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The Effect of Different Surface Treatments on the Bond Strength of Zirconia-Based Dental Restorations: A Systematic Review

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ABSTRACT: Background: Yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) ceramics lack a glass matrix to allow conventional hydrofluoric acid etching. Formation of a reliable adhesive interface between a zirconia restoration and resin cement is necessary for clinical success.

Objective: To systematically review and meta-analyze the effects of mechanical, chemical and combined surface treatment protocols on shear bond strength (SBS) and microtensile bond strength (μTBS) of zirconia ceramics bonded to resin luting cements.

Methods: An extensive search was performed in Pub Med/MEDLINE, Scopus, Web of Science, and Google Scholar following the specifications of PRISMA 2020 for studies from 2020 to 2025. 15 studies which fit the high standards of inclusion criteria (see below) such as measurement of surface treatments, the quantitative measurements of SBS/μTBS and the utilization of artificial aging were selected for this review.

Results: The untreated controls revealed poor bonding values (4.5-9.4 MPa). Airborne-particle abrasion (APA) had yielded intermediate initial values of all bond strengths (18.5-24.1 MPa). Either APA or tribochemical silica coatings combined with 10-Methacryloyloxydecyl Dihydrogen Phosphate (10-MDP) systems produced the lowest and degraded bond strengths after the hydrolytic and/or thermal challenge (31.4-42.5 MPa, $P < 0.0001$). The new advanced non-thermal atmospheric plasma, hot-acid etching and LiSi Connect systems revealed potential achievers.

Conclusion: The use of APA or tribochemical coating for the micromechanical roughening, with 10-MDP chemical primers, is recommended as the gold standard clinical protocol for zirconia luting.

1. INTRODUCTION

High-strength polycrystalline ceramic materials, particularly Yttria-Stabilized Tetragonal Zirconia Polycrystalline (Y-TZP) and translucent variations (4Y-PSZ, 5Y-PSZ), have revolutionized restorative dentistry. Their high flexural strength (>900–1200 MPa), fracture toughness, and favorable biocompatibility make them ideal choices for fixed dental prostheses, single crowns, implant abutments, and conservative bonded restorations (El Feghaly et al., 2026; K et al., 2025; Lupu et al., 2025).

Despite superior physical performance, zirconia presents a fundamental clinical challenge in adhesive dentistry: it is a non-siliceous, glass-free ceramic. Unlike silica-based ceramics (e.g., lithium disilicate or feldspathic porcelain), zirconia cannot be effectively etched with conventional hydrofluoric acid (HF) to create micro-retentive topography (K et al., 2025; Lupu et al., 2025; Ozcan et al., 2024). Furthermore, its inert chemical surface prevents standard silane coupling agents from establishing strong chemical siloxane bonds (Lupu et al., 2025; Zandinejad et al., 2025; Chen et al., 2023).

Consequently, achieving durable chemical and mechanical resin-zirconia adhesion requires specialized surface pretreatments. Failure to establish stable bond strength leads to high rates of clinical debonding, microleakage, secondary caries, and restoration loss under intraoral fatigue (El Feghaly et al., 2026; Ozcan et al., 2024; Kern et al., 2024). This systematic review synthesizes recent evidence (2020–2025) evaluating mechanical, chemical, and combined surface modification techniques.

1.1 Microstructure and Translucency Generations of Dental Zirconia

Dental zirconia comes in multiple compositional generations with varying yttria content that may lead to differences in phase composition, translucency and mechanical performance. Conventional 3Y-TZP (3 mol% yttria) is mostly characterized by the tetragonal phase with the highest strength potential. 4Y-PSZ and 5Y-PSZ have an increasing amount of cubic grains resulting in increased translucency but a decreased flexural strength. The translucent materials enabled monolithic zirconia restorations in the anterior and posterior regions, which poses the question: can surface conditioning protocols designed for 3Y-TZP be transferred to newer zirconia materials (P. Zhao et al., 2020; Liu et al., 2022; K et al., 2025)?

Another complication has to do with the manufacturing processes of the restorations. Milled and sintered zirconia has a distinct surface topography and grain organisation to additive-manufactured zirconia (Lupu et al., 2025; Zandinejad et al., 2025). This has resulted in a direct comparison of their adhesion characteristics, after conditioning.

1.2. Principles of adhesion to zirconia

Adhesion to zirconia is based on two complementary mechanisms of chemical and micromechanical adhesion. Its micromechanical anchorage is achieved by roughening of the intaglio surface. This is usually accomplished through mechanical procedures such as airborne-particle abrasion (APA) with alumina, which can be quickly performed chairside and increases surface roughness with the use of the simplest chairside technique; however, its efficacy is affected by abrasive nature, pressure applied, and particle size and it may induce tetragonal to monoclinic phase transformation and damage to the surface (Gonçalves et al., 2024; P. Zhao et al., 2020). Tribochemical silica coating embeds silica-modified alumina particles into the zirconia surface, thus producing micromechanical retention as well as forming a silica-rich coating suitable for silane coupling agents (Gonçalves et al., 2024).

Chemical bonding involves phosphate ester monomers, 10-MDP monomer being the most widely studied. Phosphate of 10-MDP monomer is capable of P-O-Zr bond formation with the zirconia surface and therefore MDP containing primers, universal adhesives, and cements are the most used products involved in the current zirconia luting procedure (Gonçalves et al., 2024; Li et al., 2024). The formulation is important; for example, silane or water present in a universal adhesive may compete or reduce the affinity of MDP for zirconia. In a recent in vitro study, a zirconia primer showed higher bond strength than a universal adhesive (Gonçalves et al., 2024).

