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Evaluation of the Effect of Different Surface Treatments on the Bond Strength of Zirconia to Resin Cement

Abdulrahman Omar Alahmadi

Dentist, Islamic University of Madinah, Madinah, Saudi Arabia, 17RD0028922

ABSTRACT: Background Zirconia, which is resistant to both chemical and acid attack, requires a surface modification to reliably bond with resin cement in the luting process. Various protocols (air-abrasion, silica-coating, etching, lasers, plasma, 10-MDP primer, and combinations thereof) have been suggested to improve adhesion of zirconia to resin cements, but no consensus has been reached based on hundreds of small in-vitro studies.

Objective To analyze the evidence published between 2020 and 2025 in order to evaluate the effect of various surface treatments on the adhesion strength of zirconia to resin cement.

Methods: A search for in vitro studies and secondary research on surface treatment of zirconia and the bond strength to resin-cement was performed in Pub Med. The results of 10 systematic reviews or meta-analyses and 18 primary studies of the in vitro research were recorded, summarized, and graphed.

Results: The review proved water washing combined with either APA and a primer or a cement with the phosphate-monomer 10-MDP as the reference protocol. Silica-coating resulted in an increase in the mean SBS from 8.45 MPa to 15.00 MPa without aging and from 6.41 MPa to 11.97 MPa after thermo cycling. While etching was found to generally underperform APA, it yielded better results with highly concentrated or heated acid systems. Laser pretreatment appears to favor bonding, with a pooled mean difference of 3.08 MPa, although Er: YAG Laser failed to deliver comparable results. Cold plasma pre-treatment resulted in an increase of the initial micro-shear bond strength from 21.6 MPa to 38.3 MPa . Saliva contamination was found to decrease the bond strength by as much as 38% in primer less conditions and re-abrasion was the most successful decontamination procedure.

Conclusion: The protocol of use of applying APA and 10-MDP appears as the best protocol, with the tribochemical silica coating as a good alternative. Conversely, laser, plasma and acid etching require further standardization and long-term data before adopting it in clinical practice

1. INTRODUCTION

Yttria-stabilized zirconia (Y-TZP) is considered as the most widely used ceramic material for many dental applications including crowns, fixed partial dentures, implant abutments, and post-and-cores due to its high flexural strength and fracture toughness. Unlike glass-ceramics, zirconia lacks a glass phase so it cannot be etched with hydrofluoric acid and silanized in a traditional manner. As zirconia's surface is dense, polycrystalline, and chemically inert, it offers little micro-retentive structure and few reactive sites, and it is for this reason that debonding remains one of the most common technical problems in zirconia restorations – especially in short or highly tapered preparations, where retention relies greatly on the adhesive interface (Ayedi et al., 2025; Alammar & Blatz, 2022).

Based on these disadvantages of bond strength, three main approaches have been suggested. First approach involves obtaining micro-mechanical retention, using surface roughening techniques, including airborne-particle abrasion (APA), laser irradiation, or etching; second approach is related to gaining a chemical bond via functional monomers, especially phosphate monomer 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) with chemical affinity to bonds to the metal oxides on the zirconia surface. The third approach combines two approaches described above, which contains tribochemical silica coating, and silanization, or APA technique, with the use of MDP primer containing (Lima et al., 2023). Recently, non-thermal plasma and femtosecond lasers are mentioned as promising approaches (Shalaby et al., 2025; Liao et al., 2025).

The clinical scenario has become more complicated with the advent of high-translucency zirconia (4Y and 5Y), glass-infiltrated zirconia, and additively manufactured zirconia. These different types of zirconia may respond differently to the same surface treatment protocol (Abd Elaziz et al., 2025; Alammar & Blatz, 2022; Bömicke et al., 2024; Wang et al., 2025). Furthermore, the intraoral try-in results in saliva or cement contamination which must then be remediated prior to final cementation (Silva et al., 2022; Thammajaruk et al., 2023). Given that various studies use different types of zirconia, cements, testing methods, and aging regimes, it is difficult to compare study results. This article, therefore, seeks to review the effect of different surface treatments on the zirconia-resin cement bond strength based on a systematic review of studies from the years 2020-2025 and determine which protocols have the most reliable evidence.

2. Materials and Methods

2.1 Design

This review is a planned, structured narrative synthesis of in vitro studies. No experimental data were generated as part of this review and no new samples were tested. No numeric data in the tables and figures have been altered from that reported in the referenced papers; percentages have been calculated from the original mean values and are referred to as such.

2.2 Search and Selection

On 6 November 2026 a Pub Med search for reports published 1 January 2020 – 31 December 2025 was performed, various search combinations using the search term, zirconia, surface treatment, resin cement, bond strength, airborne-particle abrasion, MDP primer, laser, and plasma. The main search (zirconia surface treatment resin cement bond strength) returned 213 results, with other searches for systematic reviews, meta-analyses, lasers, plasma, contamination, and primers. The author screened titles and abstracts, and study inclusion criteria were as follows: 1) – evaluation of at least one surface treatment applied to zirconia; 2) – evaluation of the bond strength of at least one resin based cement or luting composite; and 3) – an in vitro study, or a review of in vitro studies. Included studies on other ceramics, orthodontic bracket-only systems without a resin cement interface, or containing inconsistent or impossible to interpret units, were excluded or included as qualitative results only.

2.3 Extraction and Presentation of Data

Data collected from each study are as follows: type of zirconia, surface treatments evaluated, cement and adhesive system used, bond testing method (shear, micro-shear, and micro-tensile), aging method, mean and standard deviation of groups where available, and major finding. It is important to note that where only data at abstract level were available, estimated values for groups not reported at this level are not provided. Bond strength values obtained with different testing methods, cements, and aging methods cannot be directly compared across studies; as such, comparisons between different tests in Figures 1–4 are only made within each study, and any comparisons between different studies are based on averaging of systematic review data (Tables 1 and 2).

