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RESEARCH AND EDUCATION

The effect of mechanical and chemical surface pretreatment on the repair bond strength of resins used in additive or subtractive manufacturing of definitive prostheses

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ABSTRACT

Statement of problem. Although minimally invasive repair of existing resin-based restorations is clinically advantageous, the effects of different surface pretreatments on additively and subtractively manufactured resins remain insufficiently studied. This lack of evidence hinders the development of a standardized and reliable protocol for the repair of such materials.

Purpose. This in vitro study aimed to evaluate the impact of different mechanical and chemical surface pretreatments (airborne-particle abrasion, grinding, universal adhesive application, or no treatment) on the shear bond strength (SBS) of composite resin repairs on hydrothermally aged resin-based materials, used either additively or subtractively for definitive fixed dental prostheses.

Material and methods. A total of 240 resin disks (Ø10×2 mm) were fabricated using 3 additive manufacturing resins (C&B Permanent; Tera Harz TC-80DP; and Crowntec); and 1 subtractive manufacturing resin (Brillant Crios) (n=60 each). All specimens underwent hydrothermal aging through 5000 thermal cycles between 5 °C and 55 °C. Disks were randomly assigned into 3 mechanical pretreatment groups: airborne-particle abrasion with 50 μm Al_2O_3 particles, grinding with a diamond rotary instrument, or no treatment (control) (n=20 each). Each group was then randomly divided into 2 chemical surface pretreatment subgroups: application of a universal adhesive (Clearfil Universal Bond Quick) or no treatment (control) (n=10 each) and then composite resin (Clearfil Majesty ES-2 Classic) was bonded in the center of the surface-treated area. SBS was assessed using a universal testing machine at a crosshead speed of 1 mm/minute. Failure modes were analyzed under a microscope at ×12.5 magnification. Statistical analysis included a 3-way ANOVA and chi-squared test to evaluate the effects of material, mechanical pretreatment, and adhesive on SBS (α=.05).

Results. The application of an adhesive substantially increased the SBS (Mean difference (MD): 6.91 ±3.30 MPa; $P<.001$). When adhesive was used, no differences were observed between resin materials or mechanical surface pretreatments (airborne-particle abrasion or grinding) in either SBS or failure mode (chi-squared test). In contrast, in the absence of adhesive, significant differences were found between materials ($P<.001$) and mechanical pretreatment ($P=.001$) for both outcomes.

Conclusions. Repair bond strength depended on the application of an adhesive. When applied, the impact of resin material and mechanical pretreatment remained minimal. (J Prosthet Dent 2026;135:821.e1-e11)

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Clinical Implications

The use of a universal adhesive enhances the repair bond strength of both additively and subtractively manufactured resin-based restorations. With that, the choice of resin material and mechanical surface pretreatment becomes less critical which potentially simplifies clinical protocols. These results contribute to the development of a more standardized and predictable approach for intraoral repair of definitive printed restorations.

Resin-based materials for definitive fixed dental prostheses are gaining interest because of their compatibility with computer-aided design and computer-aided manufacturing (CAD-CAM) processes and their acceptable mechanical,[1,2] biological, esthetic, and adhesive properties, along with favorable cost-effectiveness and minimal material waste.[3] Traditionally, complications such as secondary caries, discoloration, abrasion, or fractures associated with conventional materials have required complete restoration replacement.[4] However, one of the characteristics of resin-based materials for definitive fixed dental prostheses, is that they enable direct repairs by removing only the affected tissue and the application of new composite resin material through adhesive techniques.[5] This minimally invasive approach preserves dental tissue, minimizes the risk of iatrogenic damage (pulp irritation),[6] and reduces both treatment time and cost,[7] ultimately achieving a clinically acceptable outcome.

The bond between the existing and new resin materials depends on micromechanical interlocking, created by surface irregularities, and chemical adhesion to filler particles and the organic matrix.[8] Consequently, current repair protocols are hybrid,[9] combining mechanical surface pretreatment to enhance surface roughness through predominantly airborne-particle abrasion with aluminum oxide (Al_2O_3) or diamond rotary instrument-abrasion (grinding) with, for example, diamond rotary instruments, with chemical pretreatment to improve chemical interaction through the application of adhesives.[9] However, the effects of these pretreatments on available additively manufactured (AM) and subtractively manufactured (SM) resins have not been studied to an extent that allows for the establishment of a standardized repair protocol. According to previous studies, different combinations of surface pretreatments may influence bond performance by altering surface free energy, wettability, roughness, topography, and hydrophilicity.[10–15] Shear bond strength testing and failure mode analysis have been commonly used in vitro methods to assess the performance of direct composite resin repairs.[16–22]

Therefore, the aim of this in vitro study was to evaluate the effect of surface conditioning, airborne-particle abrasion or grinding (mechanical surface pretreatment), and adhesive application (chemical pretreatment), on the repair shear bond strength (SBS) of hydrothermally aged resin-based materials intended for AM and SM definitive fixed dental prostheses. The null hypothesis was that the type of resin-based material, mechanical pretreatment, or application of adhesive would not affect the repair bond strength.

MATERIAL AND METHODS

A Ø10×2 mm disk in standard tessellation language (STL) format was designed in a software program (Meshmixer v3.5.474; Autodesk Inc), fabricated using AM or SM (N=240), and hydrothermally aged. The disk surfaces were treated by airborne-particle abrasion or grinding, with or without subsequent application of an adhesive. Composite resin (Clearfil Majesty ES-2 Classic; Kuraray) was then bonded to the treated surfaces.

The experimental design is presented in Figure 1. Groups were established according to the material used: Group AM-C&B: AM with urethane acrylate-based resin (C &B Permanent; ODS Co.; Group AM-TH: AM with urethane acrylate-based resin (Tera Harz TC-80DP; Graphy): Group AM-C: AM with glass-filled composite resin (Crowntec; Saremco Dental AG); Group SM-BC: SM with reinforced composite resin (Brillant Crios; Coltène), the mechanical surface pretreatment: Subgroup APA: Airborne-particle abrasion with 50-μm Al_2O_3; Subgroup G: Grinding with a diamond rotary instrument; Subgroup NT (control): No mechanical surface pretreatment, and the adhesive application: Subgroup A: Application of a universal adhesive (Clearfil Universal Bond Quick; Kuraray Noritake); Subgroup NT (control): No adhesive application.

