. After the combined APA + HF treatment (Fig. 4D), the acid affected both the protruded fibers and the surrounding matrix, potentially reducing the overall surface irregularities/roughness (Ra = 1.4) compared to the initial APA treated topography (Ra = 0.9) (Fig. 5).

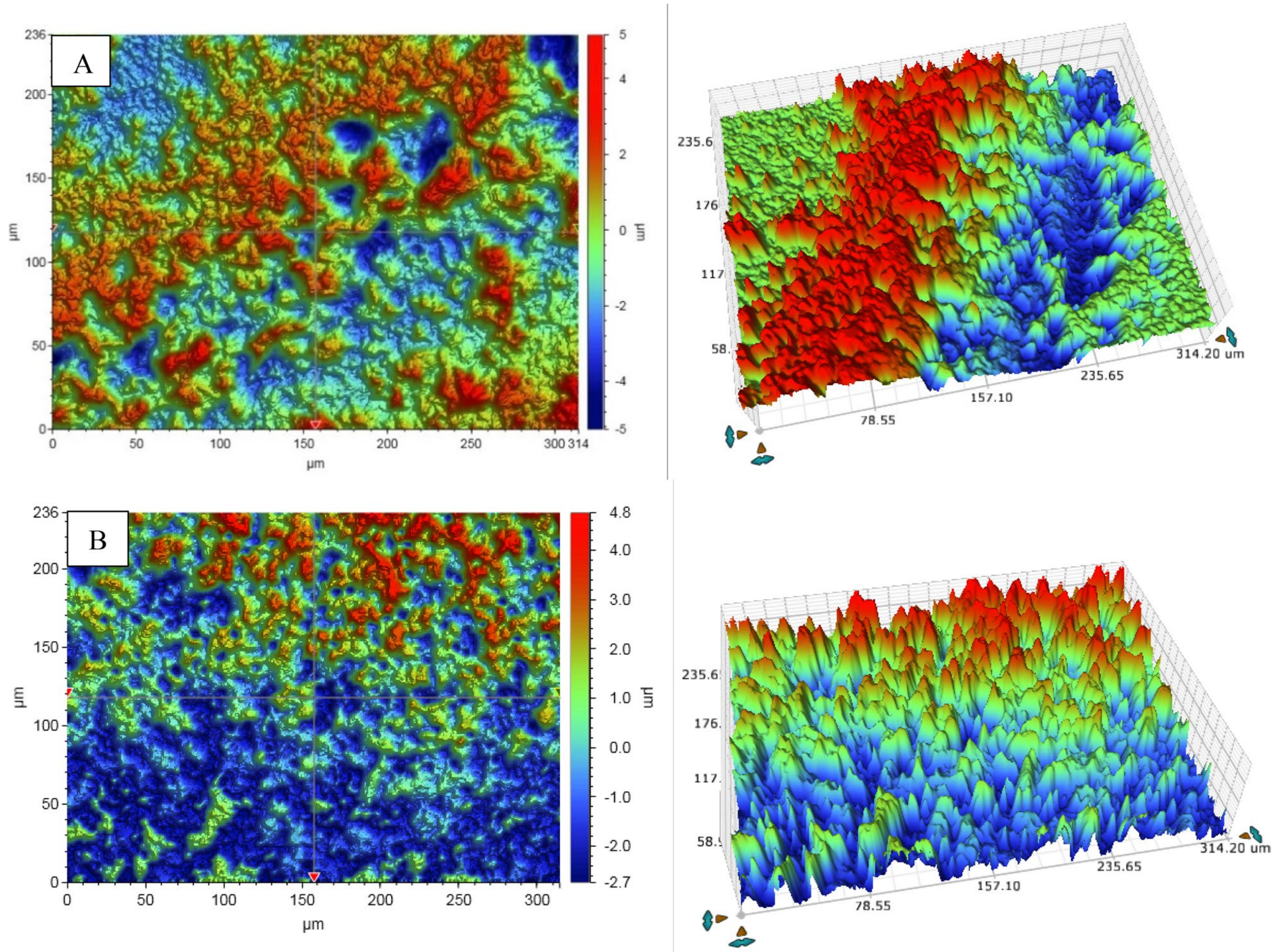

Fig. 5 2D and 3D representative images of SFRC composite surfaces after airborne-particle abrasion (**a**) and airborne-particle abrasion followed by hydrofluoric acid etching (**b**)

Discussion

This study evaluated the shear bond strength (SBS), failure mode, and surface morphology of a conventional CAD/CAM composite (Cerasmart 270) and a short fiber–reinforced CAD/CAM composite (SFRC) following different surface pretreatments and hydrothermal aging. The results demonstrated that material type had a significant influence on SBS, while the effects of surface pretreatment and aging were dependent on their interaction with the material. Therefore, the null hypothesis was rejected.