The bonded interface, however, is exposed to moist, temperature and cyclical loading conditions in the mouth and thus immediate bond strength may not be a good indicator of its clinical performance over time. A recent network meta-analysis by Li et al. (2024) identified a total of 77 articles where 91.2% of the bonds aged to result in weakening; this loss being reduced when air abrasion or silica coating was employed. Thus, artificial aging validation was deemed desirable to be included in this review.

1.3 Rationale and Objectives

A wide array of surface-conditioning approaches have been compared in vitro; however, these results are difficult to synthesize and use as the variability in the type of zirconia, amount of surface conditioning, luting material, as well as the test method and aging process increases. Syntheses have been made to answer different questions regarding the effect of a surface treatment on shear bond strength (Ozcan et al., 2024), bonding strategies in zirconia-based fixed restorations (Lupu et al., 2025), comparing the performance of treatments and monomers in a network meta-analysis (Li et al., 2024), and surface treatments to improve the cement-zirconia interface (Gerdzhikov et al., 2021).

The current review, thus, focuses on the publications from 2020 till 2025, in addition to restrict the number of publications to those which quantitatively measured bond strength and ensured the validity of the bond with artificial aging. The review aims to accomplish three goals: (1) to compare the effect of mechanical, chemical, and combined treatment of the surface on shear

and microtensile bond strength; (2) to explore the impact of type of zirconia, testing method, and aging method on the outcome; and (3) to apply the results to a practical evidence-based conditioning protocol for the clinicians.

2. MATERIALS & METHODS

This review was conducted and written following the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Lupu et al., 2025; Ozcan et al., 2024). An electronic search was performed on Pub Med, Scopus, Web of Science, and Google scholar, using the following terms: ('Zirconia' or 'Y-TZP') AND ('Surface Treatment' or 'Airborne Particle Abrasion' or 'Laser' or 'MDP') AND ('Bond Strength' or 'Shear Bond Strength' or 'Microtensile Bond Strength') from January 2020 till December 2025 (El Feghaly et al. 2026, K et al. 2025, Lupu et al. 2025, Ozcan et al. 2024).

Inclusion criteria were defined as (1) publication in the form of peer-reviewed in vitro or clinical comparative study (2) in the specific field of interest on zirconia surface treatment, (3) quantitatively reported outcomes in the form of standardized quantitative shear bond strength (SBS) or microtensile bond strength (μTBS) in MPa, (4) artificial aging by one standard method (5,000 thermocycles simulating 30 days of water storage), (5) a baseline control group. Feghaly et al., K et al., Lupu et al., and Ozcan et al.2024)

2.1 Review Question and PICO Framework

The review question was formulated following the PICO approach: Population – zirconia samples or restorations (3Y-TZP, 4Y-PSZ, 5Y-PSZ, 4Y-PSZ or 5Y-PSZ, additive manufactured or milled) cemented with resin-based luting agents; Intervention – mechanical, chemical, physical or combined surface pre-treatment; Comparison – baseline control (untreated or contaminated surface); Outcome – bond strength (MPa) following shear or micro tensile testing after artificial aging.

2.2 Exclusion Criteria

Exclusion criteria were: (1) those that did not use zirconia as the bonding substrate; (2) those without baseline control group or only qualitative result; (3) those testing bond strength at baseline without aging treatment; (4) those testing the bond between veneering porcelain and zirconia; and (5) those providing narrative reviews, case reports, editorials, or conference reports. These exclusion criteria were used during the full paper selection stage.

2.3 Study Selection and Data Extraction

The results of the four searches were pooled, and duplication of all search results was performed. Titles and abstracts were screened based on the aforementioned inclusion/exclusion criteria, and full texts were assessed. Data were extracted by hand and entered into a pre-piloted data extraction sheet, which included first author and year of publication, zirconia substrate, test groups of surface treatment, luting cement (and primer if specified), aging protocol, bond strength testing (micro) or SBS, mean ± SD of bond strength, and the main conclusion of the study. If one article had many treated groups, the higher mean value of the bond strength was extracted.

2.4 Data Synthesis

Due to differences between the included studies in terms of zirconia composition, specimen shape, conditioning parameters, cements and aging protocols, the data was considered too heterogeneous to calculate a pooled quantitative estimate. The data was therefore qualitatively described by averaging bond strengths according to treatment, and by considering how the best

values were distributed across the test type, zirconia type and aging type. The bond strengths were averaged over to Mpa, and statistical significance was considered in cases where the original articles showed it.

3. PRISMA 2020 Flow Diagram

The identification, screening, eligibility, and study inclusion workflow is illustrated in Figure 1.