3. RESULTS

3.1 Evidence Base

In all, ten secondary studies and eighteen primary in vitro studies were included (Tables 1 and 2). The secondary studies included from six to fifty-four studies (Figure 2) and most studies evaluated risk of bias as medium (D'Alessandro et al., 2024; Ayedi et al., 2025). The primary studies were generally small, usually ten to sixteen specimens per group, used 3Y-TZP and included

aging via thermo cycling (ranged from 1,000 to 15,000 cycles). The three families of treatments and proposed mechanisms of action are presented in Figure 1.

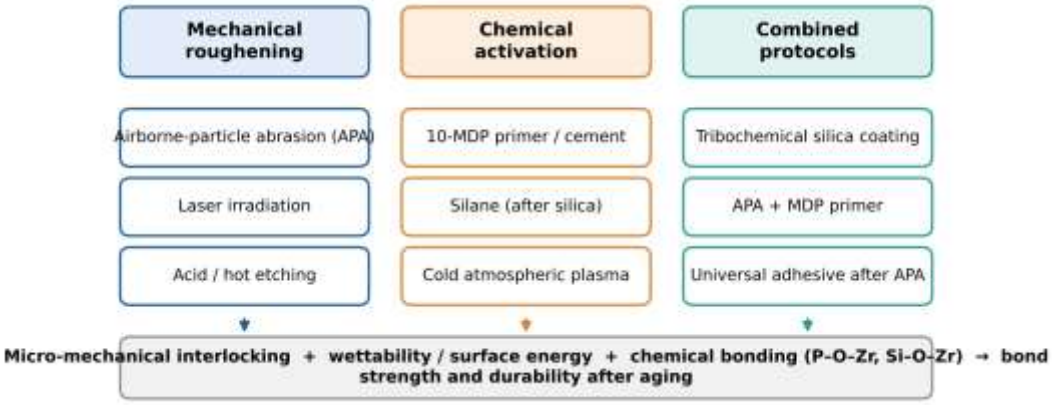

Figure 1. Conceptual map of surface-treatment strategies for zirconia and the mechanisms by which they improve resin-cement bonding.

Table 1. *Characteristics of the primary in vitro studies included in the synthesis.*

Study	Zirconia / substrate	Surface treatments compared	Test and aging	Main finding
Hjerppe et al. (2021)	Zirconia	APA + MDP; silica-coated alumina + silane; KHF etching + silane	SBS; 6,000 thermocycles	Equal when dry; after aging APA + MDP lower than the other two
Peçanha et al. (2021)	Zirconia	Alumina APA ± MDP; silica-modified alumina ± MDP; two cements	μSBS; 3,000 thermocycles	Self-adhesive cement gave the most stable bond after aging
Xiong et al. (2021)	High-translucency	APA at 0.1, 0.3, 0.6 MPa ± MDP primer	SBS ± thermocycling	MDP primer outperformed APA alone, immediate and aged
Bömicke et al. (2024)	Milled vs printed	Alumina APA vs tribochemical silicatisation; disinfection	TBS; 24 h vs 30 d + 7,500 cycles	Silicatisation highest; printed ≈ milled
Yaqoob et al. (2025)	Glass-infiltrated	Grit-blasting; silica coating; HF etching	MTBS; n = 10/group	Silica coating highest (28.23 MPa)
Shalaby et al. (2025)	Multilayer	APA vs femtosecond laser (385, 800, 870 nm)	SBS; n = 16/group	800/870 nm comparable to APA; 385 nm lowest
Basunbul (2025)	3Y-TZP	Sandblasting; Er,Cr:YSGG; Yb fiber laser; Rose Bengal LLLT	SBS after aging; n = 16	Yb fiber laser highest (9.34 MPa)
Liao et al. (2025)	Sandblasted zirconia	Argon cold plasma + MDP primer vs none	μSBS; 30 d water; 1,000 cycles	Plasma 300 s: 38.3 vs 21.6 MPa

Study	Zirconia / substrate	Surface treatments compared	Test and aging	Main finding
Idris et al. (2025)	Opaque Y-TZP	Control; air abrasion; G-Multi primer; both; ± saliva	μSBS	AA + G best when dry (8.06 MPa)
Suwannachot et al. (2025)	Zirconia	Furnace or scaler cleaning of cement ± re-abrasion	SBS; aged; n = 10	Cleaning + air abrasion restored bond (6.60 MPa)
Neto et al. (2025)	3Y-TZP	Sandblasting + six primer conditions	SBS; 10,000 cycles	MDP + silane primer highest
AbdElaziz et al. (2025)	3Y and 5Y	APA; HF; warm HF ± primer	SBS; 160 specimens	Warm HF + primer highest in both types
Al Imam et al. (2025)	5Y	APA vs APA + Zircos-E (30 or 120 min); two cements	SBS; 24 h	Zircos-E added to APA increased SBS ($p < 0.001$)
Wang et al. (2025)	Additively manufactured	Printed microstructures ± APA	SBS ± 15,000 cycles	Microstructure + APA highest (6.78 MPa)
Teerakanok et al. (2025)	Slip-cast	ZrO_2 slurry (15%, 30%) vs APA	SBS; 210 discs	No significant differences
Ozkan Ata & Okur (2025)	4Y and 6Y	Decontamination of saliva-contaminated zirconia	SBS at 1 wk, 6 and 12 mo	Ivoclean or Al_2O_3 abrasion best for 4Y
Zhong et al. (2025)	Zirconia post-and-cores	Non-thermal plasma on ceramic, primer or cement surface	SBS, TBS, push-out; aged	Plasma on ceramic + cement surface optimal
Naderi et al. (2025)	Zirconia (repair model)	No treatment; SiC grinding; sandblasting; 9% HF; silane + universal adhesive	μSBS; 10,000 cycles	No significant effect of treatment on zirconia

Abbreviations: APA, airborne-particle abrasion; HF, hydrofluoric acid; KHF, potassium hydrogen difluoride; LLLT, low-level laser therapy; MDP, 10-methacryloyloxydecyl dihydrogen phosphate; MTBS, micro-tensile bond strength; SBS, shear bond strength; TBS, tensile bond strength; μSBS, micro-shear bond strength.