The longevity of indirect restorations depends on establishing a reliable adhesive interface between the resin cement and the restoration's fitting surface. CAD/CAM composites are industrially polymerized under high temperature and pressure, producing a highly converted, homogeneous structure with a high filler content (up to 80 wt%). Owing to their high degree of monomer conversion, these materials contain fewer residual monomers and possess a more stable surface, which makes chemical bonding with resin cement challenging [28, 29]. Consequently, surface texture modification is essential to achieve effective micromechanical adhesion [29]. For CAD/CAM resin composites, bonding is predominantly micromechanical; thus, the substrate's surface energy and wettability are critical factors. Increased surface roughness enhances these properties by enlarging the available surface area, thereby improving the potential for adhesion [15].

Surface pretreatment with airborne-particle abrasion is widely recommended by manufacturers and has been shown to enhance the bond strength of CAD/CAM composite blocks across various resin-based materials [15, 30, 31]. As mentioned earlier, creating an appropriately roughened surface increases the effective bonding area and promotes micromechanical interlocking. Currently, airborne-particle abrasion is the most commonly employed method for surface roughening. However, the resulting surface morphology can vary depending on the substrate material and the airborne-particle abrasion parameters, such as particle size, pressure, and duration. Among these parameters, airborne-particle abrasion with 50 µm alumina particles under controlled air pressure (1–3 bar) has been reported to provide the most reliable bond durability [30, 32].

Acid etching is another widely used surface pretreatment. It dissolves the silica-based (SiO_2) glassy phase in ceramics, effectively creating a micro-roughened surface suitable for adhesion [33, 34]. Since composite blocks also contain SiO_2 fillers, acid treatment has been applied to roughen their surfaces prior to bonding [35, 36]. While airborne-particle abrasion with aluminum oxide produces a nonselective and irregular surface, acid etching works by selectively dissolving filler particles, resulting in a more uniform, porous surface [37]. Abdou et al., [29] further reported that combining airborne-particle abrasion and acid etching increased the surface roughness of composite blocks, which correlated strongly with higher surface energy and improved bonding performance.

Nevertheless, the literature presents conflicting results. Some studies have reported that airborne-particle abrasion alone yields superior bond strength [38, 39], whereas others have found comparable or even enhanced bonding when airborne-particle abrasion and acid etching are combined [29, 40].

The key finding of this study is that SFRC achieved a strong and durable bond using only airborne-particle abrasion, whereas Cerasmart 270 required both airborne-particle abrasion and acid etching to attain comparable bond strength. The superior performance of SFRC, particularly after airborne-particle abrasion, can be attributed to its distinctive microstructure. Airborne-particle abrasion effectively exposes a dense network of short glass fibers, generating a micro-retentive surface that promotes mechanical adhesion [41, 42]. The high bond strength values observed which was maintained even after aging (Fig. 3), indicate that this micromechanical interlocking is highly stable over time. In contrast, hydrofluoric acid etching did not further improve the bond strength of SFRC. SEM analysis revealed that HF application resulted in a smoother surface morphology compared with airborne-particle abrasion alone (Fig. 4C and D), which may have reduced surface roughness and limited micromechanical retention. This finding explains the lack of bond strength enhancement observed in the APA + HF groups for SFRC and highlights the limited effectiveness of HF etching on resin-rich, fiber-reinforced CAD/CAM composites. From a clinical perspective, these findings suggest that aggressive chemical surface treatments may not provide additional benefits for fiber-reinforced CAD/CAM composites.

The consistent adhesive failure mode observed exclusively in the SFRC groups is especially noteworthy. Even at high bond strength levels, failure occurred at the cement–composite interface, indicating that the cohesive strength of the SFRC material itself was not exceeded. Clinically, this behavior may be advantageous, as it preserves the structural integrity of the restoration and may facilitate repair procedures without compromising the bulk material. This behavior may be attributed to the fiber-reinforced architecture of SFRC, which is known to enhance crack resistance and damage tolerance compared with conventional composite materials [23, 24], thereby reducing the likelihood of catastrophic cohesive failure within the restoration. These results align with the findings of Mangoush et al., who also reported the absence of cohesive failure in SFRC composites [41].