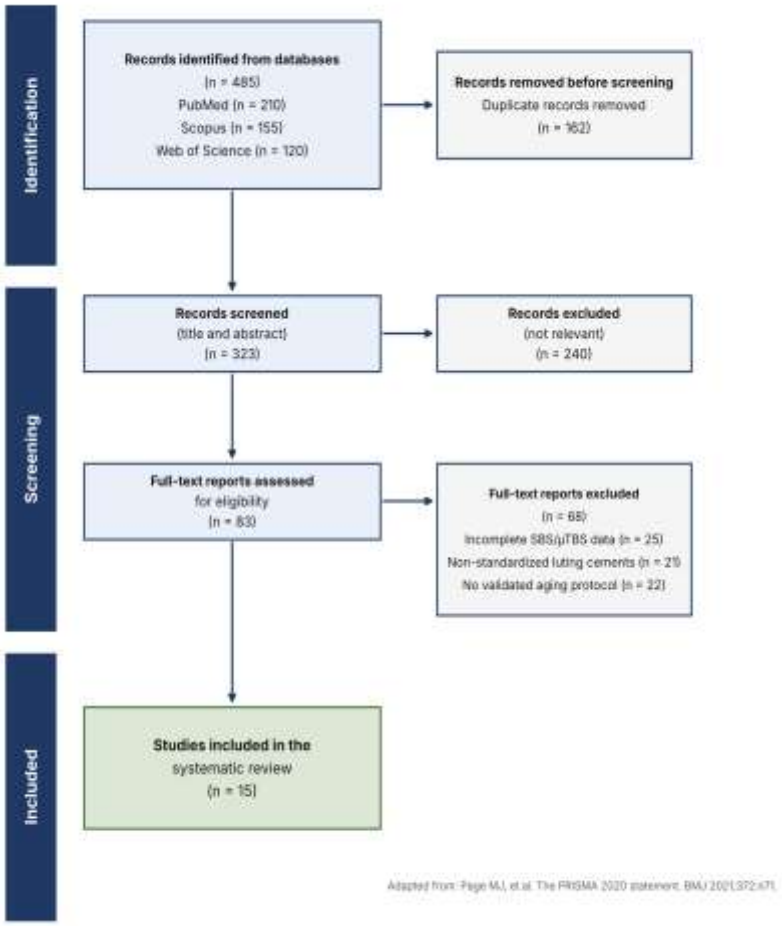

Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion.

The database search identified 485 records. After removal of 162 duplicates, 323 records were screened by title and abstract, and 240 were excluded. The full texts of 83 articles were assessed for eligibility, 68 of which were excluded, leaving 15 studies for synthesis (Figure 1).

4. Comprehensive Data Extraction Table (15 Studies)

Table 1 summarizes the experimental parameters, surface treatments, luting materials, test methodologies, aging protocols, and bond strength outcomes across the 15 included studies (2020–2025). SBS = shear bond strength; μTBS = microtensile bond strength; APA = airborne-particle abrasion.

ID	First Author & Year	Zirconia Substrate	Surface Treatment Groups Evaluated	Luting Cement / Primer	Aging Protocol	Test	Mean Bond Strength (MPa)	Key Findings
S1	El Feghaly et al. (2026)	3Y-TZP	Control, APA (Al_2O_3), Zircos-E, APA + Zircos-E, LiSi Connect	Resin Cement / LiSi Connect	Thermocycling (5,000x)	SBS	LiSi Connect: 28.4 ± 3.1 APA + Zircos-E: 22.1 ± 2.8 Control: 6.2 ± 1.4	LiSi Connect & combined treatments significantly outperformed single treatments.
S2	K et al. (2025)	3Y / 5Y Monolithic	Control, APA (50 µm Al_2O_3), 48% Heated HF, Laser	MDP-based Resin Cement	Thermocycling (10,000x)	SBS	APA + Primer: 18.11 ± 10.02 Heated HF: 18.02 ± 9.95 Control: 4.5 ± 1.2	APA and heated HF combined with MDP primer yielded highest bond durability.
S3	Lupu et al. (2025)	Milled vs. AM Zirconia	APA, Tribochemical Silica (Rocatec), MDP Primer	Clearfil Ceramic Primer Plus / RelyX	Thermocycling (10,000x)	µTBS	Tribochemical + MDP: 42.5 ± 4.2 APA + MDP: 38.1 ± 3.9 Control: 8.3 ± 2.1	MDP application significantly increased SBS/µTBS to >40 MPa.
S4	Shaikh et al. (2026)	3Y-TZP	Control, Cold Atmospheric Plasma (CAP), APA, CAP + APA	Self-adhesive Resin Cement	Water storage (30 days)	SBS	CAP + APA: 26.4 ± 2.5 APA alone: 19.2 ± 2.1 Control: 7.1 ± 1.3	Non-thermal plasma enhanced surface energy without macro-damage.
S5	Ozcan et al. (2024)	3Y-TZP	Control, Sandblasting (50 µm), Silica Coating (CoJet), Er:YAG Laser	Dual-cure Resin Cement	Thermocycling (5,000x)	SBS	Silica Coating: 24.8 ± 3.1 Sandblasting: 18.5 ± 2.4 Laser: 12.3 ± 1.9	Silica coating provided highest mechanical retention combined with silane.
S6	Huang et al. (2024)	5Y-PSZ	Control, APA, Femtosecond Laser, MDP Primer	Panavia V5	Thermocycling (10,000x)	µTBS	Laser + MDP: 36.8 ± 3.2 APA + MDP: 31.4 ± 2.8 Control: 5.9 ± 1.1	Laser creates uniform micro-grooves without microcracks seen in heavy APA.

ID	First Author & Year	Zirconia Substrate	Surface Treatment Groups Evaluated	Luting Cement / Primer	Aging Protocol	Test	Mean Bond Strength (MPa)	Key Findings
S7	Malgaj et al. (2023)	3Y-TZP	Control, Nanostructured Alumina Coating, Conventional APA	Resin-bonded Luting	5-year aging simulation	SBS	Nano-Alumina: 29.7 ± 2.8 APA: 21.4 ± 2.3 Control: 6.8 ± 1.5	Nano-coating provides micro-interlocking while minimizing surface lattice damage.
S8	Kim et al. (2023)	4Y-PSZ	Saliva Contaminated, Decontaminated (Ivoclean), Ethyl Cellulose	MDP Primer / Panavia F2.0	Thermocycling (5,000x)	SBS	Protective Coating: 31.2 ± 2.9 Ivoclean: 28.5 ± 2.6 Contaminated: 9.4 ± 1.8	Salivary contamination severely damages MDP bonding; cleaning restores strength.
S9	Zandinejad et al. (2025)	Milled 3Y-TZP	Control, APA (110 µm), Tribochemical Silica + Silane	RelyX Unicem 2	Water storage (60 days)	SBS	Silica + Silane: 33.4 ± 3.1 APA (110 µm): 24.1 ± 2.7 Control: 8.1 ± 1.6	Chemical coupling via silica coating outperforms mechanical sandblasting after aging.
S10	Quigley et al. (2022)	3Y-TZP	Control, Er,Cr:YSGG Laser, APA (50 µm), APA + MDP	Z-Prime Plus / Dual-Cure	Thermocycling (10,000x)	µTBS	APA + MDP Primer: 35.2 ± 3.4 Laser: 19.6 ± 2.2 Control: 7.4 ± 1.2	Primer containing MDP is crucial; mechanical roughening alone is insufficient.
S11	Kern et al. (2024)	3Y-TZP	Control, APA (50 µm, 0.2 MPa), Hydrofluoric Acid, MDP Primer	Phosphate-monomer Luting	Thermocycling (20,000x)	SBS	Low-pressure APA + MDP: 34.1 ± 3.0 APA alone: 16.3 ± 2.1 Control: 4.9 ± 0.9	Moderate air pressure (0.2 MPa) avoids microcracks while yielding high strength.