The sample size for this study was determined through a priori power analysis (α=.05, 1-β=95%, and an effect size of f=.493), which deemed 9 specimens per subgroup adequate (STATA, v 17.0; StataCorp LP); however, to increase statistical power, 10 specimens were fabricated. Detailed fabrication for AM and SM specimens is presented in Table 1.[23]

After fabrication, a stainless-steel mold was used to embed all AM and SM specimens in autopolymerizing acrylic resin (Paladur; Kulzer GmbH). The specimens were centered in the mold, and the free surface of each AM and SM specimen was placed in contact with the table surface. This positioning ensured that the free surface of each specimen was flush with the surface of the acrylic resin.[24] To mimic the time in function in the oral cavity before experiencing a fracture which would necessitate a repair, the embedded specimens were hydrothermally aged in distilled water (5 °C to 55 °C,

Figure 1. Study design. A, universal adhesive; AM-C, Crowntec; AM-C&B, C&B Permanent; AM-TH, Tera Harz TC-80DP; APA, airborne-particle abrasion; G, grinding with diamond rotary instrument; NT, no pretreatment (control); SM-BC, Brillant.

10 seconds transfer time, 30 seconds dwell time, 5000 thermal cycles, SD Mechatronik Thermocycler; SD Mechatronik GmbH). Following hydrothermal aging, the bonding surface of each specimen was wet-ground for 5 seconds using silicon carbide abrasive papers (Struers Labo-Pol 21 #500; Struers). The specimens were then steam cleaned (Minivapor 93; Effegi Brega) for 5 seconds and air-dried using oil-free air.

The AM and SM specimens were then randomly divided (Excel; Microsoft Corp) into 3 subgroups which underwent 1 of the following mechanical surface pretreatments: no surface treatment (control), airborne-particle abrasion with 50 µm Al_2O_3 (Cobra; Renfert) at 0.2 MPa at 10 mm for 10 seconds, and grinding with a coarse grit Ø2-mm diamond fissure rotary instrument (837 L; Jota AG) at 40 000 rpm.[10] The diamond rotary instrument was lightly moved across the surface 10 times (5 times in 2 different directions) without application of any additional force. A new diamond rotary instrument was used for every 5 specimens to ensure consistency. The 2 directions were standardized—1 parallel and 1 perpendicular to the long axis of the specimen—to provide uniform surface roughening. All procedures were performed by a single operator (G.S.) to minimize variability. Airborne-particle abraded, and ground specimens were steam cleaned (Dampfstrahler Wasi-Steam Compact 174987 & 174994; Wassermann) for 10 seconds. One additional specimen per group was fabricated for evaluation of the surface characteristics by using scanning electron microscopy (SEM) (LEO 440; Zeiss). The surface topography of specimens was evaluated under ×100, ×1000, and ×2000 magnification at 20 kV.[11]

Having been subjected to mechanical surface pretreatment, half of the specimens in each group received no further surface pretreatment (control), while the other half underwent an adhesive application surface pretreatment in the form of a universal adhesive (Clearfil Universal Bond Quick; Kuraray Noritake) used according to the manufacturer's instructions as follows: application with a microbrush, gentle air-drying for 5 seconds, and light polymerization for 10 seconds with a light-emitting diode (LED) polymerization unit (Bluephase; Ivoclar AG) in high power mode (light power density: 950 mW/cm^2). A radiometer (Bluephase Meter; Ivoclar AG) was used to verify the light power density during the study. Subsequently, a cylinder of composite resin (Clearfil Majesty ES-2 Classic; Kuraray) was bonded in the center of the surface-treated area using a split Teflon mold (inner diameter: 1.5 mm, adhesive area approximately 1.8 mm^2, height: 2 mm) mounted in a holding device. The small diameter of the cylinder, and hence the small hole in the Teflon mold precluded the use of adhesive tape to demarcate the bonding area. The composite resin cylinder was light polymerized for 20 seconds (Bluephase; Ivoclar AG) and the specimen was then stored in a light-proof box. After 5 minutes, the Teflon mold was removed, and all specimens were returned to light-proof boxes and kept at 37 °C and 100% humidity for 24 hours. All repair procedures were performed by one operator (G.S.). The primary outcome measure was the SBS. After 24 hours, SBS was measured in a universal testing machine (ZwickZ1.0TN; Zwick). The load was applied at a right angle to the composite resin cylinder at a crosshead speed of 1mm/minute by using a wire loop positioned at the base of the composite resin

Table 1. Detailed fabrication for additively and subtractively manufactured specimens

Process Step	Specimen Type	Equipment and Materials	Parameters and Conditions	Duration and Details
Fabrication				
3D Printing	AM-C&B, AM-TH, AM-C	DLP 3D Printer (MAX UV; Asiga) Nesting Software Program (Composer v1.3)	• Horizontal printing (0°) • Layer thickness: 50 µm • Auto-generated supports • Design duplicated for standardization	-
Milling	SM-BC	5-axis milling unit (PrograMill PM7; Ivoclar AG)	No post-processing required	-
Post-processing				
Cleaning	AM-C&B, AM-TH	Ultrasonic cleaner + Ethanol (96%) (Ethanol Absolut; Dr. Grogg Chemie AG) Ethanol-soaked cloth (96%)	• Ultrasonic cleaning in ethanol • Additional ethanol-soaked (96% ethanol) cloth cleaning	45 s ultrasonic cleaning+ cloth cleaning until all resin residues removed
	AM-C	Ethanol-soaked cloth (96%)	• Ethanol-soaked (96% ethanol) cloth cleaning	Until all resin residues removed
Drying	All AM specimens	Air drying	• Specimens were air dried and then left at ambient temperature and humidity for 30 min to ensure no alcohol residues left	30 min
Polymerization	All AM specimens	Xenon Polymerization Device (Otoflash G171; NK Optik) Nitrogen gas	• 4000 flash exposures under nitrogen atmosphere	2000 per surface
Support Removal	All specimens	Cut-off Wheel (Keystone Cut-off Wheels; Keystone Industries)	• Mechanical removal of supports under magnification loupes (EyeMag Pro ×3.5; CarlZeiss)	Manual process

cylinder in contact with the AM or SM resin surface. The SBS testing was performed by the same operator (G.S.), who also performed the repair procedures. The strength required for fracture (Fmax(N)) was determined and the SBS (MPa) was calculated as (Fmax (N)/bonding area (mm^2)).