Table 2. *Systematic reviews and meta-analyses included in the synthesis.*

Review	Focus	Studies included	Key conclusion
Bitencourt et al. (2021)	Laser irradiation	37	Lasers improved bond strength (MD 3.08 MPa); Er:YAG did not
Alammar & Blatz (2022)	High-translucent zirconia	18 (of 629)	Protocols for 3Y-TZP also work; APA + phosphate-monomer primer or cement durable

Review	Focus	Studies included	Key conclusion
Silva et al. (2022)	Cleaning of saliva contamination	13 (11 in meta-analysis)	Al_2O_3 sandblasting > Ivoclean > water
Feiz et al. (2022)	Cleansing methods, aged bonds	14 (of 162)	Air abrasion effective; NaOCl and cleaning gel comparable
Thammajaruk et al. (2023)	Cleaning of contaminated zirconia	25 (of 1,181)	Alumina abrasion and NaOCl comparable to uncontaminated zirconia
Lima et al. (2023)	Universal adhesives	23	Higher than phosphate primers; similar to phosphate-silane primers after abrasion
D'Alessandro et al. (2024)	Etching vs APA	54 (19 meta-analysed)	APA usually superior; 40–48% HF similar to APA
Kagaoan et al. (2024)	Additively manufactured crowns	6	Alumina APA generally recommended; evidence scarce
Ayedi et al. (2025)	Durability after aging	15 (of 714)	APA + 10-MDP + self-adhesive cement most durable
Lara-Hernández et al. (2025)	Silica coatings	Not stated in abstract	Silica coating 15.00 vs 8.45 MPa (no aging); 11.97 vs 6.41 MPa (aged)

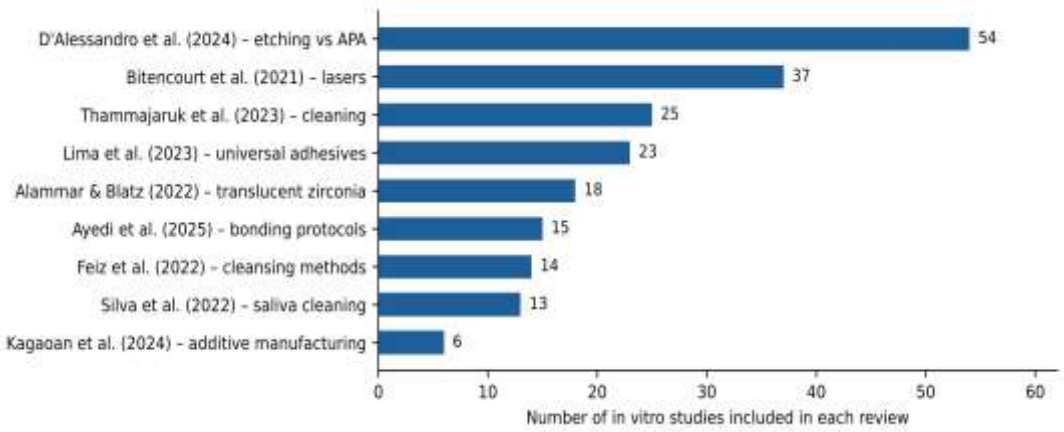

Figure 2. Number of in vitro studies included in each systematic review. Larger reviews were mainly those comparing laser and etching protocols with airborne-particle abrasion.

3.2 Mechanical roughening and silica coating

Airborne-particle abrasion was the comparator used in all but one of the studies, and was the comparator in all of the reviews. Airborne-particle abrasion with a 10-MDP primer/universal adhesive and with a preference of a self-adhesive resin cement, was the most durable adhesion after aging according to the study by Ayedi et al. (2025). For the high-translucency zirconia, Alammar and Blatz (2022) reported that the protocols which proved to be effective for 3Y-TZP (airborne-particle abrasion with phosphate-monomer primer/ cement) also effectively yielded a durable bond in 4Y and 5Y materials. The role of the abrasion pressure is also important: while surface roughness increased with pressure (from 0.1 to 0.6 MPa), the MDP primer

caused a more significant improvement in bond strength and a smaller decline after aging than abrasion alone (Xiong et al., 2021).

Tribochemical silica coating creates a layer that can be silanated. For silica coating of zirconia the review by Lara-Hernández et al. (2025) shows a mean bond strength of 15.00 MPa before and 11.97 MPa after thermocycling compared to 8.45 MPa and 6.41 MPa for un-treated zirconia, corresponding to an 77% and 87% increase (calculation based on the means reported). Cohesive and mixed failure were prominent in the silica groups while the control groups showed mostly adhesive failures. As can be seen in Figure 3 and Table 3, glass-infiltrated zirconia showed a comparable trend, with silica coating (28.23 ± 1.53 MPa) being superior to grit-blasting (20.27 ± 2.33 MPa) and HF-etching (10.41 ± 1.46 MPa) (Yaqoob et al., 2025). In both printed and milled zirconia, again only silicatisation led to higher tensile bond strength than alumina-abrasion; in this case the aging loss was worsened by isopropanol disinfection after the silicatisation (Bömicke et al., 2024).

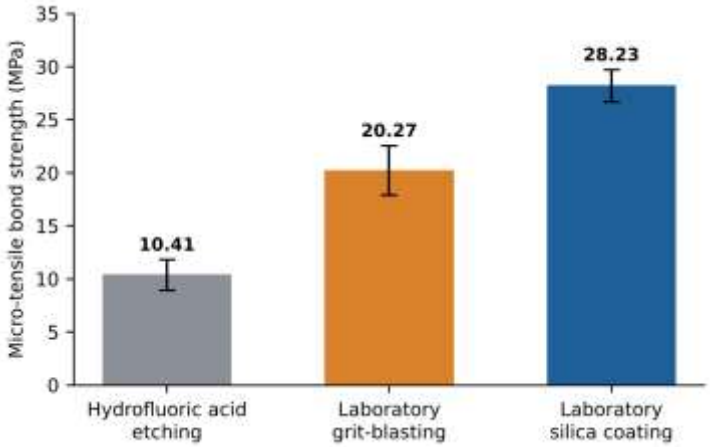

Figure 3. Micro-tensile bond strength of glass-infiltrated zirconia to resin cement after three surface treatments (mean ± SD, n = 10 per group). Data from Yaqoob et al. (2025).