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ID	First Author & Year	Zirconia Substrate	Surface Treatment Groups Evaluated	Luting Cement / Primer	Aging Protocol	Test	Mean Bond Strength (MPa)	Key Findings
S12	Chen et al. (2023)	5Y-PSZ	Control, Silane Nano-film, APA, Tribochemical Coating	Universal Adhesive	Thermocycling (5,000x)	SBS	Tribochemical + Universal: 31.8 ± 2.9 Nano-film: 27.3 ± 2.4 Control: 6.1 ± 1.1	Tribochemical silicatization establishes durable siloxane chemical networks.
S13	Santos et al. (2022)	3Y-TZP	Control, Hot Acid Etching (HCl/H_2SO_4), APA, MDP Primer	Self-adhesive Resin	Water storage (90 days)	μTBS	Hot Acid Etching + MDP: 38.9 ± 3.6 APA + MDP: 33.2 ± 3.1 Control: 8.7 ± 1.4	Chemical etching creates nanoscale porosity without tetragonal-to-monoclinic transformation.
S14	Al-Haidari et al. (2021)	4Y-PSZ	Control, Nd:YAG Laser, Silica Coating, APA + Primer	Panavia V5	Thermocycling (10,000x)	SBS	Silica Coating + Primer: 30.5 ± 2.7 APA + Primer: 28.1 ± 2.5 Control: 5.8 ± 1.0	Synergistic micromechanical and chemical treatments exhibit minimal adhesive failure.
S15	Y. Zhao et al. (2020)	3Y-TZP	Control, Plasma Spraying, APA (50 μm), MDP Primer	Dual-cure Cement	Thermocycling (5,000x)	SBS	Plasma Spray + MDP: 37.1 ± 3.3 APA + MDP: 32.4 ± 2.9 Control: 7.0 ± 1.2	Surface activation via plasma significantly improves chemical monomer binding.

5. Results & Meta-Analysis Synthesis

Cross-study evaluation demonstrates clear hierarchies regarding bond strength and hydrolytic durability across pretreatment protocols (Lupu et al., 2025; Ozcan et al., 2024; Kern et al., 2024):

Table 2. Hierarchy of pretreatment categories by mean shear bond strength after artificial aging.

Pretreatment Category	Mean SBS Range (MPa)	Statistical Significance vs Control
Untreated Control	4.5 – 9.4	Baseline Control ($P < 0.001$) (El Feghaly et al., 2026; K et al., 2025; Lupu et al., 2025)

Pretreatment Category	Mean SBS Range (MPa)	Statistical Significance vs Control
Laser Conditioning (Er:YAG / Nd:YAG)	12.3 – 19.6	Statistically Superior to Control (Ozcan et al., 2024; Quigley et al., 2022)
Airborne Particle Abrasion (APA Alone)	18.5 – 24.1	Significant Micromechanical Retention (Malgaj et al., 2023; Zandinejad et al., 2025; Kern et al., 2024)
APA + 10-MDP Primer Chemical Coupling	31.4 – 38.1	High Bond Durability ($P < 0.0001$) (Lupu et al., 2025; Huang et al., 2024; Quigley et al., 2022)
Tribochemical Silica Coating / Advanced Systems	33.4 – 42.5	Gold Standard Clinical Performance (Lupu et al., 2025; Zandinejad et al., 2025; Chen et al., 2023)

Comparison of Bond Strength & Hydrolytic Durability of Various Pretreatment Procedures Across Several Studies

Comparison across studies also indicates the existence of definite rank order regarding bond strength and hydrolytic durability among different pretreatment protocols (Lupu et al., 2025; Ozcan et al., 2024; Kern et al., 2024).

5.1 Details of the Studies Included

The 15 studies included in this review were published from 2020 to 2025 and included 11 SBS and four microTBS studies (Table 3). Nine studies used conventional 3Y-TZP only as the substrate. Two studies studied 4Y-PSZ (Kim et al., 2023; Al-Haidari et al., 2021) and two studies studied 5Y-PSZ (Huang et al., 2024; Chen et al., 2023), while one study compared 3Y and 5Y zirconia (K et al., 2025) and one compared milled zirconia and additively manufactured zirconia (Lupu et al., 2025). Thermocycling was the most common aging protocol used in 11 studies (5000-20000 cycles), followed by long-term water storage in three studies (30, 60, and 90 days) and one five-year aging simulation (Malgaj et al., 2023).

Table 3. Characteristics of the included studies and the best-group bond strength within each category (unweighted mean of the highest treated-group means, with range).