After bond strength testing, the failure mode of all specimens was assessed under a light microscope (M420; Leica) at a magnification of ×12.5 and classified into the following categories: Type 1: Adhesive failure at the interface between the AM or SM resin and the repair composite resin; Type 2: Cohesive failure in the AM or SM resin; Type 3: Mixed failure (simultaneous presence of the Type 1 and 2 failure modes).

The Shapiro-Wilk test confirmed that the groups, into which the sample was divided (AM or SM resins, mechanical surface pretreatment, and adhesive application), met the assumption of normality. A 3-way analysis of variance (ANOVA) model was used to evaluate the effect of material, mechanical surface pretreatment, and adhesive application on SBS and to analyze the effect of material and mechanical surface pretreatment, along with their interaction, for each adhesive application condition (with and without adhesive) individually. The Bonferroni post hoc test was applied comparisons. Failure modes depending on the material and the mechanical surface pretreatment within each condition was evaluated by using the chi-squared test. A statistical analysis software program was used to perform all analyses (IBM SPSS Statistics, v25.0; IBM Corp) (α=.05).

RESULTS

The mean ±standard deviation (SD) values of SBS (MPa) and the failure modes for each material and surface treatment are presented in Table 2. SBS varied between 3.27 and 14.16 MPa, and the 3-way ANOVA revealed significant differences among the groups (P<.001) (Table 3). All 3 factors: material, mechanical surface pretreatment, and chemical pretreatment, had a significant effect on SBS. Interactions were found between mechanical pretreatment and chemical pretreatment and between material and chemical pretreatment. The very high F-value (F=652.7) found for the factor chemical pretreatment, and the overall mean difference ±SD between the application and non-application of an adhesive of 6.91 ±3.30 MPa (Fig. 2) suggested that adhesive application had a considerably stronger influence than the other factors, supporting the need for separate analyses (with and without adhesive) of the SBS results. The Bonferroni test for post hoc comparisons was used to test for the effect of material (Table 4), mechanical pretreatment (Table 5), and use of adhesive (Table 6).

The effect of material (Table 4), and when the adhesive had not been applied AM-C resulted in

Table 2. Mean ±standard deviation (SD) values of shear bond strength (MPa) and proportion of failure modes for each material and surface pretreatment

Material	Mechanical Pretreatment	Chemical Pretreatment	Sample (n)	Shear Bond Strength Mean (MPa)		Adhesive Failure		Cohesive in AM and SM Resins		Mixed Failure	
				Mean	SD	N	%	N	%	N	%
AM-C	Control	Adhesive	10	11.5	2.2	0	0.0	10	100.0%	0	0.0
		No adhesive	10	5.3	1.45	8	80	2	20%	0	0.0
	Airborne-particle abrasion	Adhesive	10	11.92	2.35	0	0.0	10	100.0%	0	0.0
		No adhesive	10	7.87	2.34	8	80	2	20.0%	0	0.0
	Grinding	Adhesive	10	12.04	2.3	0	0.0	10	100.0%	0	0.0
		No adhesive	10	7.12	1.28	8	80	0	0.0%	2	20.0
AM-C&B	Control	Adhesive	10	14.16	2.93	0	0.0	10	100.0%	0	0.0
		No adhesive	10	3.4	0.8	10	100.0	0	0.0%	0	0.0
	Airborne-particle abrasion	Adhesive	10	13.15	3.73	0	0.0	10	100.0%	0	0.0
		No adhesive	10	5.68	1.36	10	100.0	0	0.0%	0	0.0
	Grinding	Adhesive	10	11.41	2.43	0	0.0	10	100.0%	0	0.0
		No adhesive	10	4.09	0.81	10	100.0	0	0.0%	0	0.0
AM-TH	Control	Adhesive	10	11.19	2.74	0	0.0	10	100.0%	0	0.0
		No adhesive	10	3.27	0.92	10	100.0	0	0.0%	0	0.0
	Airborne-particle abrasion	Adhesive	10	11.97	3.09	0	0.0	10	100.0%	0	0.0
		No adhesive	10	5.07	0.84	10	100.0	0	0.0%	0	0.0
	Grinding	Adhesive	10	11.39	2.44	0	0.0	10	100.0%	0	0.0
		No adhesive	10	3.56	0.79	10	100.0	0	0.0%	0	0.0
SM-BC	Control	Adhesive	10	12.61	3.32	1	10.0	8	80.0%	1	10.0
		No adhesive	10	4.79	0.83	10	100.0	0	0.0%	0	0.0
	Airborne-particle abrasion	Adhesive	10	13.15	2.35	0	0.0	10	100.0%	0	0.0
		No adhesive	10	6.89	1.09	10	100.0	0	0.0%	0	0.0
	Grinding	Adhesive	10	11.19	2.21	0	0.0	9	90.0%	1	10.0
		No adhesive	10	5.72	1.42	10	100.0	0	0.0%	0	0.0

significantly higher SBS than did AM-TH when the surface had been pretreated by grinding or airborne-particle abrasion and higher than AM-C&B for the grinding pretreatment ($P<.05$) (Fig. 3A). When the adhesive had been applied, AM-C&B resulted in higher SBS than did AM-TH and AM-C when the surfaces had not been pretreated (control) ($P<.05$) (Fig. 3A).

For the effect of mechanical pretreatment (Table 5), and when adhesive had not been applied, airborne-particle abrasion resulted in significantly higher SBS than did the control for the AM-C&B and for AM-C materials (Fig. 3B). No other significant differences were found among the mechanical pretreatments for the 4 materials. When the adhesive had been applied, only 1 statistically significant result was found; for the AM-C&B material, grinding resulted in lower SBS than did the control ($P<.05$) (Fig. 3B).

As regards the effect of adhesive application (Table 6), a significant effect was observed for all materials irrespective of the mechanical pretreatment ($P<.001$). Thus, comparisons between materials are also presented in Figure 2A, while comparisons between mechanical surface pretreatment are shown in Figure 2B.

When the adhesive had not been used, adhesive failure was predominant (86.7 to 100%), whereas the use of adhesive led to predominantly cohesive failure (90 to 100%). When adhesive was not used, the chi-squared test found significant differences in failure modes between the materials ($P<.001$) and mechanical surface pretreatments ($P=.021$). Notably, AM-C&B, AM-TH, and SM-BC exhibited only adhesive failure (Fig. 4). In the AM-C group, adhesive failure accounted for 86.7% of the specimens, while 6.7% exhibited cohesive failure within the resin, and another 6.7% showed mixed failure (Fig. 4). When adhesive had been applied, the chi-squared test found no significant differences in failure mode between the materials ($P=.161$) or mechanical surface pretreatments ($P=.549$) (Fig. 4).

