Japanese Dental Science Review 59 (2023) 138–159

Contents lists available at ScienceDirect

Japanese Dental Science Review

journal homepage: www.elsevier.com/locate/jdsr

Zirconia bond strength durability following artificial aging: A systematic review and meta-analysis of in vitro studies☆

Athanasios E. Rigos [a], Katia Sarafidou [b], Eleana Kontonasaki [c,*]

[a] Resident, Graduate Prosthodontics, Texas A&M School of Dentistry, Dallas, TX, USA
[b] Postdoctoral Researcher, Department of Prosthodontics, School of Dentistry, Faculty of Health Sciences, Aristotle University of Thessaloniki, Greece
[c] Associate Professor, Department of Prosthodontics, School of Dentistry, Faculty of Health Sciences, Aristotle University of Thessaloniki, Greece

ARTICLE INFO

Article history:
Received 21 July 2022
Received in revised form 27 March 2023
Accepted 19 April 2023

Keywords:
Zirconia bonding
Alumina sandblasting
Tribochemical silica coating
Aging
MDP cement
MDP primer
Resin

ABSTRACT

The present study systematically reviewed the literature regarding the bond strength durability of zirconia ceramics to resin-based luting cements after application of different bonding protocols and aging conditions. Electronic searches in PubMed, Scopus, and Web of Science databases were performed for relevant literature published between January 1st 2015 and November 15th 2022. Ninety-three (93) English language in-vitro studies were included. The percentage of the mean bond strength change was recorded prior to and after artificial aging, and the weighted mean values and 95% confidence intervals were calculated. Bonding protocols were classified based on the combination of MDP/non-MDP containing cement/primer and surface pretreatment, as well as the level of artificial aging performed. Alumina sandblasting (SA) was identified as the most frequently used surface pre-treatment while an insufficient number of studies was identified for each category of alternative surface treatments. The combination of MDP cement with tribochemical silica coating (TSC) or SA yielded more durable results after aging, while the application of SA and TSC improved bond durability when a non-MDP cement and a non-MDP primer were used. TSC may lead to increased bond durability compared to SA, whereas MDP cements may act similarly when combined with SA or TSC.

Contents

☆ Scientific field of dental Science: Prosthodontics.

* Correspondence to: Department of Prosthodontics, School of Dentistry, Faculty of Health Sciences, Aristotle University of Thessaloniki, 54124, Greece.
E-mail address: kont@dent.auth.gr (E. Kontonasaki).

https://doi.org/10.1016/j.jdsr.2023.04.002

1. Introduction

Zirconia ceramics present the highest mechanical properties among all-ceramic materials used in dentistry and hence combine favorable esthetics with increased strength [1]. One of the major complications reported for zirconia restorations is loss of retention [2]. This has been attributed to the inability of zirconia ceramics to be roughened with the use of hydrofluoric acid (HF) because they don't contain silica [3], and thus the question of the appropriate bonding protocol has not been answered yet [4]. As an oxide that does not contain silica, zirconia requires different pre-treatment of the internal surface prior to cementation, compared to silica containing ceramics such as lithium disilicate.

The effect of several surface treatments, cements and primers on the bond strength of zirconia has been the topic of extensive research. In vitro studies have evaluated a wide range of different adhesive protocols but there is lack of evidence to support one of them in clinical practice. Nonetheless, alumina sandblasting (SA), tribochemical silica coating (TSC) and the use of MDP containing cements and primers have been proposed as more effective in achieving a strong bond [5,6]. However, there are still conflicting findings in terms of bond durability after artificial aging and/or water storage.

Several testing methods - shear, tensile, push-out bond strength tests and the Brazil nut method [7,8] - have been used to evaluate the bond strength of zirconia to luting cements. The present systematic review and meta-analysis aims to identify a correlation between the difference of the bond strength following artificial aging, such as water storage (WS) or thermal cycling (TC), and a particular surface treatment or luting cement by classifying studies based on the type of cement, primer or surface treatment. The primary goal was to identify whether the application of different bonding protocols – sandblasting surface pretreatment (SA), tribochemical silica coating (TSC), use of an MDP or non-MDP cement, use of an MDP or non-MDP primer – can yield durable bond strength after different types of thermal cycling. Although there is no ISO standard or other consensus in literature defining the term "durable bond", it is important, as a first step, to systematically investigate the percentage of change in bond strength after application of different bonding strategies and thermal cycling. Based on this, the purpose of this review and meta-analysis was to evaluate the bond strength change of zirconia ceramics to resin-based luting cements after the application of various bonding protocols and thermal cycling. The null hypothesis of the study was that the application of different bonding protocols and thermal cycling would not significantly affect the bond strength of zirconia ceramic to resin-based luting cements.

2. Materials and methods

The PRISMA (Preferred Items for Reporting Systematic Reviews and Meta-Analyses) search strategy was adopted for the conduction of the present systematic review. The question to be addressed was: 'Among different adhesive cementation protocols and pretreatment methods of zirconia ceramics to resin-based luting cements, which one ensures the least mean bond strength change after artificial aging?'.

The PICO method was adopted to state the scope of the review accurately. Participants in the study included zirconia specimens, Interventions consisted of the zirconia surface treatment method and the luting cement used, Comparators comprised of the control group of each study (where control was considered the study group that was named control by the authors of each individual study) and the artificially aged groups, and Outcomes were considered the values of the Shear and Tensile Bond Strength. Three databases (PubMed, Scopus and Web of Science) were searched by two independent reviewers (TR and KS). The reference lists of all articles that were selected for full text evaluation were also screened manually. The search terms were: ((monolithic zirconia) OR (zirconia) OR (YTZP) OR (Y-TZP) OR (YPSZ) OR (Y-PSZ)) AND ((luting cement) OR (cementation) OR (resin cement) OR (composite resin cement)) AND ((bond strength) OR (shear bond strength) OR (microshear bond strength) OR (tensile bond strength) OR (micro-tensile bond strength)) AND ((aging) OR (hydrothermal treatment) OR (water) OR (thermal cycling)).

Inclusion criteria were: in-vitro studies, studies in English language published between January 1st 2015 and November 2022, studies performing in-vitro shear or tensile bond strength test regardless of their micro- or macro- classification, studies reporting on zirconia specimens with a disc or block geometry, studies including a control group (baseline) of artificial aging with a performance time span of 0–7 days, studies performing artificial aging in water storage (37 °C) for a minimum of 6 months or thermal cycling, or a combination of the above mentioned protocols and studies containing groups with ≥ 5 samples. The following types of studies were excluded: systematic reviews, meta-analyses, clinical studies, studies testing zirconia abutments, studies evaluating indirect composite materials, repaired zirconia or orthodontic bracket bond strength, studies evaluating the bond strength of zirconia ceramics to dentin or enamel, studies including loading (chewing simulators), studies not stating the exact zirconia ceramic product or articles using commercially unavailable (experimental) zirconia, studies investigating glass infiltrated zirconia, zirconia reinforced lithium disilicate or other zirconia-based ceramics, studies not reporting numerical mean bond strength values with standard deviation, studies investigating the effects of saliva contamination, silicone disclosing materials or zirconia coloring on the bond strength. Since there is no standard risk of bias tool to assess the methodological quality of in-vitro studies to date, strict inclusion and exclusion criteria were applied. Disagreements among the reviewers (TR, KS) were resolved by discussion and then by consulting a third author (EK) for arbitration.

Data extraction was also undertaken independently to minimize the likelihood of error and in order to reduce bias. Extracted data were recorded in supplementary Tables 1 and 2 as they were divided in shear bond strength studies and tensile bond strength studies respectively. Descriptive analysis was performed using the R statistical software. From all the included studies, mean and standard deviation values for the outcome of bond strength were extracted. Then, pooled mean difference and 95% confidence intervals were calculated for different factors: surface treatment (SA + no other surface treatment, SA + other surface treatment, TSC+ no other surface treatment, TSC + other surface treatments, no SA + no other surface treatment, SA + other surface treatments), aging (WS, TC < 10000, TC≥10000, WS + TC < 10000, WS + TC≥10000) and cement/primer combination (MDP cement + MDP primer, MDP cement + non-MDP primer, non-MDP cement + MDP primer, Non-MDP cement + non-MDP primer, MDP cement-no primer, Non-MDP cement-no primer). Moreover, the percentage of change in mean bond strength was calculated in each group with the same surface treatment, cement/primer combination and aging.

3. Results

The electronic search and hand search concluded in 1227 records, 1142 through the electronic search and 85 through manual search. After duplicates removed 536 articles were selected for screening, from which 354 abstracts were evaluated. Finally, 169 articles were subjected to full-text assessment. The excluded articles after full-text analysis and reasons for exclusion are given in Table 1. Eventually, 93 studies fulfilled the inclusion criteria and were included in this review (Fig. 1, Supplementary tables 1 and 2).

Table 1
Excluded studies after full-text evaluation and reasons for exclusion.