Conversely, achieving durable adhesion between the resin cement and Cerasmart 270 proved more challenging. The combination of airborne-particle abrasion and hydrofluoric acid etching produced a micro-porous, honeycomb-like surface that yielded the highest initial bond strength. However, this bond was susceptible to hydrolytic degradation, as evidenced by the significant reduction in strength following hydrothermal accelerated aging. Previous studies have shown that boiling in water promotes water penetration into the matrix of composite structures, leading to softening of the polymer matrix at the interface [43, 44]. Moreover, the infiltrated water can hydrolyze the interfacial silane coupling agent, thereby weakening the chemical bond between the resin matrix and the fillers [44]. The frequent occurrence of cohesive failures within Cerasmart 270 in high-strength groups further supports that its toughness is lower than that of SFRC, making it the limiting factor in the overall bond complex.

When comparing the tested CAD/CAM materials within the APA group, higher shear bond strength values were obtained for the SFRC blocks compared to the Cerasmart 270 blocks. The SFRC CAD/CAM composite contains fibers with a larger diameter (≈ 6 µm) than the filler particles in Cerasmart 270 (≈ 300 nm), which produces a rougher surface and, consequently, higher bond strength values. However, when bond strength was evaluated after applying acid etching for 60 s following airborne-particle abrasion, no significant difference was observed between the two CAD/CAM materials ($p > 0.05$). This suggests that acid etching may dissolve both the fillers in Cerasmart 270 and the glass fibers in the SFRC blocks, resulting in a similar surface roughness.

Considering the surface conditions (dry/slighly humid), when the specimens prepared under dry conditions exhibited little higher SBS values. This trend was observed across both materials, indicating that moisture control is a critical factor for achieving optimal bond strength.

In this study, a single self-adhesive resin cement was used to isolate and clarify the effects of surface pretreatments on different CAD/CAM composites. The self-adhesive resin cement (G-CEM One) contains

10-methacryloyloxydecyl dihydrogen phosphate (MDP), which contribute to adhesion by providing a priming effect on the resin matrix of the composites. Although silane application has been suggested for certain CAD/CAM composite materials, its effectiveness remains controversial. Previous studies have reported reduced bond strength after silane application following airborne-particle abrasion or acid etching in composite blocks [29, 45], possibly due to the absence of a glass-rich phase. Based on these findings to avoid potential confounding effects, no silane or ceramic primer was applied in the present experimental design.

Dental luting cement is applied in a very thin layer, which makes it challenging to accurately measure its sole adhesive strength to the substrate. To address this, the present study was designed with two adhesive interfaces. Metal substrates were used instead of dentin discs to eliminate the influence of the naturally weaker tooth–cement interface and to focus solely on the bond between the luting cement and the CAD/CAM composites. This setup minimized the risk of failures occurring at unintended sites, which could otherwise mask the effects of the surface pretreatment protocols under investigation [35, 38]. However, this approach excludes clinically relevant variables such as dentinal tubule orientation, dentin moisture, hybrid layer formation, and resin infiltration into dentin. Therefore, the bonding performance observed in this study may not fully reflect clinical dentin–cement interactions.

This study has certain limitations that should be considered when interpreting the results. First, only one type of self-adhesive resin cement was tested, which may limit the generalizability of the findings to other adhesive systems with different compositions or chemistries. Second, only two types of CAD/CAM composite blocks were evaluated, which restricts the applicability of the results to other composite materials. Third, while the SBS test model is widely used, it is inherently sensitive to specimen geometry, loading direction, and stress concentration, which may lead to over- or underestimation of true bonding strength. The use of a microtensile bond strength (μTBS) test would have provided more uniform stress distribution and potentially a more reliable assessment of the interfacial region; however, μTBS is technically demanding and prone to premature failures in brittle composites.

Additionally, the aging process simulated hydrothermal accelerated degradation but did not account for other intraoral factors such as pH fluctuations, mechanical loading, long-term water storage, or repeated thermal cycling. Therefore, further studies using a wider range of composite materials and aging protocols are needed to confirm and extend these findings.

Conclusion

Airborne-particle abrasion alone proved sufficient for achieving high bond strength when luting the SFRC CAD/CAM composite. Conversely, the addition of hydrofluoric acid after airborne-particle abrasion appears necessary for achieving optimal bonding of the self-adhesive resin cement to the conventional CAD/CAM composite.

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Authors' contributions
Study design, L.L. and S.G.; collection of data, S.G.; and U.MB. and D.M.; data analysis/interpretation, S.G., U.MB. and D.M.; writing-original draft preparation, U.MB. and S.G.; writing-review and editing, L.L. and P.V.

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

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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