The SEM images at magnifications of ×100, ×1000, and ×2000 of the materials under different mechanical surface pretreatment conditions are presented in Figure 5. AM-C&B and AM-TH presented rougher surfaces than AM-C and SM-BC irrespective of the mechanical surface pretreatment. For mechanical surface pretreatments, grinding, and airborne-particle abrasion resulted in rougher surfaces compared with the control, with airborne-particle abraded surfaces showing a slightly deeper relief than the ground surfaces.

DISCUSSION

The findings of this in vitro study led to the rejection of the null hypotheses that the type of resin-based

Table 3. Three-way ANOVA results of shear bond strength according to material, mechanical surface pretreatment and chemical surface pretreatment: F value, degrees of freedom (df) and *P*-value

	F	df	*P*
Material	6.41	3	<.001
Mechanical pretreatment	8.26	2	<.001
Chemical pretreatment	652.70	1	<.001
Material × mechanical pretreatment	1.04	6	.396
Mechanical pretreatment × chemical pretreatment	5.52	2	.005
Material × chemical pretreatment	7.47	3	<.001
Material × mechanical pretreatment × chemical pretreatment	0.70	6	.649
Error		216	

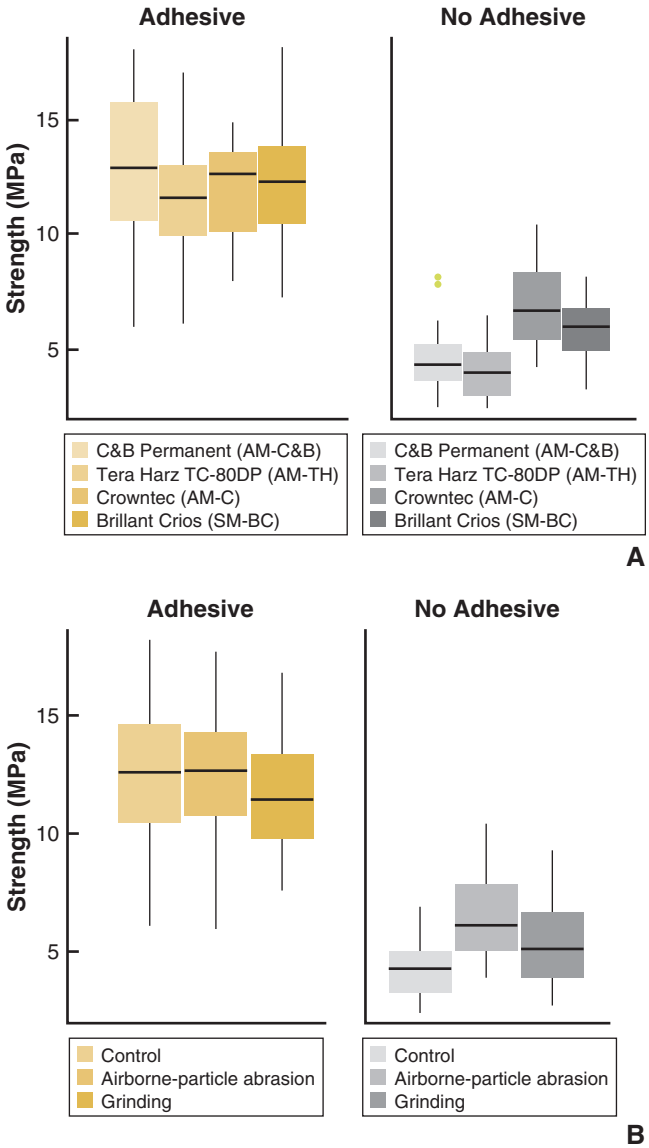

Figure 2. Box plots of overall shear bond strength of materials and surface treatments studied. A, By material type. B, By type of mechanical surface pretreatment.

material, mechanical pretreatment, or application of adhesive would not affect the repair bond strength, as evaluated materials, mechanical surface pretreatments, and adhesive application exhibited significant differences in repair SBS. The primary distinction in findings was observed between the application and non-application of an adhesive.

When the adhesive was applied, the repair SBS was significantly higher than without the adhesive, and differences between AM or SM resins and mechanical surface pretreatments were not significant. The SM-BC resin did not show any differences compared to the AM resins. Also, the failure mode analysis demonstrated predominantly cohesive failures in the AM and SM resins implying that the true repair bond strengths surpassed the inherent strength of the AM or SM resins. Additionally, the overshadowing and positive effect of the adhesive was consistent with previous research,[9,12] which concluded that bond strength improved with the use of adhesives. The polymers present in the adhesive infiltrate microcracks within the polymer matrix of the AM and SM resins, creating micro-entanglements.[8] Furthermore, adhesives enhance the wettability of exposed filler particles and help prevent air void formation.[13]

When the adhesive was not applied, notable differences in repair SBS were observed between AM or SM resins and mechanical surface pretreatments, with failure mode analysis indicating predominantly adhesive failures. These findings suggested that the application of adhesives is essential and more relevant than mechanical surface pretreatment for achieving stable and strong bond strength in composite resin repairs.

Chemical bonding may occur through copolymerization between unreacted double bonds in the AM or SM resin surface and the repair composite resin.[8] The composite resin-based materials (AM-C and SM-BC) achieved the highest SBS values, possibly because of their similar chemical properties. They may also have had a lower degree of conversion of C=C bonds, providing more unconverted bonds at the interface. This remains hypothetical, as the degree of conversion was not measured, and no additional post-polymerization was performed beyond xenon light polymerization. Unreacted C=C bonds have been reported to persist in polymerized composite resins, typically 25–55% of methacrylate groups, and are crucial for chemical bonding between aged substrates and repair composite resins via copolymerization.[25–28] Although increased surface roughness has been reported to typically improve adhesion through greater contact area and micromechanical interlocking, the qualitatively rougher surfaces in AM C&B and AM TH under SEM did not yield higher SBS than AM-C and SM-BC. This finding suggests that factors such as chemical compatibility and adhesive treatment may be more decisive than surface morphology in bonding performance.