Table 3. Bond strength (mean ± SD, MPa) reported by four primary studies for different surface treatments, with differences calculated from the reported means.

Study (test)	Treatment	Mean ± SD (MPa)	Comparison with reference
Yaqoob et al. (2025) (MTBS)	HF etching	10.41 ± 1.46	−48.6% vs grit-blasting
	Laboratory grit-blasting	20.27 ± 2.33	Reference
	Laboratory silica coating	28.23 ± 1.53	+39.3% vs grit-blasting
Shalaby et al. (2025) (SBS)	APA, 50 µm Al_2O_3	17.23 ± 2.02	Reference
	Femtosecond laser, 800 nm	15.07 ± 3.42	−12.5% (no significant difference)
	Femtosecond laser, 870 nm	13.01 ± 2.74	−24.5% (no significant difference)
	Femtosecond laser, 385 nm	8.07 ± 1.26	−53.2% (p = 0.0001)
Basunbul (2025) (SBS, aged)	Rose Bengal LLLT	5.76 ± 0.34	Reference (lowest)
	Ytterbium fiber laser	9.34 ± 0.29	+62.2% vs LLLT

Study (test)	Treatment	Mean ± SD (MPa)	Comparison with reference
Liao et al. (2025) (μSBS)	Sandblasted + MDP primer	21.6 ± 7.9	Reference
	Sandblasted + plasma (300 s) + MDP	38.3 ± 5.6	+77.3% vs no plasma

Shaded rows show the highest-performing treatment in each study. SD, standard deviation. Values are not comparable between studies because test methods, cements and aging differ.

3.3 Chemical activation: MDP primers, silane and universal adhesives

The functional monomer, in particular, affects the extent of the adhesion between the cement and the surface of the zirconia. Neto et al. (2025) evaluated shear bond strength after 10,000 thermal cycles with a primer containing 10-MDP and silane which demonstrated the highest SBS scores, followed by the silane based primer and universal adhesive in second place and no primer control, and primers with PMDM in the last place. In addition, a meta-analysis involving 23 studies by Lima et al. (2023) demonstrated greater bond strengths with universal adhesives over phosphate primers on aged zirconia with similar values to phosphate-silane primers after surface preparation by air abrasion.

This interaction is between the surface treatment and the cement chemistry and is presented in Figure 4 and Table 4. Peçanha et al. (2021) assessed the bonding of two cements to silica-treated alumina and silane (SS) coated zirconia as well as the same coating plus an MDP primer (SSP). Both cements showed initial bond strengths between 10.4 to 12.6 MPa; following thermo cycling, the MDP-based cement had a reduction in bond strength of 44 to 49% whereas the self-adhesive cement exhibited a reduction of only 4 to 21%. In this case, the choice of cement determines the aging of the bond strength. Similarly, Xiong et al. (2021) advise applying the MDP primer along with a composite cement that contains an adhesive phosphate monomer.

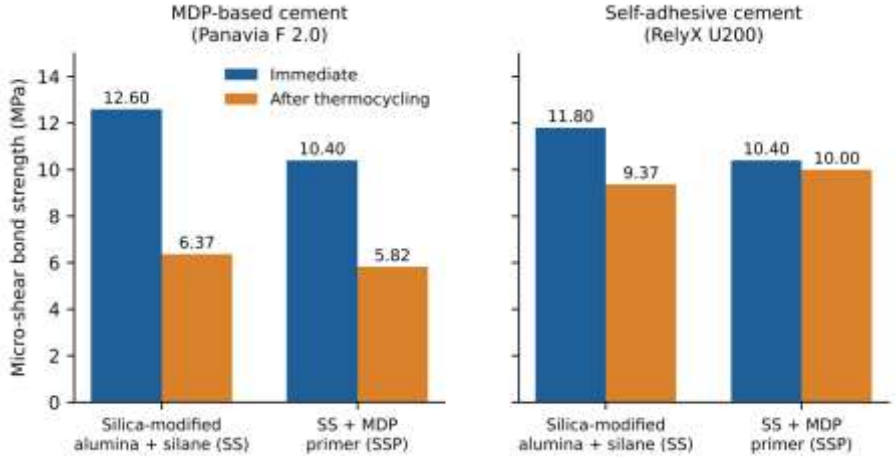

Figure 4. Micro-shear bond strength of zirconia to an MDP-based cement and a self-adhesive cement, immediately and after 3,000 thermocycles. SS, silica-modified alumina + silane; SSP, SS + MDP primer. Data from Peçanha et al. (2021).

Table 4. *Effect of thermocycling on micro-shear bond strength (MPa) according to surface treatment and cement (Peçanha et al., 2021).*

Surface treatment	Cement	Immediate	After thermocycling	Loss (%)†
SS	MDP-based (Panavia F 2.0)	12.60	6.37	49.4
SS	Self-adhesive (RelyX U200)	11.80	9.37	20.6
SSP	MDP-based (Panavia F 2.0)	10.40	5.82	44.0

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Surface treatment	Cement	Immediate	After thermocycling	Loss (%)†
SSP	Self-adhesive (RelyX U200)	10.40	10.00	3.8

†Calculated from the reported means. SS, silica-modified alumina + silane; SSP, SS + MDP primer.