Not reporting arithmetic bond strength values		
da Silva 2021 [9]	Yang et al. 2020 [17]	Bielen et al. 2015 [24]
Lima et al. 2019 [10]	Al-Dobaei et al. 2020 [18]	Kim 2019 [25]
Chen et al. 2017 [11]	Yang et al. 2018 [19]	Piest 2018 [26]
Aboushelib et al. 2018 [12]	Chen et al. 2019 [20]	Aggarwal et al. 2018 [27]
Lima et al. 2019 [13]	Vechiato-Filho et al. 2017 [21]	Tsujimoto et al. 2017 [28]
Zhang et al. 2021 [14]	Xie et al. 2016 [22]	Khanlar et al. 2022 [29,30]
Tzanakakis et al. 2021 [15]Müller et al. 2022 [16]	Yu 2021 [23]	Garcia et al. 2022 [31]
All specimens were subjected to aging, no non-aged control		
Steiner et al. 2019 [32]	Lümkemann et al. 2019 [37]Pozzobona et al. 2015 [38]	Alnassar et al. 2016 [42]
Yenisey et al. 2016 [33]	Liebermann et al. 2018 [39]	Alnassar et al. 2017 [43]
Al-Harbi et al. 2016 [34]	Kim et al. 2015 [40]	Kaimal et al. 2017 [44]
Sousa et al. 2016 [35] Lümkemann et al. 2020 [36]	Vicente et al. 2016 [41]	Fernandes Neto et al. 2022 [45]
		Sriamporn et al. 2022 [46]
Not reporting arithmetic bond strength values for all groups		
Shafiei et al. 2019 [47]	Byeon et al. 2017 [48]	
No aging		
Chen et al. 2017 [49]	Qian et al. 2016 [54]	Nagaoka et al. 2017 [59]
Yu et al. 2019 [50]	Takahashi et al. 2018 [55]	Cho et al. 2017 [60]
Murakami et al. 2017 [51]	Özdemir et al. 2019 [56]	Chen et al. 2016 [61]
Şanlı et al. 2015 [52]	Llerena-Icochea et al. 2017 [57]	Wei et al. 2018 [62]
Noro et al. 2015 [53]	Park et al. 2017 [58]	Kim et al. 2022 [63]
Only median bond strength values reported (no mean values)		
Kim et al. 2016 [64]	Bömicke et al. 2016 [66]	
Samran et al. 2019 [65]	Sawada et al. 2016 [67]	
No standard deviations reported		
Diniz et al. 2019 [68]	Malgaj et al. 2019 [69]	
Zirconia product name not reported / experimental product		
Sathish et al. 2019 [70]	De Araujo Neto et al. 2022 [71]	Malgaj et al. 2021 [72]
Bonding to enamel or zirconia to zirconia		
Liu et al. 2016 [73]	Thammajaruk et al. 2021 [74]	
Not an original research paper		
Scribante et al. 2016[75]		
Sample size < 5 specimens or not reporting sample size		
Akay et al. 2019 [76]	Gutierez et al. 2020 [78]	Silva et al. 2016 [79]
Lee MH et al. 2021 [77]		
Layered with composite resin, not cemented with a luting cement		
Sarfaraz et al. 2020 [80]	Li et al. 2020 [81]	Ataol et al. 2018 [82]
Zirconia samples were bonded following artificial aging		
Moqbel NM et al. 2022 [83]		
Contaminated samples with saliva prior to bonding		
Rui L et al. 2021 [84]		

From the 93 studies, 73 reported results of shear tests and 20 from tensile tests, while one study reported results from both shear and tensile tests[85]. In the shear testing group mean bond strength ranged between 1.3 [86] and 60.64 MPa[87] for control groups, and between 0.00 [88,89]and 47.58 [87] for artificially aged groups. Furthermore, the number of specimens per group (n) ranged between n = 7 [90] and n = 20 samples [87,91–95]. Twenty (20) studies performing tensile testing were included in the present review (Supplementary Table 2). In 13 of them, specimens were fabricated with a bonding area of > 7 mm^2 and < 28 mm^2 [85,96–107], while in 7 of them the bonding area was < 2 mm^2 (microtensile) [108–114] Mean bond strength ranged between 4.41 [115] and 90.88 MPa [112] for control groups, and between 0[115] and 90.12 [112] for artificially aged groups. Furthermore, the number of specimens per group (n) in the 20 tensile bond strength test studies ranged between 5 and 30 samples.

Mean difference and 95% confidence intervals (95% CI) of bond strength are presented in Figs. 2–4 while the percentage of change is depicted in Tables 2 and 3.

The included studies were grouped according to surface treatment, aging protocol, and the cement/primer combination applied. Seven studies [88,89,105,115,154,157,177] included groups that presented instant debonding following aging and those groups were excluded from the pooled mean difference calculation. In general, the bond strength was significantly reduced by artificial aging in most groups, especially for aging protocols including a combination of WS and TC.

3.1. Shear group

In cases where SA was applied with no other surface pre-treatment (SA+NOST), 7 studies[137,147,148,160,161,162,171] in the shear test group showed no significant difference of bond strength after aging, while mean pooled difference of groups based on cement/primer combination showed significant differences in all groups (Fig. 2A, Table 2). Four of them presented increase [86,137,147,162]. When SA was used with additional surface pre-treatments (SA + OST), mean pooled difference showed significant changes in all groups, while only 1 study[171] showed no significant mean difference of bond strength after aging and (Fig. 2B). In this study, the combination of MDP cement + non-MDP primer was used. When no SA and no other surface treatment was applied (no SA+NOST), 6 studies from the shear test group showed no significant change in bond strength after aging and even increase (Fig. 2C) [85,122,123,143,162,169]. The combinations of MDP cement with MDP primer and Non-MDP cement with MDP primer showed negative mean pooled difference. In cases where treatments other than SA or TSC were used (no SA + OST) in the shear test group, 3 studies using a non-MDP cement + non-MDP primer [128,131] or non-MDP cement + no primer[130] presented a non-significant increase in the bond strength after aging (Fig. 2D). Groups from these studies showed increase in bond strength after aging.

In cases where TSC was applied only (TSC+NOST), 11 out of 23 studies in the shear test group showed no significant difference of the bond strength after aging (Fig. 3A, Table 2), while 2 studies

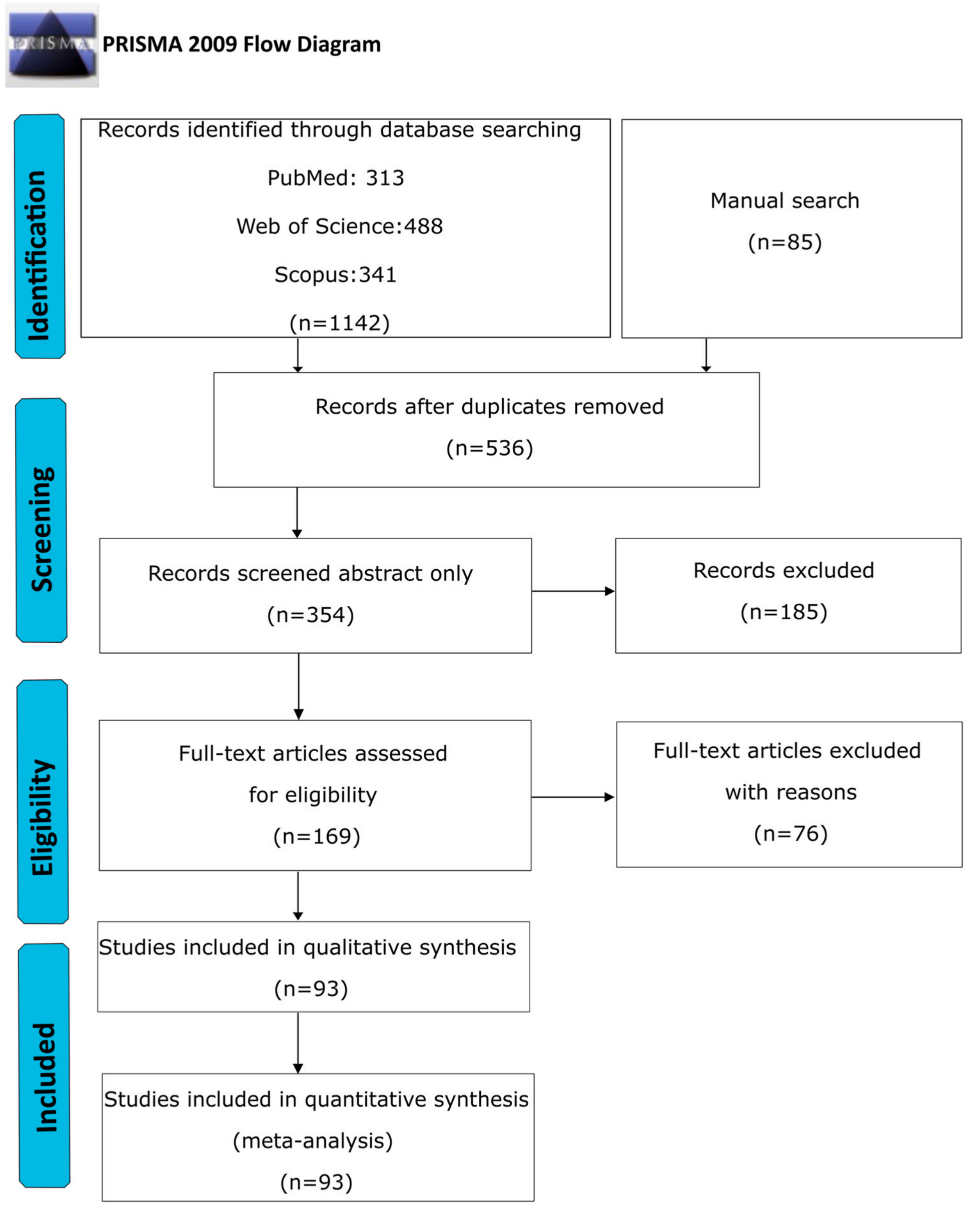

Fig. 1. PRISMA flow diagram.