Among mechanical surface pretreatments, airborne-particle abrasion was more effective than grinding in enhancing repair SBS across all AM and SM resins in

Table 4. Statistically significant differences between materials for each mechanical surface pretreatment depending on use of adhesive (chemical surface pretreatment)

Adhesive	Mechanical Pretreatment	Material			*P*
NO	Control	AM-C&B	versus	AM-TH	>.999
		AM-C&B	versus	AM-C	.266
		AM-C&B	versus	SM-BC	.850
		AM-TH	versus	AM-C	.186
		AM-TH	versus	SM-BC	.636
		AM-C	versus	SM-BC	>.999
	Airborne-particle abrasion	AM-C&B	versus	AM-TH	>.999
		AM-C&B	versus	AM-C	.122
		AM-C&B	versus	SM-BC	>.999
		AM-TH	versus	AM-C	.019*
		AM-TH	versus	SM-BC	.317
		AM-C	versus	SM-BC	>.999
	Grinding	AM-C&B	versus	AM-TH	>.999
		AM-C&B	versus	AM-C	.009*
		AM-C&B	versus	SM-BC	.494
		AM-TH	versus	AM-C	.001**
		AM-TH	versus	SM-BC	.131
		AM-C	versus	SM-BC	.832
YES	Control	AM-C&B	versus	AM-TH	.010*
		AM-C&B	versus	AM-C	.030*
		AM-C&B	versus	SM-BC	.594
		AM-TH	versus	AM-C	>.999
		AM-TH	versus	SM-BC	.779
		AM-C	versus	SM-BC	>.999
	Airborne-particle abrasion	AM-C&B	versus	AM-TH	>.999
		AM-C&B	versus	AM-C	>.999
		AM-C&B	versus	SM-BC	>.999
		AM-TH	versus	AM-C	>.999
		AM-TH	versus	SM-BC	>.999
		AM-C	versus	SM-BC	>.999
	Grinding	AM-C&B	versus	AM-TH	>.999
		AM-C&B	versus	AM-C	>.999
		AM-C&B	versus	SM-BC	>.999
		AM-TH	versus	AM-C	>.999
		AM-TH	versus	SM-BC	>.999
		AM-C	versus	SM-BC	>.999

***$P<.001$;
* $P<.05$
** $P=.001$;

Table 5. Statistically significant differences between mechanical surface pretreatments for each material depending on use of adhesive (chemical surface pretreatment)

Adhesive	Material	Mechanical Surface Pretreatment			*P*
NO	AM-C&B	Control	versus	Airborne-particle abrasion	.048*
		Control	versus	Grinding	>.999
		Airborne-particle abrasion	versus	Grinding	.272
	AM-TH	Control	versus	Airborne-particle abrasion	.167
		Control	versus	Grinding	>.999
		Airborne-particle abrasion	versus	Grinding	.326
	AM-C	Control	versus	Airborne-particle abrasion	.020*
		Control	versus	Grinding	.162
		Airborne-particle abrasion	versus	Grinding	>.999
	SM-BC	Control	versus	Airborne-particle abrasion	.077
		Control	versus	Grinding	.955
		Airborne-particle abrasion	versus	Grinding	.642
YES	AM-C&B	Control	versus	Airborne-particle abrasion	.838
		Control	versus	Grinding	.011*
		Airborne-particle abrasion	versus	Grinding	.197
	AM-TH	Control	versus	Airborne-particle abrasion	>.999
		Control	versus	Grinding	>.999
		Airborne-particle abrasion	versus	Grinding	>.999
	AM-C	Control	versus	Airborne-particle abrasion	>.999
		Control	versus	Grinding	>.999
		Airborne-particle abrasion	versus	Grinding	>.999
	SM-BC	Control	versus	Airborne-particle abrasion	>.999
		Control	versus	Grinding	.396
		Airborne-particle abrasion	versus	Grinding	.113

***$P<.001$; **$P=.001$;
* $P<.05$

Table 6. Statistically significant differences between use of adhesive (chemical surface pretreatment) for each mechanical surface pretreatment depending on material

Material	Mechanical Pretreatment	Adhesive			*P*
AM-C&B	Control	No	vs	Yes	<.001***
	Airborne-particle abrasion	No	vs	Yes	<.001***
	Grinding	No	vs	Yes	<.001***
AM-TH	Control	No	vs	Yes	<.001***
	Airborne-particle abrasion	No	vs	Yes	<.001***
	Grinding	No	vs	Yes	<.001***
AM-C	Control	No	vs	Yes	<.001***
	Airborne-particle abrasion	No	vs	Yes	<.001***
	Grinding	No	vs	Yes	<.001***
SM-BC	Control	No	vs	Yes	<.001***
	Airborne-particle abrasion	No	vs	Yes	<.001***
	Grinding	No	vs	Yes	<.001***