3.4 Etching

Since zirconia is resistant to conventional etching, it is generally thought that acid protocols are inferior to APA. D'Alessandro et al. (2024), in the largest systematic review to date which included 54 studies and 19 meta-analyses, showed that APA generally produced significantly greater bond strength than etching, with two exceptions (HF 40-48% produced no difference in SBS relative to APA and Zircos-E multi-acid solution, produced significantly greater immediate bond strength to resin cement). Recent primary literature supports these two exceptions. Abd Elaziz et al. (2025) found warm HF with primer produced the highest SBS in both 3Y and 5Y zirconia while also maintaining the tetragonal phase, and Al Imam et al. (2025) suggested that Zircos-E after APA produced a significant increase in bond strength with both MDP primed and self-adhesive cement. Potassium hydrogen difluoride was not superior to Hjerppe et al. (2021)'s methods, and zirconia slurry applied to slip-cast zirconia did not influence roughness, crystal phase, or bond strength (Teerakanok et al., 2025). In fact, etching glass-infiltrated zirconia with HF provided the worst results of all treatments (Figure 3).

3.5 Laser irradiation

In the meta-analysis of 37 studies by Bitencourt et al. (2021), laser-treated Y-TZP had a pooled mean bond-strength difference of +3.08 MPa (95% CI 2.58 to 3.58) over controls and a roughness increase of 0.96 (0.86 to 1.06), but Er:YAG lasers showed no benefit (mean difference 0.22 MPa, 95% CI −0.44 to 0.88; Figure 5b). The authors noted the lack of a standardized laser protocol. Recent primary studies illustrate this wavelength dependence. Femtosecond irradiation at 800 and 870 nm gave bond strengths comparable to APA, but 385 nm was clearly inferior (Shalaby et al., 2025; Figure 5a), and a ytterbium fiber laser outperformed Er,Cr:YSGG laser, sandblasting and Rose Bengal-activated low-level laser therapy in terms of roughness and bond strength (Basunbul, 2025). No laser protocol has surpassed APA, but several appear to be reasonable alternatives.

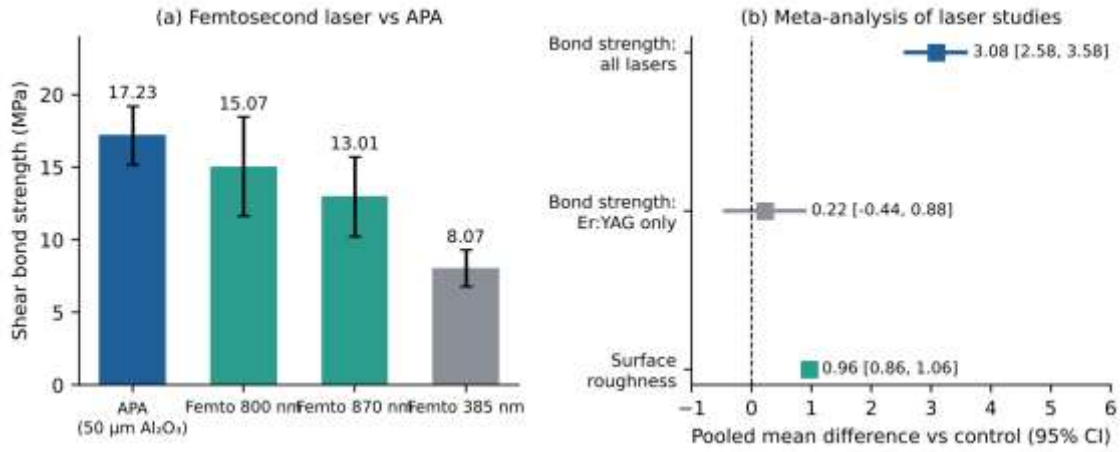

Figure 5. (a) Shear bond strength of metal brackets bonded to zirconia after APA or femtosecond laser at three wavelengths (mean ± SD; Shalaby et al., 2025). (b) Pooled mean differences from the meta-analysis of laser studies (Bitencourt et al., 2021); the dashed line marks no effect.

3.6 Cold atmospheric plasma

Effect of Argon Cold Atmospheric Plasma on Bond Strength Plasma treatment ofargon cold atmospheric sandblasted surface and before primer treatment with MDP lead to an increase in the initial micro-shear bond strength from 21.6 ± 7.9 MPa to 38.3 ± 5.6 MPa after300 seconds (Figure 6b).3 plasma-treated group was 191% higher after 30 days in water and 30.5% after 1,000 thermo cycles higher than the non-plasma-treated group (Liao et al., 2025). The hydrophilic effect of plasma disappeared within 1 hour and it was shown that it must be immediately primed. Additionally, treatment of ceramic and cement-covered

surface of customized zirconia post-and-cores with NTP improved shear, tensile and push-out bond strength, but did not have beneficial effect when applied over an already primed surface (Zhong et al., 2025).

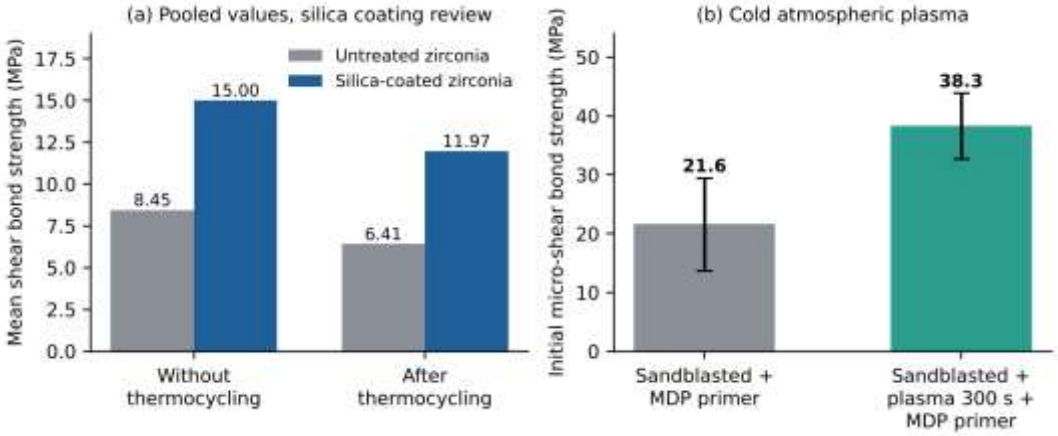

Figure 6. (a) Pooled mean shear bond strength of silica-coated and untreated zirconia before and after thermocycling (Lara-Hernández et al., 2025). (b) Micro-shear bond strength with and without 300 s argon plasma (mean ± SD; Liao et al., 2025).