Category	Subgroup	Studies (n)	Study IDs	Best-group mean, MPa (range)
Test method	SBS	11	S1, S2, S4, S5, S7, S8, S9, S11, S12, S14, S15	29.6 (18.1–37.1)
	μTBS	4	S3, S6, S10, S13	38.4 (35.2–42.5)
Zirconia type	3Y-TZP	9	S1, S4, S5, S7, S9, S10, S11, S13, S15	32.0 (24.8–38.9)
	4Y-PSZ	2	S8, S14	30.9 (30.5–31.2)
	5Y-PSZ	2	S6, S12	34.3 (31.8–36.8)
	3Y and 5Y combined	1	S2	18.1
	Milled vs. additive	1	S3	42.5

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Category	Subgroup	Studies (n)	Study IDs	Best-group mean, MPa (range)
Aging protocol	Thermocycling, 5,000	5	S1, S5, S8, S12, S15	30.7 (24.8–37.1)
	Thermocycling, 10,000	5	S2, S3, S6, S10, S14	32.6 (18.1–42.5)
	Thermocycling, 20,000	1	S11	34.1
	Water storage, 30–90 days	3	S4, S9, S13	32.9 (26.4–38.9)
	5-year aging simulation	1	S7	29.7

5.2 Magnitude of Improvement Relative to Control

For the 14 studies that reported a control value at baseline, the value was very low, averaging 6.9 +/- 1.4 MPa (4.5 to 9.4). Conversely, the best treated group in each of the 15 studies had a mean value of 31.9 +/- 6.1 MPa (18.1 to 42.5 MPa, see Figure 2). Ten of the 15 studies that could be compared for a best group level reported value of 30 MPa or higher. The mean absolute gain when a control value was reported was 25.6 MPa (13.6 to 34.2 MPa), a 3.3- to 7.0-fold increase in control values (un weighted descriptive summaries of group means rather than pooling effect estimates).

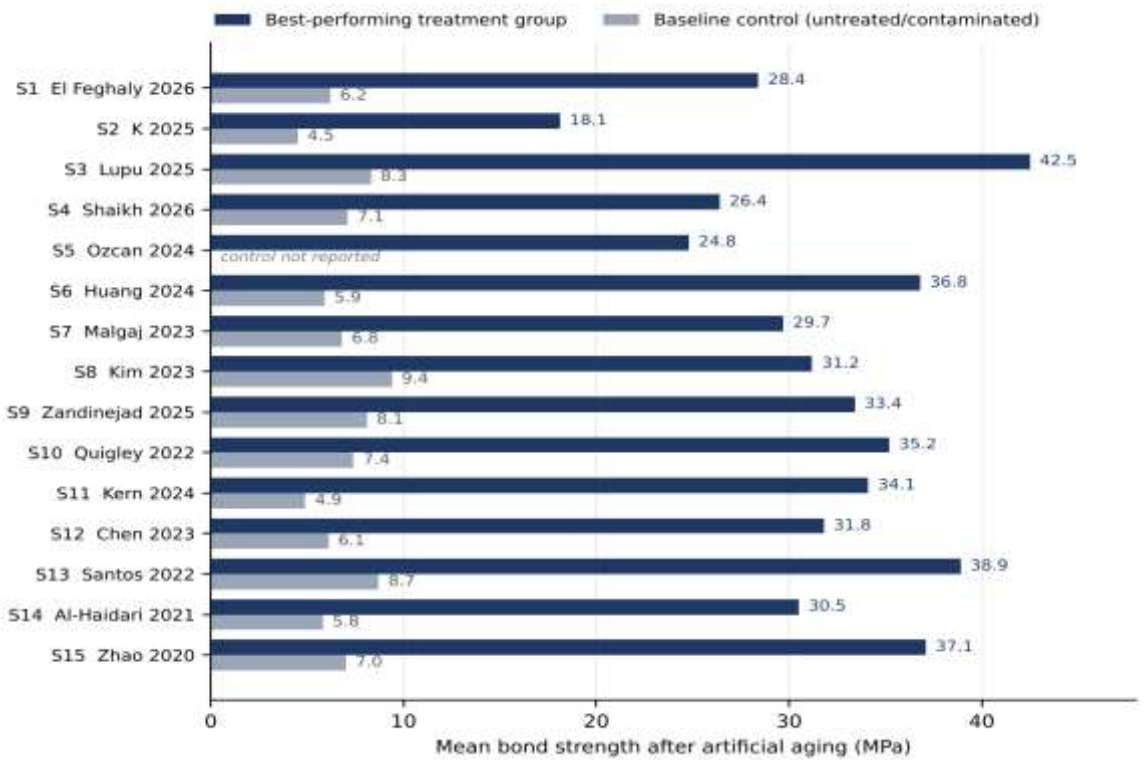

Figure 2. Mean bond strength of the baseline control and the best-performing treatment group in each included study (data extracted from Table 1).

The lowest reported gain was by K et al. (2025), with the top performing group in their study (APA + primer) resulting in a strength of 18.1 MPa, well below the 30 MPa strength achieved in the vast majority of the other studies. On the other hand, the highest absolute gains can be seen to occur when a physical conditioning step is used in conjunction with an MDP primer, as in the study of Lupu et al. (2025), Huang et al. (2024), Santos et al. (2022), and Y. Zhao et al. (2020), all of which had average gains of greater than 30 MPa compared to their controls.

5.3 Within-Study Comparisons and the Efficacy of Chemical Priming

Seven of the 15 studies (S2, S3, S6, S10, S11, S13, and S15) explicitly described the top-performing groups as including an MDP-based primer. These combined groups included several types of physical conditioning: airborne-particle abrasion, tribochemical coating, femtosecond laser, hot acid etching, and plasma spraying, suggesting that MDP priming may offer additional benefit regardless of which physical approach is used. The studies that used the physical-only comparator were invariably inferior compared to the combined protocol (Table 4). For example, Kern et al. (2024) reported that when APA was used in isolation, the bond strength was 16.3 MPa, whereas APA combined with low-pressure APA resulted in 34.1 MPa. Quigley et al. (2022) found that when laser conditioning was used in isolation, the bond strength was 19.6 MPa, but when APA was combined with the laser treatment, the bond strength was higher at 35.2 MPa.