*** *P*<.001

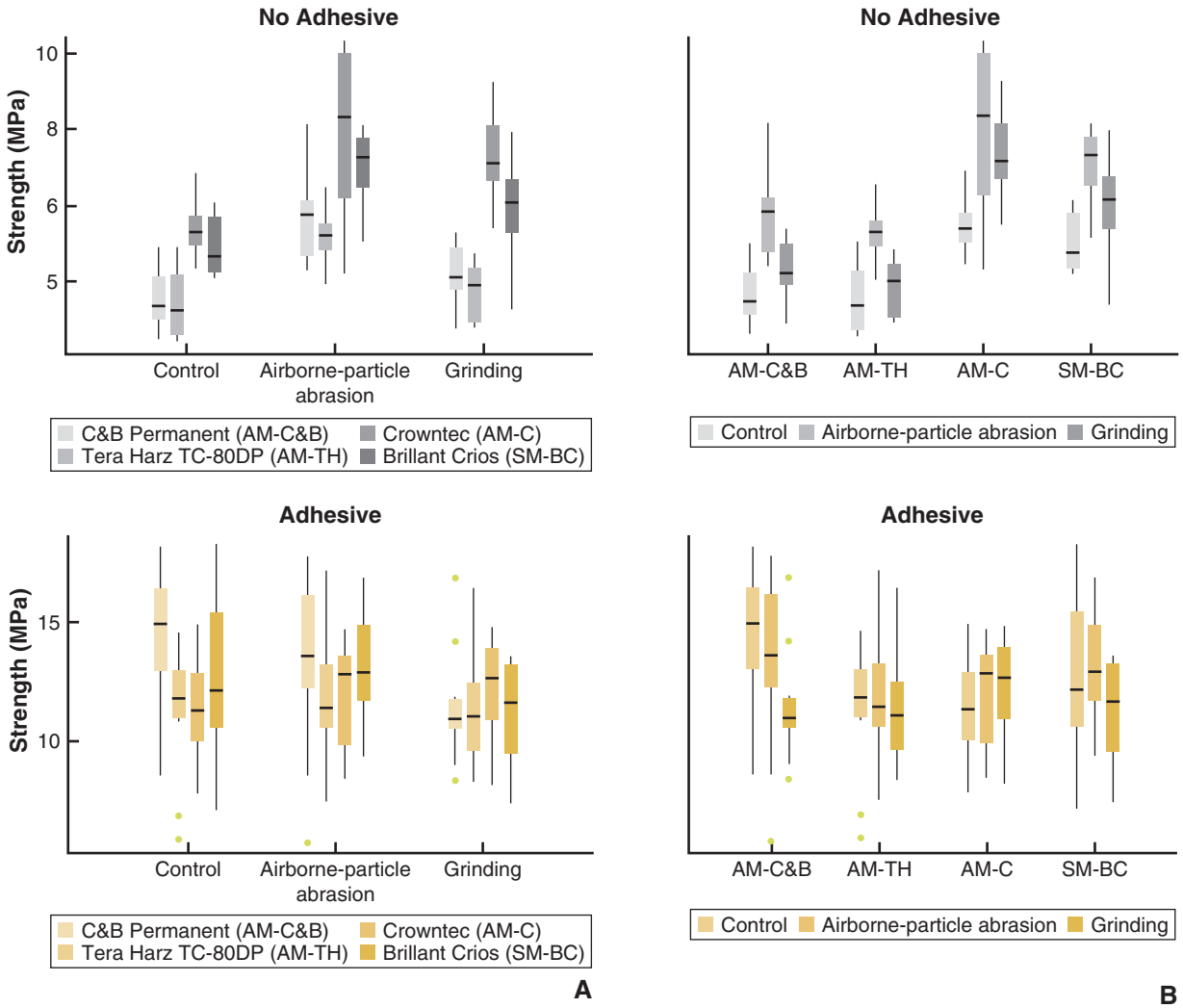

Figure 3. Box plots of shear bond strength (MPa) for each material and surface pretreatment studied. A, By material type. B, By type of mechanical surface pretreatment.

this study. The superiority of airborne-particle abrasion may stem from its ability to create slightly deeper surface reliefs than grinding, which increased surface free energy and improved wettability, facilitating the application of adhesives. However, the surface roughness achieved through mechanical surface pretreatment can vary widely across studies because of specific protocol parameters, such as particle size, application

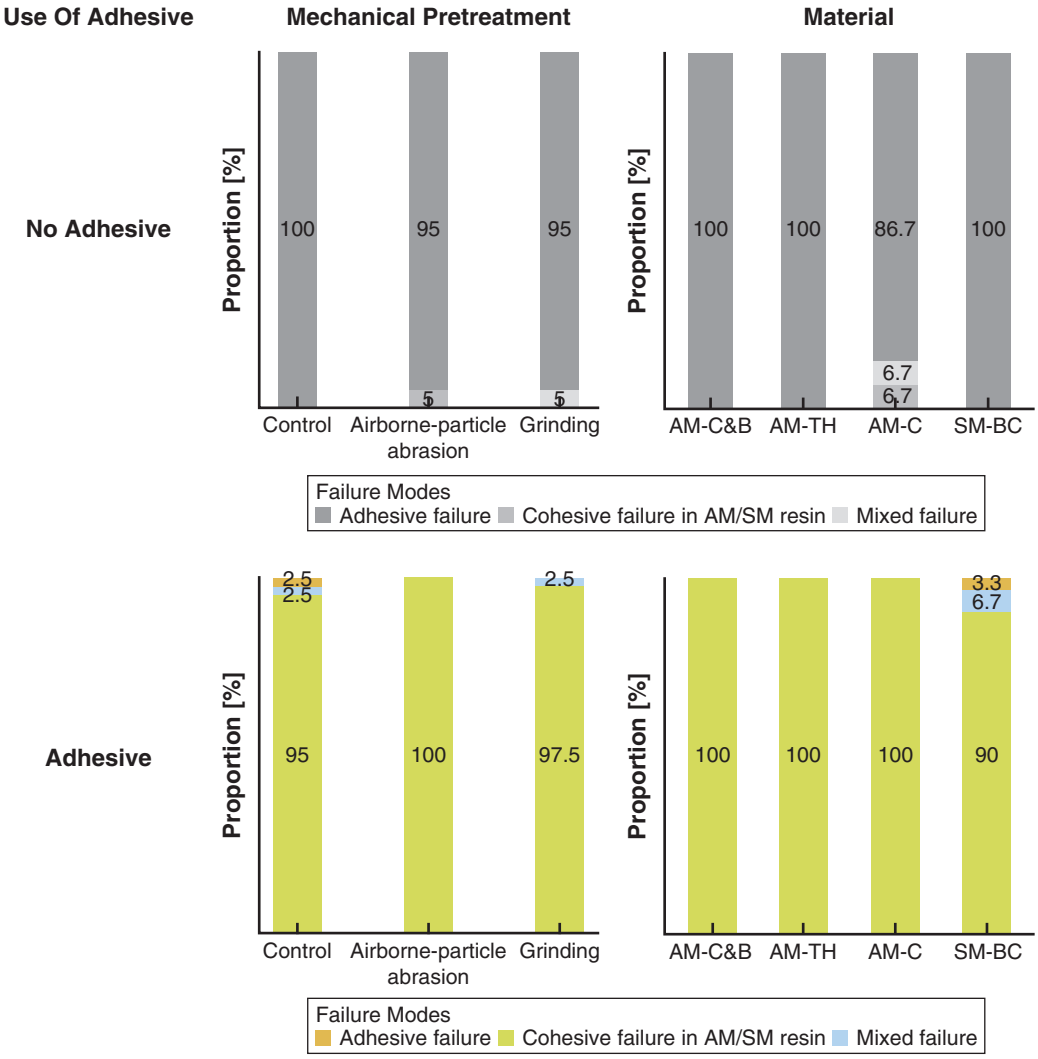

Figure 4. Stacked Bar Chart displaying proportions of each failure mode based on material, mechanical surface pretreatment, and application of adhesive (chemical surface pretreatment).

distance, grit size, pressure, and duration,[9] as well as the properties of each material. These variables challenge the establishment of general conclusions in this regard.