3.7 Contamination and decontamination

Re-contamination of saliva in the try-in process greatly affects bond failure. Idris et al. (2025) found the bond strength of sandblasted unprimed zirconia after saliva contamination was 3.13 MPa, which dropped to 0.86 MPa after saliva contamination, an overall reduction of 72.5%. The bond strength for zirconia without primer after AA + G-Multi primer was applied was 8.06 MPa, which dropped to 4.97 MPa, an overall reduction of 38.3%. Primer application was unaffected, with reported bond strengths of 5.94 MPa and 5.92 MPa (Figure 7, Table 5). The literature agrees that re-abrading would be the most dependable solution. Silva et al. (2022) found Ivoclean to outperform Al_2O_3 sandblasting. Alumina abrasion and sodium hypochlorite have shown similar results compared to uncontaminated zirconia on a meta-analysis of 25 articles (Thammajaruk et al., 2023). Cleaning paste was effective in 6/8 studies (Feiz et al., 2022). For high-translucency 4Y zirconia, Ivoclean and alumina abrasion were the most successful re-contamination protocols after 12 months of accelerated aging (Ozkan Ata & Okur, 2025).

Cement Contamination

Cement contamination can be corrected as well. Suwannachot et al. (2025) bonded clean and cement contaminated zirconia without cement after that contaminated zirconia had been cleaned in a furnace and re-abraded, that cement contaminated zirconia was cleaned in a furnace and cemented again, showed bond strength of 6.60 ± 1.10 MPa, which was not significantly different from the result of clean and abraded zirconia (6.59 ± 0.94 MPa), but significantly different from contaminated zirconia that had not been re-abraded (2.66 ± 0.51 MPa). An abraded zirconia that had been cleaned and cemented after seven days delay of cementation revealed bond strength of 4.41 MPa.

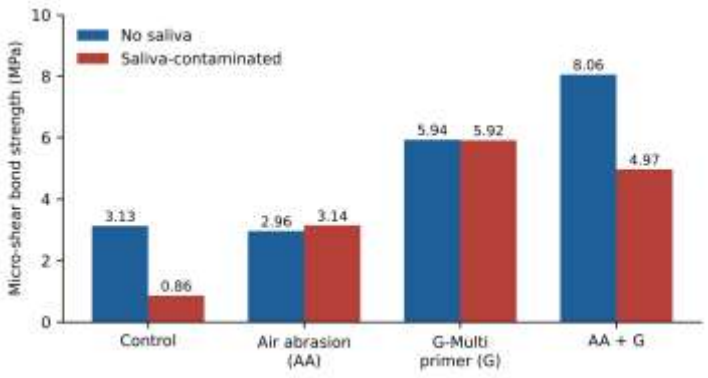

Figure 7. Micro-shear bond strength of opaque zirconia with and without saliva contamination according to surface treatment (Idris et al., 2025). AA, air abrasion; G, G-Multi primer.

Table 5. Micro-shear bond strength (MPa, mean ± SD) of opaque zirconia by surface treatment and saliva contamination (Idris et al., 2025).

Surface treatment	No saliva	Saliva	Reduction by saliva (%)†
Control	3.13 ± 2.7	0.86 ± 0.7	72.5
Air abrasion (AA)	2.96 ± 1.2	3.14 ± 2.6	None (+6.1)
G-Multi primer (G)	5.94 ± 2.2	5.92 ± 2.2	0.3
AA + G	8.06 ± 1.4	4.97 ± 0.9	38.3

†Calculated from the reported means.

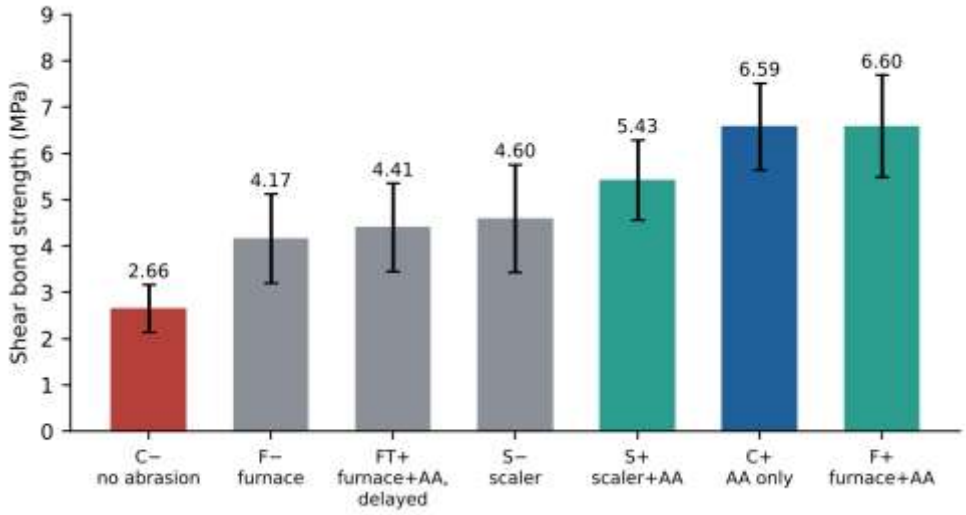

Figure 8. Shear bond strength of cement-contaminated zirconia after different cleaning and re-treatment protocols (mean ± SD, n = 10). C+, abrasion only; C−, no treatment; F, furnace cleaning; S, piezoelectric scaler; +/−, with/without additional air abrasion (AA); T, delayed re-cementation. Data from Suwannachot et al. (2025).