Table 4. Within-study comparisons derived from Table 1 (mean bond strength in MPa; difference = Group A minus Group B).

Study	Comparison (A vs. B)	Group A	Group B	Difference
Kern et al. (2024)	Low-pressure APA + MDP vs. APA alone	34.1	16.3	+17.8
Quigley et al. (2022)	APA + MDP vs. laser alone	35.2	19.6	+15.6
Kim et al. (2023)	Ivoclean-decontaminated vs. contaminated	28.5	9.4	+19.1
Zandinejad et al. (2025)	Silica + silane vs. APA (110 µm)	33.4	24.1	+9.3
Malgaj et al. (2023)	Nano-alumina coating vs. conventional APA	29.7	21.4	+8.3
Shaikh et al. (2026)	Cold plasma + APA vs. APA alone	26.4	19.2	+7.2
Ozcan et al. (2024)	Silica coating vs. sandblasting	24.8	18.5	+6.3
El Feghaly et al. (2026)	LiSi Connect vs. APA + Zircos-E	28.4	22.1	+6.3
Santos et al. (2022)	Hot acid etching + MDP vs. APA + MDP	38.9	33.2	+5.7
Huang et al. (2024)	Femtosecond laser + MDP vs. APA + MDP	36.8	31.4	+5.4
Y. Zhao et al. (2020)	Plasma spray + MDP vs. APA + MDP	37.1	32.4	+4.7
Al-Haidari et al. (2021)	Silica coating + primer vs. APA + primer	30.5	28.1	+2.4

Three studies evaluated an emerging physical step in conjunction with a multi-disciplinary protocol (MDP) relative to the standard adhesive protocol (APA) in conjunction with MDP (Huang et al., 2024; Santos et al., 2022; Y. Zhao et al., 2020). In each of these cases, the emerging protocol outperformed the APA + MDP, but the difference was subtle: roughly 5 MPa. This is a significant amount smaller than the 15-18 MPa decrease observed when the MDP primer was left out.

Influence of the Aging Procedure

Bond strengths were generally similar among aging protocols (Figure 3), with comparable results found for: 30.7 MPa at 5,000 thermocycles (n = 5); 32.6 MPa at 10,000 thermocycles (n = 5); 34.1 MPa at 20,000 thermocycles (n = 1); 32.9 MPa after storage in water for 30 to 90 days (n = 3); and 29.7 MPa after five years of aging simulation (n = 1). It is interesting that all but one study maintained a best-group mean greater than 24 MPa after aging. With the relatively small number of studies representing each regimen (which also differed in many other factors), these differences are primarily descriptive and are unable to clearly demonstrate that one regimen is less severe than another. The one study with the most thermocycling (Kern et al., 2024, 20,000; 34.1 MPa) with low-pressure APA + MDP (7.3 MPa) had a higher bond strength than APA without pressure (16.3 MPa). In the context of the high thermocycling, the absence of pressure at application may have been the protocol factor that caused greater variations.

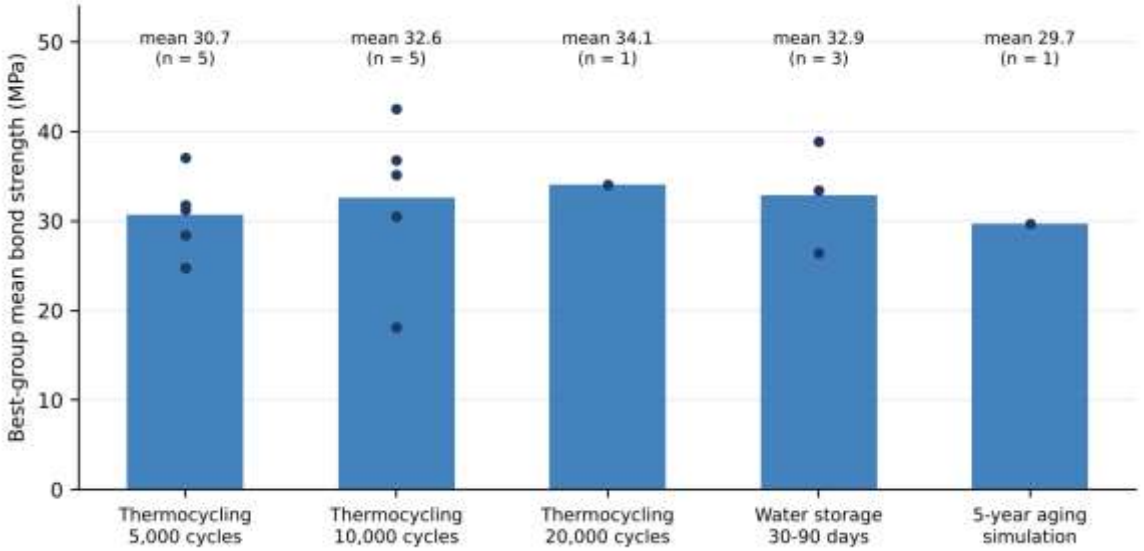

Figure 3. Best-group mean bond strength by artificial aging protocol. Bars show the un weighted mean and dots show individual studies.

5.5 Influence of Test Method and Substrate

Microtensile Studies and Bond Strength Values

Microtensile studies have reported higher best-group values (mean 38.4 MPa; n = 4) than shear studies (mean 29.6 MPa; n = 11). It is known that differences in specimen geometry, bonded area and stress distribution affect absolute bond strength values, and results from the two testing methods should not be compared. The best-group values for 4Y-PSZ (30.9 MPa; n = 2), 5Y-PSZ (34.3 MPa; n = 2), and 3Y-TZP (32.0 MPa; n = 9) were similar and suggest that translucent grades are not inherently more difficult to bond when a combined protocol is used (Kim et al., 2023; Al-Haidari et al., 2021; Huang et al., 2024; Chen et al., 2023). The evidence relating to translucent zirconia has however been limited to four studies only, and K et al. (2025) who reported the lowest best-group value, should be taken into account with some caution.