When the findings in previous studies were considered, Stawarczyk et al[12] reported, consistent with the present study observations, that adhesive application had a significant effect, and that grinding was less effective than airborne-particle abrasion. Similarly, Degirmenci et al[14] reported that when an adhesive was applied, the type of mechanical surface pretreatment, whether grinding or airborne-particle abrasion, was not a determining factor, aligning with the present findings. Although the authors did not evaluate the effect of an adhesive, Sarahneh and Günal-Abduljalil[29] reported that airborne-particle abrasion outperformed their control groups without silane, which was consistent with the present results showing the advantage of airborne-particle abrasion over inactive controls. Only Silva et al[15] reported that grinding improved SBS when using an adhesive with Vita Enamic, a finding that differs from the present study but may be explained by differences in the particle size and pressure of airborne-particle abrasion, or by the restorative material and adhesive system. As reported by Alotaibi et al,[16] when comparing 2 resins, each mechanical surface pretreatment can affect each material differently according to its properties. This highlights the need for further research to assess substrate roughness in relation to subsequent SBS, in order to better understand how mechanical surface pretreatments interact.

Shear bond strength (SBS) testing and failure mode analysis have been widely used for evaluating direct composite resin repairs in vitro.[10,15,17–19] Microtensile bond strength (μTBS) testing has been used instead, depending on sample size, test area, and force type.[12,20–22] μTBS typically yields higher values than SBS. Despite these efforts, a consensus on acceptable repair bond strength is lacking, except the International Organization for Standardization

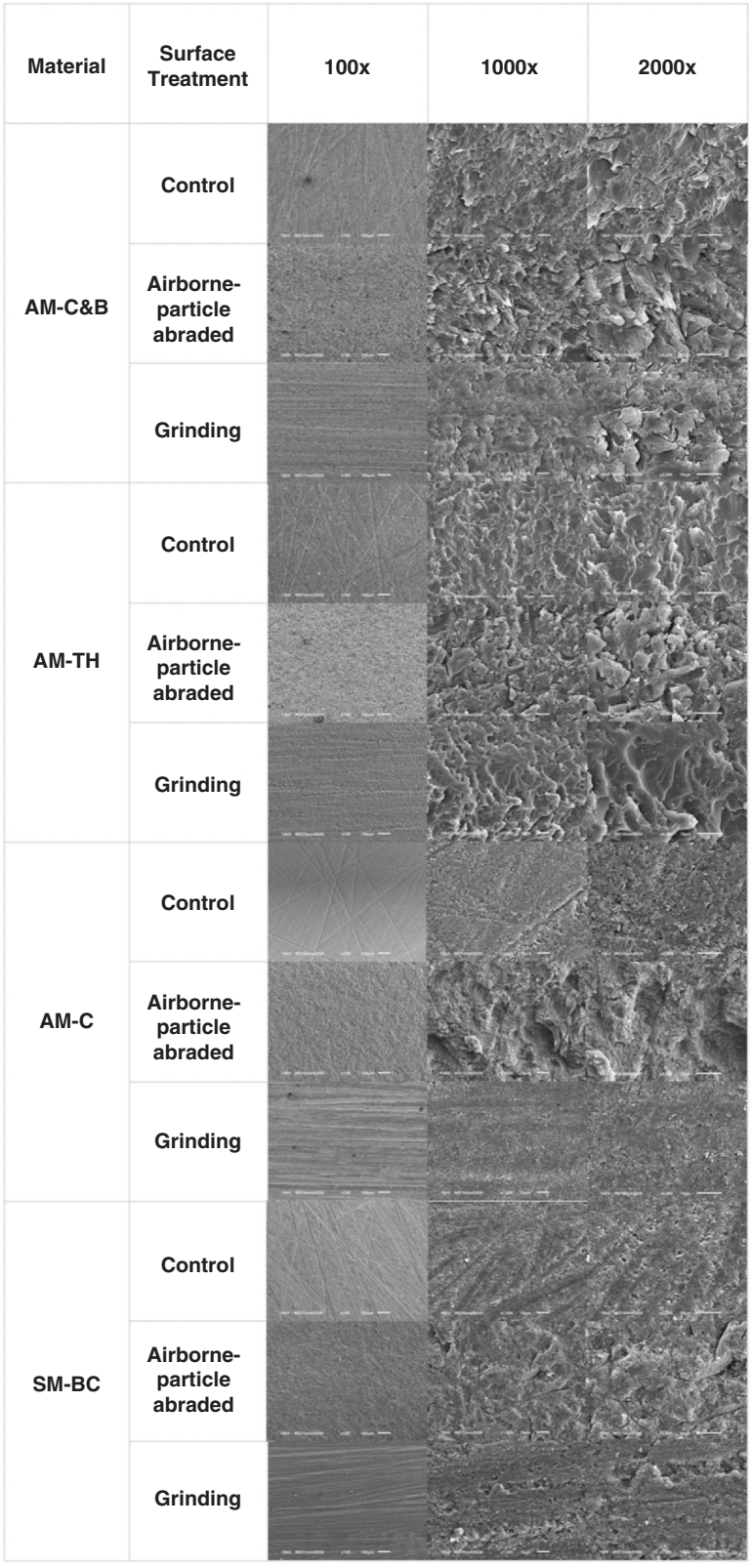

Figure 5. Scanning electron microscopy (SEM) at magnifications of ×100, ×1000 and ×2000 of materials under different mechanical surface pretreatment conditions.

(ISO) 10477–2020 standard,[30] which set a minimum of 5 MPa. Thus, values approaching cohesive failure strength may serve as a clinical reference. This in vitro study offers preliminary findings that require validation through randomized clinical trials. Limitations include the absence of quantitative surface roughness analysis; future studies should include profilometry to correlate surface topography with bond strength.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The repair bond strength of resins used in additive and subtractive manufacturing fundamentally depended on whether an adhesive was applied on the surface to be repaired.
2. When the adhesive was applied, the resin material and surface pretreatment did not significantly impact the repair bond strength and failure mode.
3. When the adhesive was not applied, both resin material and surface pretreatment affected the repair bond strength and the type of failure.