3.8 New substrates: translucent, printed and microstructured zirconia

There is currently limited evidence for the newer types of zirconia. Alammar and Blatz (2022) found 18 studies for high-translucency zirconia, and concluded that conventional bonding protocols would be probably appropriate. With regard to additively manufactured zirconia, Bömicke et al. (2024) found that specimens, which were bonded with MDP cement, showed similar strengths to milled zirconia after silicatisation or abrasion; however, only one zirconia study was identified from the review of additively manufactured crowns by Kagaoan et al. (2024). Wang et al. (2025) found printed microstructures combined with APA increased shear bond strength (6.78 ± 0.82 MPa pre-thermocycle and 6.25 ± 0.83 MPa after 15,000 thermocycles, corresponding to an 8% reduction) with protrusion height being the most significant predictor (β = 0.769). In a repair model, no significant effect was observed from surface treatment with regard to zirconia, which was observed with hybrid ceramics (Naderi et al., 2025).

3.9 Aging Regimes and Tests

Aging did not follow any discernible pattern, and ranged more than two orders of magnitude (from 1,000 thermal cycles (Liao et al., 2025) to 100,000 cycles to simulate 12 months of functional activity (Ozkan Ata & Okur, 2025)) (see Figure 9, Table 7). Sample geometries also showed significant variation, with shear tests most common, although micro-shear, micro-tensile, tensile, and push-out tests were also applied. This heterogeneity may explain the wide variation in absolute values, ranging from 0.9 MPa for contaminated, unprimed zirconia (Idris et al., 2025) to 38.3 MPa for plasma-treated, primed zirconia (Liao et al., 2025). Interestingly, thermocycling did not seem to compromise the strength of microstructured printed zirconia (P = 0.954),

although it was associated with an increased rate of adhesive failure (Wang et al., 2025), so failure mode may be a more sensitive indicator of aging damage.

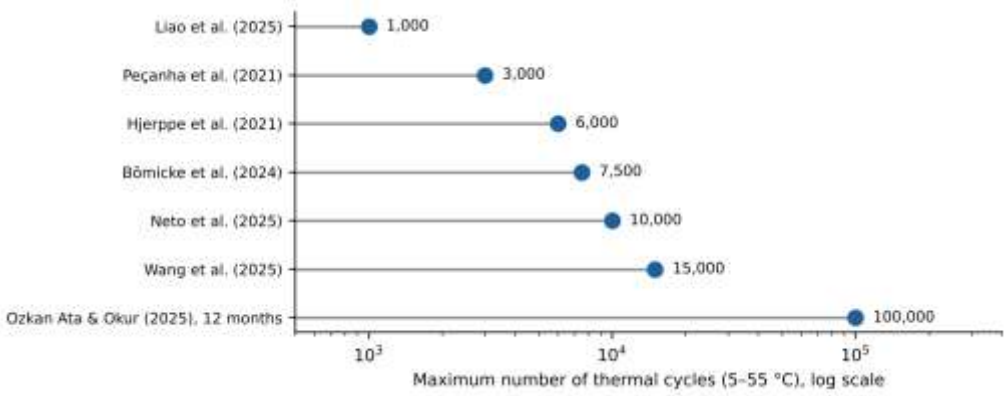

Figure 9. Maximum number of thermal cycles used for artificial aging in the primary studies that reported it. Cycle numbers are taken from the published methods; Suwannachot et al. (2025) and several others did not report cycle numbers in the abstract and are omitted.

Table 7. Bond tests and aging protocols used in representative studies.

Study	Bond test	Aging protocol	Aged outcome
Liao et al. (2025)	Micro-shear	30 days in water; 1,000 cycles	Plasma group +191% (water) and +30.5% (cycles)
Peçanha et al. (2021)	Micro-shear	3,000 cycles (5–55 °C)	Self-adhesive cement stable (−3.8% to −20.6%)
Hjerppe et al. (2021)	Shear	6,000 cycles (5–55 °C)	APA + MDP lower than silica or KHF groups
Bömicke et al. (2024)	Tensile	30 days in water + 7,500 cycles	Disinfection harmed silicatised specimens
Neto et al. (2025)	Shear	10,000 cycles	MDP + silane primer highest
Wang et al. (2025)	Shear	15,000 cycles (5–55 °C)	SBS unchanged (P = 0.954); more adhesive failures
Ozkan Ata & Okur (2025)	Shear	10,000; 50,000; 100,000 cycles (1 wk, 6, 12 mo)	Ivoclean and Al_2O_3 best for 4Y

3.10 Overall comparison

Table 8 combines the findings into a ranking. The evidence ratings are the author's qualitative appraisal based on the number, consistency and aging data of the supporting studies; they are not formal GRADE ratings.

Table 8. Summary and qualitative appraisal of the surface treatments for zirconia–resin cement bonding.

Treatment	Main mechanism	Typical result	Evidence	Key sources
APA + 10-MDP primer/cement	Roughness + chemical bond	Most durable after aging	Strong	Ayedi et al. (2025); Alammar & Blatz (2022); Xiong et al. (2021)
Silica coating + silane (± MDP)	Silica layer, silane coupling	15.00 vs 8.45 MPa (dry); 11.97 vs 6.41 MPa (aged)	Moderate to strong	Lara-Hernández et al. (2025); Yaqoob et al. (2025); Bömicke et al. (2024)
Universal adhesive after APA	Mixed monomers	Higher than phosphate primers; ≈ phosphate–silane primers	Moderate	Lima et al. (2023); Neto et al. (2025)
Acid etching (HF, hot HF, Zircos-E)	Selective grain-boundary etching	Mostly < APA; 40–48% HF and warm HF ≈ or > APA	Low to moderate	D'Alessandro et al. (2024); AbdElaziz et al. (2025); Al Imam et al. (2025)
Laser irradiation	Surface melting / ablation	+3.08 MPa overall; wavelength dependent	Low to moderate	Bitencourt et al. (2021); Shalaby et al. (2025); Basunbul (2025)
Cold plasma	Hydrophilicity, cleaning	38.3 vs 21.6 MPa; effect decays within an hour	Low	Liao et al. (2025); Zhong et al. (2025)
Re-abrasion after contamination	Removes contaminant, re-roughens	Restores bond to clean-control level	Strong	Silva et al. (2022); Thammajaruk et al. (2023); Feiz et al. (2022)

4. DISCUSSION

This synthesis does seem to suggest a hierarchy of treatment types. Treatments that afford both micro-retention and chemical bonding are probably best, rather than those that afford only one. The fact that the application of APA increases the surface roughness of a surface that is very dense, such as zirconia, and the 10-MDP compounds then create chemical bonds to the upper oxides would explain why the combination of APA and MDP was the most widely supported protocol in the recent reviews (Ayedi et al., 2025) and why the primer aided bond strength more than the abrasion pressure (Xiong et al., 2021). Likewise, the silica coating and subsequent silanization (use of siloxane bonds) provide one more avenue for chemical bonds, helping this technique to produce the highest bond strength values in two of the primary studies and a large amount of the pooled benefit in the review by Lara-Hernández et al. (2025).