[94,131] showed slight increase in bond strength. Mean pooled difference showed significant decrease in most of the cement/primer combination groups irrespectively of the aging process. In the study of Cadore-Rodriguez et al.[94], a significant increase was observed even after WS + TC≥ 10000 cycles. When TSC was used combined with other surface treatments, 1[91] out of 6 studies in the shear test group showed increase in bond strength after aging and three no significant difference [88,89,91] (Fig. 3B).

3.2. Tensile group

In cases where SA was applied with no other surface pre-treatment, all studies (20) in the tensile group showed decrease in strength after aging, with the least being observed in the study of Thammajaruk et al.[178] [95%CI 0.76 (−7.74,9.26)] which included the combination of MDP cement + MDP primer (Fig. 4A). When SA was used with additional surface pre-treatments (SA+OST), all 2 [113,178] studies in the tensile test group showed significant mean pool difference of bond strength after aging (Fig. 4 C).

When no surface treatment was applied (No SA+NOST), in the tensile group only 1[85] out of 14 study groups showed slight increase in bond strength and included the combination of MDP cement + no primer (Fig. 4B). The rest of the studies showed significant decrease in bond strength after aging. In cases where treatments other than SA or TSC were used (No SA+OST), in the tensile test group, all 3 studies presented significant decrease in bond strength (Fig. 4D)[102,110,111] In cases where TSC was applied only (TSC+NOST), 3 out of 8 study groups involved in the tensile test group showed no significant difference of the bond strength after aging (Fig. 4E), showing in fact slight increase after aging [MDP cement + non-MDP primer (2 studies)[85,109], non-MDP cement + non-MDP primer[85] (1 study).

3.3. Non-MDP cement and non-MDP primer

When non-MDP cement and non-MDP primer was used and no SA was applied in the shear group (No SA+NOST/ No SA+OST), the decrease of bond strength was < 63.3% in most of the studies, while 3 studies showed increase in bond strength [123,128,131] (Table 2).

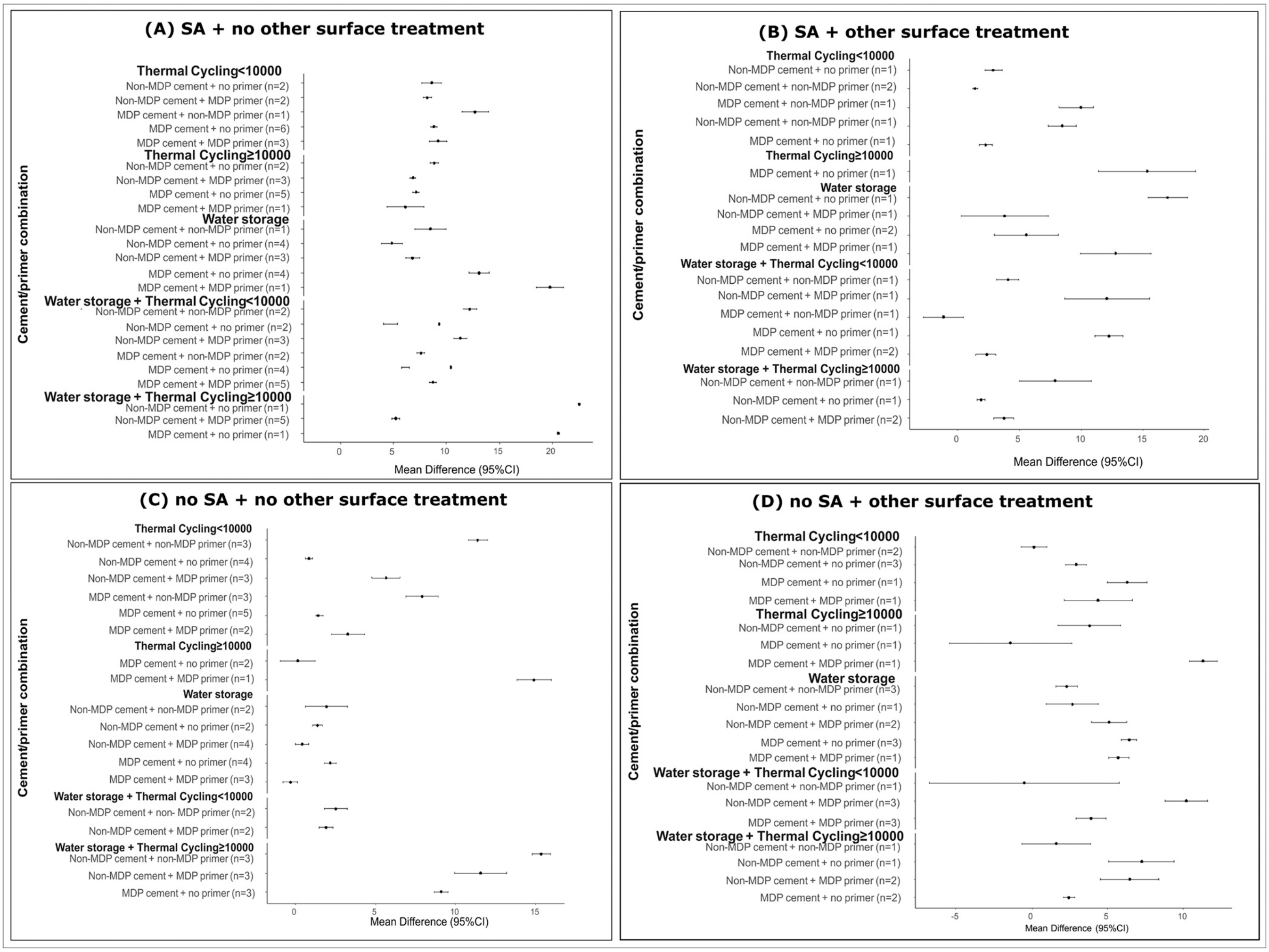

Fig. 2. Mean Difference of bond strength between control group and aging group from studies including shear tests for zirconia-resin bond strength evaluation. Classification was based on whether SA was applied or not in combination with or without other surface treatments and studies were grouped based on different cement/primer combinations. Error bars represent the 95% confidence intervals of mean difference. (A) SA + no other surface treatment, (B) SA + other surface treatment, C) no SA + no other surface treatment, (D) no SA + other surface treatment.

Similarly, in the tensile test group, the same group presented the lowest percentage of change. However, when SA was applied (SA+-NOST and SA+OST), the decrease of bond strength was ≤ 50.9% in five out of six studies for shear test [95,116,117,119,159] and below 42.2% in 4 out of 5 study groups for the tensile test (Tables 2 and 3) [96,100,107,114]. The decrease was more than double (83.4%) in the study of Elsayed et al., 2017[100], when they increased TC above 10000 cycles. Interestingly, the application of other surface treatments without SA (no SA+OST) resulted in low bond strength decrease, ranging from 7.1% to 23.7% in the shear test group[116,127,129], while in 2 studies an increase after aging was observed[128,131]. When TSC was applied with no other surface pre-treatment (TSC+NOST), all studies presented low bond strength decrease (≤28.6%), for both shear (8 studies)[85,89,122,127,129,130,132,133,145] and tensile (3 studies)[108,111,114] test groups, while in 1 study in the tensile group[85], and in 1 study in the shear group[131] an increase in bond strength was recorded.

3.4. Non-MDP cement +No primer

Several studies investigated the bond strength before and after aging, with the application of non-MDP cement for bonding alone without primer (Table 2). A trend towards low mean pooled difference is observed irrespectively of the aging process when SA was applied. When SA was used with no additional surface pre-treatment (SA+NOST), in 3[116,134,139]out of 8 studies in shear test and the 3 [103,104,108] studies in the tensile test groups revealed ≤ 42.3 decrease of bond strength as a result of different aging processes, while 2 studies showed 82.4[136] and 96.8%[117] decrease in the shear group (Tables 2 and 3). In the samples where SA was not applied, great variation of the received percentage of change cannot give any conclusive result from both shear and tensile tests. This variation was evident also when OST or TSC was applied. In 1 study however[130], an increase (−6.1%) in bond strength was calculated for the specimens that were immersed in an aqueous suspension of aluminum nitride powder for 15 min at 75 °C, however not statistically significant compared with the non-aged group.