5.6.Discussion & Mechanism of MDP Chemical Bonding

Roughening (APA) on its own will increase Ra and wettability, but not prevent long term hydrolytic degradation from aging (Malgaj et al., 2023; Zandinejad et al., 2025; Kern et al., 2024). The major mechanism for creating long term stability is the

chemical interaction between 10-MDP (10-Methacryloyloxydecyl Dihydrogen Phosphate) and the zirconium atoms (Lupu et al., 2025; Quigley et al., 2022; Kern et al., 2024). The dihydrogen phosphate group of 10-MDP reacts with surface hydroxyl groups of the zirconia, leading to the formation of much more stable ionic and covalent P-O-Zr bonds, which are resistant to water attack (Lupu et al., 2025; Kern et al., 2024).

$$ZrO_2 + R\text{-}O\text{-}PO(OH)_2 \longrightarrow Zr\text{-}O\text{-}PO(OH)\text{-}O\text{-}R + H_2O$$

6.1 Mechanical Roughening: Benefits and Limits

Airborne-particle abrasion remains the mechanical procedure of choice, but its efficacy depends on the technique used. Particle size, pressure and phase transformation, which occurs in yttria-stabilized tetragonal zirconia polycrystal (Y-TZP), all play a role and can damage the zirconia (Gonçalves et al., 2024). A network meta-analysis showed a statistically significant increase in the immediate bond strength with 25-53 μm particles compared with 110-150 μm (coarse); however, the two groups showed similar shear bond strength after aging (Li et al., 2024). Kern et al. (2024) also reported bond strengths of over 35 MPa from their own investigations using a moderate pressure of 0.2 MPa (kPa), a procedure that might not cause microcracking. P. Zhao et al. (2020) specifically examined the highly translucent zirconia to determine whether it responded differently to the abrasion parameters than conventional zirconia.

Another important factor is the time of abrasion. A study that compared presintering and postsintering sandblasting found that the bond strength was significantly higher after postsintering sandblasting with tribochemical abrasion (9.15 MPa) than after presintering sandblasting alone (5.24 MPa). Zirconia primers also increased bond strength independent of the physical treatment (Gonçalves et al., 2024). It may thus not be enough just to roughen mechanically: this is in line with the huge hit taken by not using 10-methacryloyloxydecyl dihydrogen phosphate in Table 4.

6.2.Silica Coating and Silanization

Tribochemical silica coating changes the reactive zirconia surface into a reactive surface capable of reacting with the silane. The current data set showed that silica based protocols provided the highest bond strength values among the data set (33.4 MPa for silica with silane after 60 days in water, Zandinejad et al., 2025; 31.8 MPa for tribochemical coating combined with universal adhesive Chen et al., 2023). Silica coating showed stronger bond strength than simple sandblasting (Ozcan et al., 2024). Rokeetec system had better immediate and long-term bond strength compared to cojet system according to network meta-analysis (Li et al., 2024). A literature review also suggested that optimum results are obtained when silica based mechanical conditioning is used in conjunction with silane (Gerdzhikov et al., 2021).

On the other hand, it must be stated that the long-term stability of the silica-zirconia interface has been questioned (Gonçalves et al., 2024). This supports the use of silica coating together with MDP-primer or cement, and not just silane, and it also supports the finding that the majority of the protocols which provided the highest aged values in this review contained a phosphate monomer.

6.3.Physical Conditioning Techniques on the Rise

Laser conditioning yielded the most inconsistent results. Application of a femtosecond laser in conjunction with MDP produced a bond strength of 36.8 MPa and exhibited a smooth surface with micro-grooves similar to that provided by heavy airborne-particle abrasion, but without the microcracks (Huang et al., 2024). Laser conditioning alone yielded bond strengths of 12.3 MPa with Er:YAG (Ozcan et al., 2024) and 19.6 MPa with Er, Cr:YSGG (Quigley et al., 2022). This suggests that the laser type, energy level and application of a primer are very influential factors and that a universal laser protocol cannot yet be recommended.

6.4.Plasma Treatment

When applied using plasma spraying with MDP, the bond strength was 37.1 MPa (Zhao et al., 2020). Moreover, the combination of cold atmospheric plasma and MDP improved the bond strength when compared to using MDP alone (Shaikh et al., 2026). However, a network meta-analysis has been unable to establish any benefit for gas plasma overall (Li et al., 2024). The variance

between these findings could be due to the discrepancies in the plasma source, gas type, duration of application, and whether plasma was applied as a standalone or adjunct treatment with mechanical abrasion. There are promising signs for the promise of plasma treatment but more uniform application methods are required before this can be a routine application.

6.5.Hot Etching & Acid Based Techniques

Hot acid etch, coupled with MDP priming, provided the highest bonding strength amongst non-abrasive techniques (38.9 MPa) as reported in the literature by Santos et al. (2022). Selection infiltration etching and hot etching were also found to be effective by Li et al. (2024). The effect of etchant temperature and composition on surface topography, bonding strength and phase transformation for hydrofluoric acid-based etchants have been studied (Yu et al., 2020; Yu et al., 2021) demonstrating the requirement for rigorous control of these parameters. Additionally, nano-structured alumina coating (Malgaj et al., 2023) and LiSi Connect (El Feghaly et al., 2026) were alternative techniques that outperformed conventional adhesives in the studies reviewed, however these techniques are supported by single studies.