Aging is a more fundamental assessment of the bonding process. The initial values of bond strength between the protocols showed similar performances, but there were considerable differences after thermocycling. For example, in a study by Peçanha et al., 2021 silica coating, MDP primer, and a self-adhesive cement showed only 3.8% loss of bond strength; a similar surface with an MDP-based cement showed a loss of 44% of bond strength. Also, Hjerppe et al. 2021 reported that groups that had similar bond strength under dry condition varied enormously after aging. This supports a need to interpret the result of dry or 24 hours cautiously and a great value of using a long aging protocol, such as the 12-month simulation by Ozkan Ata and Okur (2025).

Etching, laser and plasma surface treatments are all potential alternatives, but cannot yet fully replace APA. Several studies have shown that etching systems may be able to match or outperform the APA treatment, but the results are pH and time dependent (acid concentration, temperature, laser wavelength and exposure time) and limited long-term data is available (D'Alessandro et

al., 2024; Bitencourt et al., 2021). Such methods could have an important role to play for thin and high translucency restorations where the application of an acid can be less desirable and may induce phase transformation and surface damage, especially as the warm-HF protocol has been shown to maintain the tetragonal phase (Abd Elaziz et al., 2025). However, the use of laser and plasma devices in the clinic, as well as plasma's transient effect, remain important issues (Liao et al., 2025).

Another aspect to consider is the clinical workflow. Biondi et al. (2023) found a 50% decrease in bond strength on a highly conditioned surface following try-in contamination; in the three reviews that considered this topic, re-abrasion was the most effective method to rectify the contamination (Feiz et al., 2022; Silva et al., 2022; Thammajaruk et al., 2023). One applicable take-away point that can be gleaned from this synthesis is that the final conditioning step for zirconia should be performed after the try-in, immediately prior to cementation, and then quickly followed by primer or adhesive application.

4.1 Clinical Implications

The studies combined provide an simple sequence chairside (Table 9). The presented synthesis is laboratory evidence and should not be a clinical guideline; therefore, use manufacturer instructions for the cement, primer, and zirconia.

Table 9. Practical protocol suggested by the evidence for bonding zirconia restorations to resin cement.

Step	Recommendation	Supporting evidence
1. After try-in	Clean the intaglio surface; if saliva or cement contacted it, re-abrade with alumina rather than using water, alcohol or phosphoric acid	Silva et al. (2022); Thammajaruk et al. (2023); Suwannachot et al. (2025)
2. Roughening	Airborne-particle abrasion with alumina; silica-coated alumina is an alternative for glass-infiltrated or printed zirconia	Ayedi et al. (2025); Bömicke et al. (2024); Yaqoob et al. (2025)
3. Chemical priming	Apply an MDP-containing primer or universal adhesive immediately; add silane after silica coating	Lima et al. (2023); Neto et al. (2025); Xiong et al. (2021)
4. Cement	Use a cement containing an adhesive phosphate monomer or a self-adhesive cement	Peçanha et al. (2021); Ayedi et al. (2025)
5. Timing	Cement without delay after re-treatment; plasma effects fade within an hour and delayed cementation lowers bond strength	Liao et al. (2025); Suwannachot et al. (2025)

4.2 Limitations

Limitations that must be acknowledged include: i) this is a narrative synthesis rather than a registered systematic review or experiment, and the studies were selected by one reviewer using only the Pub Med database so it is likely other databases also contain relevant studies; ii) much of the data extraction was at the abstract level so group values are not available for some comparisons, and iii) the available evidence is between in vitro studies, which vary according to type of zirconia, type of cement, geometry of test, number of specimens and aging conditions, and almost all of the reviews were deemed to contain studies with medium risk of bias, meaning the absolute values (from roughly 2 to nearly 40 MPa for different studies) have limited ability to be compared. Iv) in vitro bond strength tests do not necessarily correlate to clinical retention and clinical studies on these surface treatments are very limited, v) the evidence ratings given in Table 8 are qualitative.

4.3 Future Research Suggestions

The authors recommend future investigations utilize relevant aging protocols that mimic 11,14,20 intra-oral conditions such as long-term water storage with thermocycling, and provide all group means with their standard deviations for comparison. 2T comparisons between treatment types should be made within the same zirconia generation and cement. The most pertinent

research questions to answer should include the longevity of warm hydrofluoric acid and multi-acid etch, if standardized laser parameters are achievable, the shelf-life of plasma activation, and how to best condition 4Y/5Y and printed zirconia.

5. CONCLUSIONS

Within the limitations of the in vitro evidence that is available from 2020 to 2025, the following general statements can be made: (1) airborne-particle abrasion plus a 10-MDP primer or a 10-MDP containing cement is the best supported protocol to provide long-term bonding to zirconia; (2) tribochemical silica coating with silane is a good supported alternative, especially for glass-infiltrated and printed zirconia; (3) etching is generally inferior to airborne-particle abrasion except for highly concentrated, heated or multi-acid systems; (4) laser and cold plasma have been shown to increase bond strength and provide good results, although they are dependent on parameters and lack of standardisation and long-term evidence, respectively; (5) cement choice influences to what extent bond strength deteriorates; and (6) contaminated zirconia must be re-abraded before cementation. Randomized clinical trials are needed to evaluate if the in vitro results are valid in the clinical environment.

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