3.5. Non-MDP cement + MDP-primer

With the use of a non-MDP cement and an MDP-primer, SA application resulted in 8[94,117,136,139,146,148,149] out of 11 studies presenting bond strength change ≤ 39.6% in the shear test group and ≤ 49.9% in the 9 studies [96,100,101,104,105,107,109,110] included in the tensile test group (Tables 2 and 3). The great heterogeneity of the percentage of change values (−24.3 to 100%) in the specimens where SA was not applied, does not allow any conclusive result. When other treatments were applied without SA, 2 studies out of 8 that used

Table 2
Mean difference (95% CI) and % change of bond strength before and after aging in studies included in the shear test group.

Non-MDP cement + non-MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging**			**Aging**			**Mean difference**	**% Change**
			Total No	**Mean**	**SD**	**Total No**	**Mean**	**SD**	**(95% CI)**	
SA + NOST	**WS**	Su et al 2021[116]	10	12.27	2.11	10	8.65	2.23	3.62 (1.72, 5.52)	30
	WS+TC <10000	Chuang et al 2017[117]	24	17.03	2.36	24	8.36	1.53	8.67 (7.54, 9.79)	50.9
		Silveira et al 2022[95]	120	22.20	4.85	120	14.09	4.61	8.11 (6.91, 9.30)	36.5
		Pooled Mean Difference (95%CI)							*6.14 (5.76, 6.51)*	
SA + OST	**TC <10000**	Kang et al 2022[89]	20	9.75	2.50	20	1.30	0.45	8.45 (7.34, 9.56)	86.7
	WS+TC <10000	Lee et al 2015[118]	30	10.72	1.15	30	6.65	2.23	4.07 (3.17, 4.97)	38
	WS+ TC ≥10000	Akazawa N et al[119]	11	20.50	4.30	11	12.60	2.40	7.90 (4.99,10.81)	38.5
No SA+ NOST	**TC <10000**	Yagawa et al 2018[120]	88	20.11	3.47	88	3.54	1.05	16.57 (15.82, 17.33)	82.4
		Rebholz-Zaribaf et al 2016[85]	15	12	4.2	15	4.4	1.7	7.60 (5.31, 9.89)	63.3
		Ramos 2020[121]	15	2.7	2	15	0.3	0.5	2.40 (1.36, 3.44)	88.9
		Pooled Mean Difference (95%CI)							*11.40 (10.81, 11.99)*	
	WS	Su 2021[116]	10	4.35	1.44	10	2.38	1.67	1.97 (0.60, 3.34)	45.3
		Oliveira-Ogliari et al 2015[122]	20	14	8	20	12.4	5.4	1.60 (-2.63, 5.83)	11.4
		Pooled Mean Difference (95%CI)							*1.94 (0.64, 3.24)*	
	WS+ TC <10000	Pott et al 2016[123]	30	10.8	5.37	30	12.1	3.53	-1.30 (-3.60, 1.00)	-12*
		Zhao et al 2022[124]	12	7.53	0.59	12	5.50	0.47	2.03 (1.60, 2.45)	26.9
		Pooled Mean Difference (95%CI)							*2.53 (1.83, 3.24)*	
	WS+ TC ≥10000	Noda et al 2017[125]	12	18.6	4.4	12	2.4	1.2	16.20 (13.62, 18.78)	87.1
		Kim et al 2015[92]	20	8.5	4.6	20	0.3	0.1	8.20 (6.18, 10.22)	96.5
		Alegria Acevedo et al 2022[126]	60	29.97	1.32	60	13.97		16.00 (15.38, 16.62)	53.4
		Pooled Mean Difference (95%CI)							*15.36 (14.78, 15.94)*	
No SA + OST	**TC <10000**	Lung et al 2015[127]	24	10.58	1.44	24	9.63	2.33	0.95 (-0.15, 2.04)	8.9
		Abdalla et al 2019	12	11.7	1.3	12	12.7	1.9	-1.00 (-2.30, 0.30)	-8.5*
		Pooled Mean Difference (95%CI)							*0.14 (-0.70, 0.98)*	
	WS	Lung et al 2015[127]	24	10.58	1.44	24	9.06	1.48	1.52 (0.69, 2.35)	14.4
		Su et al 2021[116]	10	21.28	3.03	10	16.23	2.17	5.05 (2.74, 7.36)	23.7
		Oliveira-Ogliari et al 2015[122]	120	29.7	6.7	120	25.17	7.78	4.53 (2.69, 6.36)	15.2
		Pooled Mean Difference (95%CI)							*2.32 (1.60, 3.04)*	
	WS+ TC <10000	Campos et al 2016[128]	10	3.31	2.67	10	3.8	9.71	-0.49 (-6.73, 5.75)	-14.8*
	WS+ TC ≥10000	Wandscher et al 2016[129]	30	22.45	5.2	30	20.85	3.7	1.60 (-0.68, 3.88)	7.1
TSC + NOST	**TC <10000**	Lung et al 2015[127]	8	15.93	1.17	8	12.6	2.17	3.33 (1.62, 5.04)	20.9
		Thammajaruk et al 2020[130]	15	38.6	8	15	33.4	5.1	5.20 (0.40, 10.00)	13.5
		Rebholz-Zaribaf et al 2016[85]	30	10.15	4.55	30	7.25	4.4	2.90 (0.64, 5.16)	28.6
		Abdalla et al 2019[131]	12	10.2	1.2	12	12	1	-1.80 (-2.68, -0.92)	-17.6 *
		Pooled Mean Difference (95%CI)							*-0.20 (-0.93, 0.53)*	
	TC ≥10000	Thammajaruk 2020[130]	15	38.6	8	15	31.7	5.4	6.90 (2.02, 11.78)	17.9
	WS	Lung et al 2015[127]	8	15.93	1.17	8	14.5	2.38	1.43 (-0.41, 3.27)	9
		Oliveira-Ogliari et al 2015[122]	30	33.3	9	30	28.17	7.27	5.13 (0.99, 9.27)	15.4
		Pooled Mean Difference (95%CI)							*2.04 (0.36, 3.72)*	
	WS+ TC ≥10000	Wandscher et al 2016[129]	15	19.9	5.3	15	18.7	3.8	1.20 (-2.10, 4.50)	6
		Chen et al 2020[132]	30	14.33	1.17	30	13.67	1.53	0.67 (-0.02, 1.36)	4.7
		Qeblawi et al 2015[133]	10	31.9	4.6	10	22.8	3.5	9.10 (5.52, 12.68)	28.5
		Pooled Mean Difference (95%CI)							*0.98 (0.31, 1.64)*	
	TC<10000	Kang et al 2022[89]	10	19.80	2.00	10	17.10	2.30	2.70 (0.81, 4.59)	13.6
TSC + OST	**WS+ TC <10000**	Dal Piva et al 2019[91]	20	15.8	7	20	2.8	2.3	13.00 (9.77, 16.23)	82.3

(continued on next page)

Table 2 (*continued*)