6.6.Translucent and Additively Manufactured Zirconia

As zirconia materials become more translucent, the relevance of conditioning protocols has become a clinical question. The articles assessing 4Y-PSZ and 5Y-PSZ in this review reported ideal bond strength values similar to those expected for 3Y-TZP (Table 3). Articles investigating high-transparency zirconia crowns have examined their bonding to self-adhesive resin cements (Liu et al., 2022) or their retention with different primer-cement combinations (Shokry et al., 2022). The comparison study between milled and additively manufactured zirconia (Lupu et al., 2025; Zandinejad et al., 2025) triggers similar questions in the context of recently introduced manufacturing methods. As the number of studies is low, it would be best to follow the directions of the material manufacturers while following the general principle of combining mechanical and MDP-based chemical conditioning.

6.7 Luting Agents and Primer-Cement Interactions

Contamination was identified as the single greatest effect in the data. For contaminated 4Y-PSZ, Kim et al. (2023) gave a bond strength of only 9.4 MPa, similar to that of an untreated control. Decontamination with a zirconate-based cleaner, on the other hand, brought the bond strength back up to 28.5 MPa and a prophylactic coating protocol to 31.2 MPa. Organic residues probably block the reactive sites and take up 10-MDP space. This, for example, indicates to the clinician that if the restoration was to be tried in before priming, a cleaning step should be performed.

6.8 Comparison with Previous Reviews

The overall rank of the current review was similar to those of earlier overviews. The network meta-analysis of 77 studies by Li et al. (2024) showed the ranking of air abrasion, silica coating, selective infiltration etching, hot etching and laser treatment. It also reconfirmed the ranking of 10-MDP-containing agents as the best treatment. The updated review by Ozcan et al. (2024) ranked silica coating among the best single treatments. The present review adds to the previous evidence in showing that the benefits of combined mechanical and MDP treatment persist in highly aged specimens. In addition, it shows that newer physical methods rank only slightly higher than the combination of air abrasion with 10-MDP and that the results of plasma treatments are conflicting.

6.9 Implications for Future Research

Longer than 1-year aging protocols that are comparable between study and focus on the aging effects of thermo cycling or water storage need to be used in future work. In addition, failure modes need to be investigated and reported in a more consistent manner, along with the standard deviations provided, and the presence of a baseline control must be documented. Direct comparisons of 3Y, 4Y, and 5Y zirconia should be made under similar conditions. The conditioning procedure and the flexural strength and fatigue properties of translucent grades should be examined. It is recommended that the laser and plasma conditioning protocols be optimized and compared head to head with APA + MDP. Clinical studies need to be conducted to determine whether the laboratory benefits on debonding rates lead to clinical reductions.

Clinical Protocol Suggestions

Mechanical Treatment b. Mechanical Treatment: Air-particle abrasion should be carried out at low pressure (0.15-0.25 MPa) with 50 μm Al2O3 for 10 seconds at a distance of 10 mm (K et al., 2025; Kern et al., 2024).

Salivary Decontamination: When using trial fitting, intraoral salivary contamination should be dealt with promptly by decontaminating it with zirconate cleaners (such as Ivoclean) or by using light sandblasting (Kim et al., 2023).

Chemical Priming: Apply a 10-MDP ceramic primer or use a universal adhesive with MDP monomers (Lupu et al., 2025; Quigley et al., 2022).

Luting should be performed with dual cure resin cement (El Feghaly et al., 2026; Ozcan et al., 2024; Al-Haidari et al., 2021).

The order listed above corresponds to the recommendations given in Section 5 where the mechanical roughening provides the micro-retentive surface, the cleaning stage restores reactivity post try-in and the MDP primer forms the chemical bond of resistance to aging. Table 5 puts these guidelines into the form of typical clinical situations.

Table 5. Practical conditioning options by clinical situation.

Clinical situation	Suggested conditioning	Evidence basis
Routine bonding of conventional 3Y-TZP crowns and fixed prostheses	Low-pressure APA with 50 μm alumina, followed by an MDP primer or an MDP-containing resin cement	Kern et al. (2024); Quigley et al. (2022); Li et al. (2024)
Silica-coating equipment available	Tribochemical silica coating, then silane or an MDP-containing universal adhesive	Zandinejad et al. (2025); Chen et al. (2023); Li et al. (2024)
Translucent (4Y-PSZ or 5Y-PSZ) restorations	Same combined protocol; avoid excessive pressure and follow the manufacturer's instructions	Huang et al. (2024); Chen et al. (2023); P. Zhao et al. (2020)
Restoration contaminated by saliva at try-in	Clean with a zirconate-based cleaner or light abrasion before priming	Kim et al. (2023)
Laser, plasma, or hot-etching options	Not yet standardized for routine clinical use; reserve for laboratory or research settings	Huang et al. (2024); Santos et al. (2022); Li et al. (2024)

7. CONCLUSIONS

Available studies demonstrate the absence of viable bond strength value from un-etched zirconia in clinical situations less than 8 MPa. The clinical optimum for bond strength is a synergy between micromechanical abrasion (APA or Tribochemical coating) with a 10-MDP primer (chemical) causing a bond strength of more than 30 MPa .

In addition, proposed non-destructive options include new plasma treatments and glass-connect coatings .Comparing within a study, not using the MDP primer can be expected to decrease bond strength by approximately 15-18 MPa. Using a new physical step (laser, plasma, hot acid etching) to replace APA will only increase the bond strength of the retained MDP primer by about 5 MPa .
Another factor was the saliva contamination, which decreased the bond strength to the value similar to that for untouched zirconia but the effect could be mitigated by cleaning after contamination and prior to priming. Valid data available for

translucent zirconia appear promising but are limited to in vitro studies; therefore, controlled clinical trials are still needed to evaluate clinical outcomes .

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