REFERENCES

1. Zimmermann M, Ender A, Attin T, Mehl A. Fracture load of three-unit full-contour fixed dental prostheses fabricated with subtractive and additive CAD-CAM technology. *Clin Oral Investig*. 2020;24:1035–1042.
2. Zimmermann M, Ender A, Egli G, Özcan M, Mehl A. Fracture load of CAD-CAM-fabricated and 3D-printed composite crowns as a function of material thickness. *Clin Oral Investig*. 2019;23:2777–2784.
3. Daher R, Ardu S, di Bella E, Krejci I, Duc O. Efficiency of 3D printed composite resin restorations compared with subtractive materials: Evaluation of fatigue behavior, cost, and time of production. *J Prosthet Dent*. 2024;131:943–950.
4. Sailer I, Balmer M, Hüsler J, Hämmerle CHF, Känel S, Thoma DS. 10-year randomized trial (RCT) of zirconia-ceramic and metal-ceramic fixed dental prostheses. *J Dent*. 2018;76:32–39.
5. Çağlayan E, Sasany R, Bolat BN, et al. Optical properties of repaired additively manufactured resin composites and zirconia and subtractively manufactured ceramics: A comparative study of composite resins. *BMC Oral Health*. 2025;25:144.
6. Blum IR, Jagger DC, Wilson NH. Defective dental restorations: To repair or not to repair? Part 2: All-ceramics and porcelain fused to metal systems. *Dent Update*. 2011;38:150–152. 154-156,158.
7. Hickel R, Brüshaver K, Ilie N. Repair of restorations – criteria for decision making and clinical recommendations. *Dent Mater*. 2013;29:28–50.
8. Brosh T, Pilo R, Bichacho N, Blutstein R. Effect of combinations of surface treatments and bonding agents on the bond strength of repaired composites. *J Prosthet Dent*. 1997;77:122–126.
9. Neto HNM, Leite JVC, de Medeiros JM, da, et al. Scoping review: Effect of surface treatments on bond strength of resin composite repair. *J Dent*. 2024;140:104737.
10. Doğan İ, Karaman E. How the repair bonding strength of hybrid ceramic CAD-CAM blocks is influenced by the use of surface treatments and universal adhesives. *Dent Mater J*. 2024;43:312–319.
11. Çakmak G, Asadolahi NW, Schimmel M, et al. Effect of coffee thermal cycling on the surface properties and stainability of additively manufactured denture base resins in different layer thicknesses. *J Prosthodont*. 2025;34:157–166.
12. Stawarczyk B, Krawczuk A, Ilie N. Tensile bond strength of resin composite repair in vitro using different surface preparation conditionings to an aged CAD-CAM resin nanoceramic. *Clin Oral Investig*. 2015;19:299–308.
13. Crumpler DC, Bayne SC, Sockwell S, Brunson D, Roberson TM. Bonding to resurfaced posterior composites. *Dent Mater*. 1989;5:417–424.
14. Degirmenci A, Unalan Degirmenci B. Effects of Er,Cr:YSGG Laser surface treatments and composites with different viscosities on the repair bond strength of CAD-CAM resin nanoceramic. *Polymers ((Basel))*. 2024;16:2212.
15. Silva P, Martinelli-Lobo CM, Bottino MA, Melo RM, Valandro LF. Bond strength between a polymer-infiltrated ceramic network and a composite for repair: effect of several ceramic surface treatments. *Braz Oral Res*. 2018;32:e28.
16. Alotaibi AA, Taher NM. Effect of surface treatment on the repair bond strength of OMNICHROMA and Charisma Diamond ONE resin composites bonded to variable substrates. *Heliyon*. 2023;9:e17786.
17. Moura DMD, Dal Piva AMO, Januário A, et al. Repair bond strength of a CAD-CAM nanoceramic resin and direct composite resin: effect of aging and surface conditioning methods. *J Adhes Dent*. 2020;22:275–283.
18. Arkoy S, Ulusoy M. Effect of different surface treatments on repair bond strength of CAD-CAM resin-matrix ceramics. *Materials ((Basel))*. 2022;15:6314.
19. Prabriputaloong S, Krajangta N, Klaisiri A. The effect of different chemical surface treatments on the bond strength of resin-matrix ceramic repaired with resin composite. *Eur J Dent*. 2025;19:165–172.
20. Bahadır HS, Bayraktar Y. Evaluation of the repair capacities and color stabilities of a resin nanoceramic and hybrid CAD-CAM blocks. *J Adv Prosthodont*. 2020;12:140–149.
21. Bello YD, Di Domenico MB, Magro LD, Lise MW, Corazza PH. Bond strength between composite repair and polymer-infiltrated ceramic-network material: Effect of different surface treatments. *J Esthet Restor Dent*. 2019;31:275–279.
22. Elsaka SE. Repair bond strength of resin composite to a novel CAD-CAM hybrid ceramic using different repair systems. *Dent Mater J*. 2015;34:161–167.
23. Çakmak G, Wiegner S, Sabatini GP, et al. Influence of cleaning solutions and hydrothermal aging on the flexural strength and microhardness of resins for additively manufactured definitive fixed restorations. *J Prosthet Dent* 2025.
24. Donmez MB, Çakmak G, Yılmaz D, et al. Bond strength of additively manufactured composite resins to dentin and titanium when bonded with dual-polymerizing resin cements. *J Prosthet Dent*. 2024;132:1067.e1–1067.e8.
25. Wendler M, Belli R, Panzer R, Skibbe D, Petschelt A, Lohbauer U. Repair bond strength of aged resin composite after different surface and bonding treatments. *Materials (Basel)*. 2016;9:547.
26. 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 (Basel)*. 2020;12:882.
27. Cramer NB, Stansbury JW, Bowman CN. Recent advances and developments in composite dental restorative materials. *J Dent Res*. 2011;90:402–416.
28. Almutairi MA, Salama FS, Alzeghaibi LY, Albalawi SW, Alhawsawi BZ. Surface treatments on repair bond strength of aged resin composites. *J Int Soc Prev Community Dent*. 2022;12:449–455.
29. Sarahneh O, Günal-Abduljalil B. The effect of silane and universal adhesives on the micro-shear bond strength of current resin-matrix ceramics. *J Adv Prosthodont*. 2021;13:292–303.
30. International Organization for Standardization. Dentistry: Polymer-based crown and bridge materials. ISO 10477:2020. 3rd ed.,. Geneva: ISO; 2020.

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