Non-MDP cement + non-MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging**			**Aging**			**Mean difference**	**% Change**
			Total No	**Mean**	**SD**	**Total No**	**Mean**	**SD**	**(95% CI)**	
Non-MDP cement + no primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA + NOST	**TC <10000**	Feitosa et al 2015[134]	12	20.5	8.39	12	14.5	3.27	6.00 (0.91, 11.09)	29.3
		Mano et al 2020[135]	30	6.07	2.83	30	2.43	1.8	3.63 (2.43, 4.83)	59.8
		Pooled Mean Difference (95%CI)							*3.76 (2.59, 4.93)*	
	TC ≥10000	Yang et al 2018[136]	30	4.99	1.1	30	0.88	1.01	4.11 (3.58, 4.64)	82.4
		Pitta et al 2018[137]	20	17.05	4.99	20	13.15	2.14	3.90 (1.52, 6.28)	22.9
		Pooled Mean Difference (95%CI)							*4.10 (3.58, 4.62)*	
	WS	Su et al 2021[116]	10	13.38	2.38	10	8.12	1.97	5.26 (3.35, 7.17)	39
		Feitosa et al 2015[134]	12	20.5	8.39	12	6.8	1.76	13.70 (8.85, 18.55)	67
		Lopes et al 2016[86]	12	14.60	4.90	12	16.00	4.80	-1.40 (-5.28, 2.48)	-9.6*
		Soto Montero et al 2022[138]	20	11.90	3.45	20	23.20	3.35	-11.30 (-13.41, -9.19)	94.9
		Pooled Mean Difference (95%CI)							*9.55 (8.30, 10.80)*	
	WS+ TC <10000	Liu et al 2020[139]	10	17.19	1.12	10	13.74	1.09	3.45 (2.48, 4.42)	20.1
		Chuang et al 2017[117]	12	5.99	1.49	12	0.19	0.6	5.80 (4.89, 6.71)	96.8
		Pooled Mean Difference (95%CI)							*4.70 (4.04, 5.36)*	
SA + OST	**TC <10000**	Lee et al 2015[140]	12	6.6	1.1	12	3.7	0.6	2.90 (2.19, 3.61)	43.9
	WS	Sanal et al 2020[141]	30	18.33	4.48	30	1.34	0.57	16.99 (15.38, 18.61)	92.7
	WS+ TC ≥10000	Akazawa et al 2017[119]	11	2.4	0.5	11	0.5	0.1	1.90 (1.60, 2.20)	79.2
No SA + NOST	**TC <10000**	Yagawa et al 2018[120]	22	13.9	2.6	22	0.15	0.1	13.75 (12.66, 14.84)	98.9
		Gomes et al 2015[88]**	15	7.5	5.6	15	0	0	7.5	100
		Lee et al 2015[142]	50	3.32	0.61	50	3.07	0.53	0.25 (0.03, 0.48)	7.6
		Lee et al 2015[140]	12	34.7	4.1	12	29.8	3.9	4.90 (1.70, 8.10)	14.1
		Rebholz-Zaribaf et al 2016[85]	30	12.1	5.2	30	6.3	4.3	5.80 (3.39, 8.21)	47.9
		Pooled Mean Difference(95%CI)							*0.86 (0.64, 1.08)*	
	WS	Zhao L et al 2016[143]	16	4.16	0.59	16	2.83	0.22	1.33 (1.03, 1.64)	32.1
		Su et al 2021[116]	10	5.23	1.39	10	2.57	1.72	2.66 (1.29, 4.03)	50.9
		Pooled Mean Difference(95%CI)							*1.40 (1.10, 1.70)*	
No SA + OST	**TC <10000**	Thammajaruk et al 2020[130]	15	27.7	5.2	15	29.4	6.7	-1.70 (-5.99, 2.59)	-6.1*
		Gomes et al 2015[88]	15	5.7	2.3	15	1.8	3.8	3.90 (1.65, 6.15)	68.4
		Lee et al 2015[140]	60	14.9	2.26	60	11.94	1.86	2.96 (2.22, 3.70)	19.9
		Pooled Mean Difference (95%CI)							*2.93 (2.23, 3.62)*	
	TC ≥10000	Saade et al 2020[144]	28	30.95	4.05	28	27.15	3.9	3.80 (1.72, 5.88)	12.3
	WS	Su et al 2021[116]	10	10.59	1.91	10	7.91	1.98	2.68 (0.97, 4.39)	25.3
	WS+ TC ≥10000	Druck et al 2015[145]	24	10.33	4.73	24	3.07	2.53	7.26 (5.12, 9.41)	70.3
TSC + NOST	**TC <10000**	Gomes et al 2015[88]	15	17.3	17.3	15	1.9	1.5	15.40 (6.61, 24.19)	89
	WS+ TC ≥10000	Druck et al 2015[145]	8	10.2	5.1	8	9.1	4.4	1.10 (-3.57, 5.77)	10.8
		Feitosa et al 2017[134]	15	18.2	6.1	15	11.2	5.4	7.00 (2.88, 11.120	38.5
		Pooled Mean Difference (95%CI)							*4.41 (1.32, 7.50)*	
TSC + OST	**TC <10000**	Gomes et al 2015[88]	15	18.9	4.6	15	0.9	2.2	18.0 (15.42, 20.58)	95.2

(*continued on next page*)

Table 2 (*continued*)

Surface treatment	Aging	Study	Non- aging Total No	Mean	SD	Aging Total No	Mean	SD	Mean difference (95% CI)	% Change
Non-MDP cement + non-MDP primer										
Non-MDP cement + MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA + NOST	**TC <10000**	Salem et al 2019[146]	24	9.67	0.95	24	7.11	0.79	2.57 (2.07, 3.06)	26.6
		Elgendy et al 2020[147]	20	18	2.9	20	5.95	2.85	12.05 (10.27, 13.83)	66.9
		Pooled Mean Difference (95%CI)							*3.25 (2.77, 3.72)*	
	TC ≥10000	Yoshida et al 2018[148]	8	24.1	1.4	8	22.5	1.7	1.60 (0.07, 3.13)	6.6
		Pitta et al 2018[137]	40	31.62	6.37	40	22.7	4.57	8.92 (6.50, 11.35)	28.2
		Yang et al 2018[136]	120	12	1.18	120	10.63	1.11	1.37 (1.08, 1.66)	11.4
		Pooled Mean Difference (95%CI)							*4.10 (3.58, 4.62)*	
	WS	Su et al 2021[116]	10	18.27	3.13	10	10.65	2.01	7.62 (5.31, 9.93)	42
		Lopes et al 2016[86]	48	5.97	2.28	48	5.68	1.90	0.30 (-0.54, 1.14)	5.0
		Darvizeh et al 2015[149]	18	21.4	4.1	18	15.1	5.1	6.30 (3.28, 9.32)	29
		Pooled Mean Difference (95%CI)							*1.48 (0.69, 2.29)*	
	WS+TC <10000	Liu et al 2020[139]	10	22.38	1.54	10	20.11	1.73	2.27 (0.83, 3.71)	10.1
		Chuang et al 2017[117]	36	23.59	3	36	14.24	1.47	9.35 (8.26, 10.44)	39.6
		Ahn et al 2020[150]	10	25.66	2.55	10	15.03	2.56	10.63 (8.39, 12.87)	41.4
		Pooled Mean Difference (95%CI)							*8.40 (7.58, 9.22)*	
	WS+TC ≥10000	Ishi et al 2015[151]	20	16.4	2.9	20	14.25	2.6	2.15 (0.44, 3.86)	13.1
		Cadore-Rodriguez et al 2020[94]	20	28.15	7.93	20	19.69	6.06	8.46 (4.09, 12.83)	30.1
		Rohr et al 2022[152]	24	11.75	2.95	24	1.75	2.30	10.00 (8.50, 11.50)	85.1
		Awad et al 2022[153]	16	19.33	5.14	16	7.48	3.64	11.85 (8.76, 14.94)	61.3
		Yan et al 2021[154]	210	16.69	2.29	210	11.75	1.85	4.95 (4.55, 5.34)	29.6
		Pooled Mean Difference (95%CI)							*5.18 (4.81, 5.55)*	
SA + OST	**WS**	Darvizeh et al 2015[149]	18	29.1	5.6	18	25.3	5.2	3.80 (0.27, 7.33)	13.1
	TC <10000	El-Wassefy 2021[155]	112	4.11	0.81	112	2.97	0.84	1.13 (0.92, 1.35)	27.5
		Kang 2022[89]	40	18.98	2.33	40	12.00	2.05	6.98 (6.01, 7.94)	36.8
		Pooled Mean Difference (95%CI)							*1.41 (1.20, 1.63)*	
	WS+TC <10000	Ahn et al 2020[150]	10	21.82	5.43	10	9.72	0.75	12.10 (8.70, 15.50)	55.5
	WS+TC ≥10000	Akazawa et al 2017[119]	22	18.35	1.15	22	15.55	1.7	2.80 (1.94, 3.66)	15.3
		Feitosa et al 2017[156]	15	27.8	5	15	11.09	3.8	16.71 (13.53, 19.89)	60.1
		Pooled Mean Difference 95%CI)							*3.74 (2.92, 4.57)*	
No SA + NOST	**TC <10000**	Yagawa et al 2018[120]	44	44.72	3.55	44	38.17	3.17	6.55 (5.14, 7.96)	14.6
		Rebholz-Zaribaf et al 2016[85]	45	14.1	4.57	45	8.63	3.4	5.47 (3.80, 7.13)	38.8
		Mangione et al 2019[157]	10	6.9	1.3	10	2.3	2.4	4.60 (2.91, 6.29)	66.7
		Pooled Mean Difference (95%CI)							*5.67 (4.76, 6.57)*	
	WS	Zhao et al 2016[143]	16	8.68	0.6	16	10.78	0.9	-2.10 (-2.64, -1.57)	-24.3*
		Su et al 2021[116]	10	9.03	1.64	10	3.62	1.74	5.41 (3.93, 6.890	59.9
		Darvizeh et al 2015[149]	18	14.5	2.2	18	4.5	3.2	10.00 (8.21, 11.79)	69
		Pooled Mean Difference (95%CI)							*-0.43 (-0.92, 0.05)*	
	WS+TC <10000	Pott et al 2016 [123]	60	17.72	4.62	60	13.92	5	3.80 (2.08, 5.52)	21.4
		Zhao et al 2022[124]	12	7.53	0.59	12	5.50	0.47	2.03 (1.60, 2.45)	26.9
		Pooled Mean Difference (95%CI)							*1.92 (1.50, 2.33)*	
	WS+TC ≥10000	Noda et al 2017[125]	48	25.92	5.85	48	17.92	4.2	8.00 (5.96, 10.04)	30.9
		Kim et al 2015[92]	60	31.97	5.27	60	19.43	5.67	12.53 (10.58, 14.49)	39.2
		Alegria Acevedo et al 2022[126]	60	29.97	1.32	60	13.97	2.08	16.00 (15.38, 16.62)	53.4
		Pooled Mean Difference (95%CI)							*11.56 (9.97, 13.17)*	

(*continued on next page*)

Table 2 (*continued*)

Non-MDP cement + non-MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging**			**Aging**			**Mean difference**	**% Change**
			Total No	**Mean**	**SD**	**Total No**	**Mean**	**SD**	**(95% CI)**	
No SA + OST	**TC <10000**	Mangione et al 2019[157]**	10	5.7	1.4	10	0	0	5.7	100
	WS	Su et al 2021[116]	10	14.39	2.23	10	9.56	1.88	4.83 (3.02, 6.64)	33.6
		Darvizeh et al 2015[149]	54	28.47	3.63	54	23.17	4.43	5.30 (3.77, 6.83)	18.6
		Pooled Mean Difference (95%CI)							*5.10 (3.94, 6.27)*	
	WS+ TC <10000	Campos et al 2016[128]	10	11.64	5.31	10	3.62	3.79	8.02(3.98, 12.06)	68.9
		Ahn et al 2020[150]	10	19.99	4.67	10	6.66	0.81	13.33 (10.39, 16.27)	66.7
		Dal Piva et al 2019[91]	20	9.8	3.9	20	0.3	0.4	9.50 (7.78, 11.22)	96.9
		Pooled Mean Difference (95%CI)							*10.18 (8.79, 11.58)*	
	WS+TC ≥10000	Feitosa et al 2017[156]	30	22.55	7.49	30	15.1	5.38	7.45 (4.15, 10.75)	33
		Cadore-Rodriguez et al 2020[94]	40	29.09	5.89	40	23.17	4.91	17.30 (16.29, 18.31)	59.5
		Pooled Mean Difference (95%CI)							*6.45 (4.52, 8.38)*	
TSC + NOST	**TC <10000**	Dal Piva et al 2019[91]	20	9.5	3.7	20	7.7	3.9	1.80 (-0.56, 4.16)	18.9
	WS+TC ≥10000	Cadore-Rodriguez et al 2020[94]	20	27.28	7.35	20	31.43	5.08	-4.15 (-8.07, -0.23)	-15.2*
TSC + OST	**TC <10000**	Kang et al 2022[89]	10	25.80	4.60	10	24.20	3.40	1.60 (-1.02, 4.22)	6
	WS+TC <10000	Dal Piva et al 2019[91]	20	8.2	2.2	20	10.4	4.9	-2.20 (-4.55, 0.15)	-26.8*
	WS+TC ≥10000	Feitosa et al 2017[156]	15	29.7	9.4	15	16.4	9.4	13.30 (6.57, 20.03)	44.8
MDP cement + no primer										
Surface treatment	**Aging**	**Study**	**Non- aging**			**Aging**			**Mean difference**	**% Change**
			Total No	**Mean**	**SD**	**Total No**	**Mean**	**SD**	**(95% CI)**	
SA + NOST	**TC <10000**	Re et al 2015[93]	60	15.18	2.4	60	8.33	1.71	6.85 (6.11, 7.60)	45.1
		Le et al 2018[158]	185	38.16	5.06	185	34.92	6.8	2.02 (4.46, 5.20)	5.3
		Moon et al 2016[159]	240	13.18	2.87	240	9.72	2.79	3.56 (2.95, 3.96)	27
		Kwon et al 2020[160]	30	20.85	4.25	30	18.85	4.75	2.00 (-0.28, 4.28)	9.6
		Liu et al 2020[161]	9	26.26	1.33	9	25.22	1.38	1.04 (-0.21, 2.29)	3.9
		Mano et al 2020[135]	10	20.3	5.7	10	11.3	3.9	9.00 (4.72, 13.28)	44.3
		Pooled Mean Difference (95%CI)							*4.07 (3.70, 4.44)*	
	TC ≥10000	Saade et al 2020[144]	14	28.3	3.2	14	24.4	3.4	3.90 (1.45, 6.35)	13.8
		Pitta et al 2018[137]	20	19.6	2.01	20	22.65	5.18	-3.05 (-5.49, -0.61)	-15.6*
		Yang et al 2018[136]	60	13.73	1.06	60	12.11	1.12	1.61 (1.22, 2.00)	11.7
		Pardo et al 2016[162]	10	7.7	2.18	10	7.88	3.97	-0.18 (-2.98, 2.63)	-2.3 *
		Franco-Tabares et al 2019[163]	20	20.12	4.64	20	6.28	1.35	13.84 (11.72, 15.95)	68.8
		Pooled Mean Difference (95%CI)							*1.90 (1.53, 2.27)*	
	WS	De Mendonca et al 2019[164]	30	19.5	3.1	30	14.3	7.3	5.20 (2.36, 8.04)	27
		Saade et al 2020[144]	28	28.3	3.2	28	19	5.05	9.30 (7.09, 11.51)	33
		Negreiros et al 2017[90]	14	40.8	2.35	14	23.45	3.1	17.35 (15.31, 19.39)	43
		Soto Montero et al 2022[138]	10	14.30	5.5	10	22.10	2.20	-7.80 (-11.47, -4.13)	-54.5*
		Pooled Mean Difference (95%CI)							*9.55 (8.30, 10.80)*	
	WS+ TC <10000	Liu et al 2020[139]	20	27.15	0.96	20	20.71	0.85	6.44 (5.87, 7.00)	23.7
		Cheung et al 2015[165]	10	5.5	1.1	10	0.06	0.04	5.44 (4.76, 6.12)	98.9
		Kasraei et al 2015[166]	15	23.35	3.12	15	1.8	1.2	21.55 (19.86, 23.24)	92.3
		Petkosit et al 2020[167]	30	8.75	2.07	30	5.64	0.76	3.11 (2.32, 3.90)	35.5
		Pooled Mean Difference (95%CI)							*6.14 (5.76, 6.51)*	
SA + OST	**TC <1000**	Liu et al 2020[161]	45	22.97	1.38	45	20.68	1.19	2.29 (1.75, 2.82)	10.1
	TC ≥1000	Franco-Tabares et al 2019[163]	10	20.47	6.2	10	5.13	1.21	15.34 (11.42, 19.26)	74.9
	WS	De Mendonca et al 2019[164]	30	18.15	5.85	30	12.6	4.25	5.55 (2.96, 8.14)	30.6
		Sanal et al 2020[141,118]	30	19.26	4.28	30	3.08	0.7	16.18 (14.63, 17.74)	84
		Pooled Mean Difference (95%CI)							*13.38 (12.04, 14.70)*	
	WS+ TC <10000	Kasraei et al 2015[166]	30	16.48	2.71	30	4.24	1.64	12.24 (11.11, 13.37)	74.3

(*continued on next page*)

Table 2 (*continued*)

Non-MDP cement + non-MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging**			**Aging**			**Mean difference**	**% Change**
			Total No	**Mean**	**SD**	**Total No**	**Mean**	**SD**	**(95% CI)**	
No SA + NOST	**TC <10000**	Gomes et al 2015[88]	15	6.8	3.4	15	1.5	2.6	5.30 (3.13, 7.47)	77.9
		Lee et al 2015[142]	20	3.4	0.58	20	2.51	0.47	0.89 (0.56, 1.22)	26.2
		Le et al 2018[158]	185	19.62	4.78	185	12.3	6.4	7.32 (6.17, 8.47)	37.3
		Moon et al 2016[159]	10	6.7	1.95	10	3	1.12	3.70 (2.31, 5.09)	55.2
		Rebholz-Zaribaf et al 2016[85]	15	5.7	1.7	15	9.7	3.4	-4.00 (-5.92, -2.08)	-70.2*
		Pooled Mean Difference (95%CI)							*1.43 (1.27, 1.73)*	
	TC ≥10000	Saade et al 2020[144]	14	10.4	7.2	14	6.2	3.1	4.20 (0.09, 8.31)	40.4
		Pardo et al 2016[162]	10	5.97	0.41	10	6.11	1.77	-0.14 (-1.26, 0.99)	-2.3*
		Pooled Mean Difference (95%CI)							*0.17 (-0.92, 1.25)*	
	WS	Zhao et al 2016[143]	8	5.84	0.54	8	5.42	0.5	0.42 (-0.09, 0.93)	7.2
		De Mendonca et al 2019[164]	30	11.5	3.8	30	7.35	2.65	4.15 (2.49, 5.81)	36.1
		Negreiros et al 2021[168]	20	5.7	1.15	20	2.05	0.35	3.65 (3.12, 4.18)	64
		Saade et al 2020[144]	28	10.4	7.2	28	1.4	1.8	9.00 (6.25, 11.75)	86.5
		Pooled Mean Difference (95%CI)							*2.20 (1.84, 2.55)*	
	WS+ TC ≥10000	Liu et al 2015[169]	10	3.87	1.17	10	3.81	1.07	0.06 (-0.92, 1.04)	1.6
		Kwon et al 2020[160]	20	6.2	1.4	20	0.95	0.35	5.25 (4.62, 5.88)	84.7
		Le et al 2018[158]	185	19.62	4.78	185	0.94	1.2	18.68 (17.97, 19.39)	95.2
		Pooled Mean Difference (95%CI)							*9.10 (8.68, 9.53)*	
No SA+OST	**TC <10000**	Gomes et al 2015[88]**	15	6.9	2	15	0	0	6.9	100
		Le et al 2018[158]	185	23.04	5.46	185	16.74	7.44	6.30 (4.97, 7.63)	27.3
	TC ≥10000	Thammajaruk et al 2020[130]	15	27.7	5.2	15	29.1	6	-1.40 (-5.42, 2.62)	-5.1*
	WS	De Mendonca et al 2019[164]	30	11.3	4.25	30	7.4	4	3.90 (1.81, 5.99)	34.5
		Negreiros et al 2021[168]	40	9.18	1.65	40	2.9	0.55	6.28 (5.74, 6.81)	68.4
		Saade et al 2020[144]	56	30.95	4.05	56	20.17	6.45	10.78 (0.97, 4.39)	34.8
		Pooled Mean Difference (95%CI)							*6.42 (5.92, 6.93)*	
	WS+ TC ≥10000	Liu et al 2015[169]	90	4.96	1.4	90	4.67	1.24	0.29 (-0.10, 0.68)	5.8
		Le et al 2018[158]	185	23.04	5.46	185	5.74	4.36	17.30 (16.29, 18.31)	75.1
		Pooled Mean Difference (95%CI)							*2.47 (2.11, 2.83)*	
TSC + NOST	**TC <1000**	Re et al 2015[93]	40	16.55	1.82	40	8.29	1.23	8.26 (7.58, 8.93)	50
		Gomes et al 2015[88]	15	15.8	4.8	15	15.3	5.8	0.50 (-3.31, 4.31)	3.2
		Pooled Mean Difference (95%CI)							*8.02 (7.35, 8.69)*	
	TC ≥1000	Pardo et al 2016[162]	10	8.78	1.92	10	9.53	2.78	-0.75 (-2.84, 1.34)	8.5
TSC + OST	**TC <1000**	Gomes et al 2015[88]	15	11.1	3.8	15	9.9	3.5	1.20 (-1.41, 3.81)	10.8
MDP cement + non-MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging**			**Aging**			**Mean difference**	
			Total No	**Mean**	**SD**	**Total No**	**Mean**	**SD**	**(95% CI)**	**% Change**
SA + NOST	**TC <10000**	Paschoalino et al 2019[170]	14	13.40	2.52	14	4.34	1.74	9.06 (7.46, 10.66)	67.6
	WS+TC <10000	Zaia et al 2016[171]	12	5.74	1.32	12	5.61	1.89	0.13 (-1.17, 1.43)	2.3
		Cao et al 2022[172]	66	10.34	1.37	66	7.55	1.45	2.79 (2.30, 3.27)	26.9
		Pooled Mean Difference (95%CI)							*2.47 (2.02, 2.92)*	
SA + OST	**TC <10000**	Paschoalino et al 2019[170]	28	14.15	2.58	28	4.18	1.20	9.97 (8.19, 11.02)	70.5
	WS+TC <10000	Zaia et al 2016[171]	12	6.55	2.27	12	7.7	1.82	-1.15 (-2.80, 0.50)	-17.6*
	WS+TC ≥10000	Akazawa et al 2017[119]	11	20.5	4.3	11	12.6	2.4	7.90 (4.99, 10.81)	38.5
No SA + NOST	**TC <10000**	Rebholz-Zaribaf et al 2016[85]	15	10.3	4.8	15	14	4.9	-3.70 (-7.17, -0.23)	-35.9*
		Hjerppe et al 2021[173]	10	21.8	4.2	10	7.4	5.4	14.40 (10.16, 18.64)	66.1
		Paschoalino et al 2019[170]	7	10.5	1.42	7	1.86	0.3	8.64 (7.56, 9.72)	82.3
		Pooled Mean Difference (95%CI)							*7.94 (6.94, 8.94)*	
TSC + NOST	**TC <10000**	Rebholz-Zaribaf et al 2016[85]	30	12.9	3.55	30	12.85	4.15	0.05 (-1.90, 2.00)	0.4
		Hjerppe et al 2021[173]	10	22.5	4.2	10	5.9	4.1	16.60 (12.96, 20.24)	73.8
		Pooled Mean Difference (95%CI)							*3.76 (2.04, 5.48)*	

(*continued on next page*)

Table 2 (continued)

Non-MDP cement + non-MDP primer										
Surface treatment	Aging	Study	Non- aging			Aging			Mean difference	% Change
			Total No	Mean	SD	Total No	Mean	SD	(95% CI)	
MDP cement + MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA + NOST	**TC <10000**	Salem et al 2019[146]	12	16.47	1.5	12	12.52	1.34	3.95 (2.81, 5.09)	24
		Elgendy et al 2020[147]	10	22.9	6.4	10	23.2	5.6	-0.30 (-5.57, 4.97)	-1.3 *
		Hjerppe et al 2021[173]	10	19.5	6.9	10	2.4	1.5	17.10 (12.72, 21.48)	87.7
		Pooled Mean Difference (95%CI)							*4.57 (3.49, 5.65)*	
	TC ≥10000	Yoshida et al 2018[148]	8	24.3	1.9	8	23.7	2.6	0.60 (-1.63, 2.83)	2.5
	WS	Negreiros et al 2017 [90]	14	39.5	2.7	14	21.3	1.55	18.20 (16.57, 19.83)	46
	WS+ TC <10000	Liu et al 2020[139]	10	24.35	1.45	10	13.84	1.02	10.51 (9.41, 11.61)	43.2
		Cheung et al 2015[165]	10	10.2	1.3	10	8.2	0.9	2.00 (1.02, 2.98)	19.6
		Alvim HC et al 2018[174]	10	16.1	6	10	9.73	4.75	6.37 (1.63,11.11)	39.6
		Ahn et al 2020[150]	10	16.62	0.9	10	14.37	0.93	2.25 (1.45, 3.05)	13.5
		Cao et al 2022[172]	44	13.07	1.73	44	9.62	1.69	3.45 (2.73, 4.16)	26.4
		Pooled Mean Difference (95%CI)							*3.93 (3.50, 4.36)*	
SA + OST	**WS**	Sanal et al 2020[141]	30	16.3	8.04	30	3.5	0.59	12.81 (9.92, 15.69)	78.6
	WS+TC <10000	Cheung et al 2015[165]	20	9.2	1.3	20	7	1.35	2.20 (1.38, 3.02)	23.9
		Ahn et al 2020[150]	10	12.89	2.34	10	9.39	2.33	3.50 (1.45, 5.55)	27.2
		Pooled Mean Difference (95%CI)							*2.38 (1.62, 3.14)*	
No SA + NOST	**TC <10000**	Rebholz-Zaribaf et al 2016[85]	45	11.63	2.9	45	9.63	3.13	2.00 90.75, 3.25)	17.2
		Mangione et al 2019 [157]	10	8.2	1.9	10	2.2	2.2	6.00 (4.20, 7.80)	73.2
		Pooled Mean Difference (95%CI)							*3.29 (2.27, 4.32)*	
	TC ≥10000	Liu et al 2015 [175]	24	16.8	2.4	24	1.9	1.1	14.90 (13.84, 15.96)	88.7
	WS	Zhao et al 2016 [143]	8	5.73	0.74	8	11.36	0.61	-5.63 (-6.29, -4.97)	-98.3*
		Negreiros et al 2021 [168]	20	6.35	1.25	20	2.4	0.65	3.95 (3.333, 4.570	62.2
		Emamieh et al 2019 [176]	28	24.47	4.28	28	17.13	6.84	7.34 (4.35, 10.34)	30
		Monteiro 2022[177]	90	15.67	4.53	90	9.50	3.87	6.17 (4.94, 7.40)	39.4
		Pooled Mean Difference (95%CI)							*0.44 (0.02, 0.86)*	
No SA + OST	**TC <1000**	Mangione et al 2019 [157,130]	10	5.7	2.9	10	1.3	2.2	4.40 (2.14, 6.66)	77.2
	TC ≥1000	Liu et al 2015 [175]	72	22.2	3.43	72	10.87	2.01	11.33 (10.41, 12.25)	51.1
	WS	Negreiros et al 2021[168]	40	10.77	1.98	40	5.05	0.77	5.72 (5.07, 6.38)	53.1
	WS+TC <10000	Cheung et al 2015[165]	20	10.9	1.65	20	8.5	1.9	2.40 (1.30, 3.50)	22
		Alvim et al 2018[174]	10	17.31	7.84	10	2.14	1.7	15.17 (10.20, 20.14)	87.6
		Ahn J et al 2020 [150]	10	12.62	3.82	10	4.14	0.61	8.48 (6.08, 10.88)	67.2
		Pooled Mean Difference (95%CI)							*0.44 (0.02, 0.86)*	
	WS+TC ≥10000	Feitosa et al 2017[156]	30	22.55	7.49	30	15.1	5.38	7.45 (4.15, 10.75)	33
TSC + NOST	**TC ≥1000**	Liu et al 2015[175]	24	25.1	2.7	24	11.9	1.9	13.20 (11.88, 14.52)	52.6
	WS+TC <10000	Alvim HC et al 2018[174]	10	14.36	3.14	10	3.81	3.94	10.55 (7.43, 13.67)	73.5

*Negative values means that specimens in non-aging group have lower mean bond strength than those in the aging group.**study is excluded from the pooled mean difference.
NOST: No Other Surface Treatment, OST: Other Surface Treatment

Table 3
Mean difference (95% CI) and % change of bond strength before and after aging in studies included in the tensile test group.

Surface treatment	Aging	Study	Non- aging Total No	Non- aging Mean	Non- aging SD	Aging Total No	Aging Mean	Aging SD	Mean difference (95% CI)	% Change
Non-MDP cement + non-MDP primer										
SA + NOST	**TC <10000**	Elsayed et al 2017[100]	16	24.35	6.65	16	14.85	4.30	9.50 (5.62, 13.38)	39.0
		Madrigal et al 2021[107]	16	21.70	4.90	16	19.35	3.80	2.35 (-0.69, 5.39)	10.8
		Pooled Mean Difference (95%CI)							*5.07 (2.68, 7.46)*	
	TC ≥10000	Elsayed et al 2017[100]	16	24.35	6.65	16	4.05	1.70	20.30 (16.94, 23.66)	83.4
	WS+ TC <10000	Wille et al 2017[96]	8	24.40	0.80	8	14.10	2.40	10.30 (8.55, 12.05)	42.2
		Lenz et al 2021[114]	30	22.00	6.30	30	21.60	1.66	0.40 (-2.90, 3.70)	1.8
		Pooled Mean Difference (95%CI)							*8.13 (6.58, 9.67)*	
No SA+ NOST	**TC <10000**	Rebholz-Zaribaf et al 2016[85]	15	10.30	6.50	15	6.00	5.00	4.30 (0.15, 8.45)	41.7
	WS+ TC ≥10000	Yoshida et al 2020[103]	16	22.9	2.35	16	9.25	1.45	13.65 (12.29, 15.00)	59.6
TSC + NOST	**TC <10000**	Thammajaruk et al 2018[111]	20	85.10	15.68	20	80.56	17.12	4.54 (-5.63, 14.71)	5.3
		Rebholz-Zaribaf et al 2016[85]	30	8.80	4.20	30	9.15	3.50	-0.35 (-2.31, 1.61)	-4.0*
		Pooled Mean Difference (95%CI)							*-0.18 (-2.10, 1.75)*	
	TC ≥10000	Thammajaruk et al 2018[111]	20	85.10	15.68	20	70.45	19.85	14.65 (3.56, 25.74)	17.2
	WS	Lenz et al 2021[114]	30	25.7	8.2	30	20.95	6.2	4.75 (1.07, 8.43)	18.5
	WS+ TC ≥10000	Ebeid 2018[105]	8	23.10	3.70	8	15.70	5.40	7.40 (2.86,11.94)	32
Non-MDP cement + no primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA+ NOST	**WS+ TC <10000**	Abu Ruja et al 2019[108]	5	21.14	2.28	5	17.87	1.66	3.27 (0.80, 5.74)	15.5
	WS+ TC ≥10000	Yoshida et al 2020[103]	16	38.35	3.40	16	31.85	2.80	6.50 (4.34, 8.66)	16.9
		Passia et al 2016[104]	16	32.25	6.80	16	18.60	6.35	13.65 (9.09, 18.21)	42.3
		Pooled Mean Difference (95%CI)							*7.81 (5.86, 9.76)*	
No SA+ NOST	**TC <10000**	Sakrana et al 2017[110]	20	17.40	1.10	20	5.10	0.50	12.30 (11.77, 12.83)	70.7
		Rebholz-Zaribaf et al 2016[85]	30	6.25	1.80	30	5.00	2.75	1.25 (0.07, 2.43)	20.0
		Pooled Mean Difference (95%CI)							*10.44 (9.96, 10.92)*	
	WS+ TC <10000	Abu Ruja et al 2019[108]	15	31.43	2.75	15	23.07	1.65	8.35 (6.73, 9.98)	26.6
	WS+ TC ≥10000	Yoshida et al 2020[103]	16	22.9	2.35	16	9.25	1.45	13.65 (12.29, 15.00)	59.6
No SA+ OST	**TC <10000**	Sakrana et al 2017[110]	40	42.90	1.30	40	38.75	0.95	4.15 (3.65, 4.65)	9.7
		Thammajaruk et al 2018[111]	20	87.18	10.22	20	79.43	14.60	7.75 (-0.06, 15.56)	8.9
		Pooled Mean Difference (95%CI)							*4.17 (3.67, 4.66)*	
	TC ≥10000	Thammajaruk et al 2018[111]	20	87.18	10.22	20	72.00	16.27	15.18 (6.76, 23.60)	17.4

(continued on next page)

Table 3 (*continued*)

Surface treatment	Aging	Study	Non- aging Total No	Mean	SD	Aging Total No	Mean	SD	Mean difference (95% CI)	% Change
Non-MDP cement + non-MDP primer										
TSC + NOST	**WS+ TC <10000**	Abu Ruja et al 2019[108]	5	23.11	2.60	5	16.80	2.02	6.31 (3.42, 9.20)	27.3
Non-MDP cement + MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA + NOST	**TC <10000**	Elsayed et al 2017[100]	24	44.07	8.07	24	40.90	10.57	3.17 (-2.15, 8.49)	7.2
		Sakrana et al 2017[110][	20	43.70	1.70	20	38.50	1.20	5.20 (4.29, 6.11)	11.9
		Madrigal et al 2021[107]	16	33.95	6.00	16	32.30	4.35	1.65 (-1.98, 5.28)	4.9
		Koko et al 2020[101]	25	30.30	5.24	25	15.52	3.48	14.78 (12.31, 17.25)	48.8
		Pooled Mean Difference (95%CI)							*6.04 (5.21, 6.86)*	
	TC ≥10000	Elsayed et al 2017[100]	24	44.07	8.07	24	31.87	7.57	12.20 (7.78, 16.62)	22.7
		Ruales-Carrera et al 2019[109]	60	18.63	4.74	60	17.58	4.95	1.04 (-0.70, 2.78)	5.6
		Pooled Mean Difference (95%CI)							*2.53 (0.91, 4.14)*	
	WS+TC <10000	Wille et al 2017[96]	8	31.10	3.50	8	25.20	2.90	5.90 (2.75, 9.05)	19
	WS+TC ≥10000	Passia et al 2016[104]	16	38.50	6.30	16	19.30	3.45	19.20 (15.68, 22.72)	49.9
		Ebeid et al 2018[105]	8	22.20	3.60	8	17.20	5.10	5.00 (0.67, 9.33)	22.5
		Pooled Mean Difference (95%CI)							*13.54 (10.81, 16.27)*	
No SA+ NOST	**TC <10000**	Yoshida et al 2021[97]	20	23.90	2.65	20	17.45	1.20	6.45 (5.18, 7.72)	27
		Rebholz-Zaribaf et al 2016[85]	45	16.37	4.57	45	15.10	4.83	1.27 (-0.68, 3.21)	7.7
		Pooled Mean Difference (95%CI)							*4.89 (3.82, 5.96)*	
	TC ≥10000	Ruales-Carrera et al 2019[109]	54	7.93	4.61	56	5.01	2.96	2.91 (1.46, 4.37)	36.8
	WS+TC ≥10000	Ebeid et al 2018[105]**	8	12.7	2.2	8	0	0	12.7	100
MDP cement + no primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA+ NOST	**TC ≥10000**	Hallman et al 2016[102]	16	38.85	6.25	16	35.30	10.25	3.55 (-2.33, 9.43)	9.1
		Al-Akhali et al 2021[106]	50	35.00	6.66	50	31.06	6.24	3.94 (1.41, 6.47)	11.3
		Pooled Mean Difference (95%CI)							*3.88 (1.56, 6.20)*	
	WS+ TC ≥10000	Passia et al 2016[104]	8	35.00	6.30	8	23.50	11.60	11.50 (2.35, 20.65)	32.9
		Sakrana et al 2020[113][	30	25.10	6.00	30	19.17	3.87	5.93 (3.38, 8.49)	23.6
		Guers et al 2019[98]	76	42.92	4.97	76	37.70	6.90	5.22 (3.31, 7.14)	12.2
		Pooled Mean Difference (95%CI)							*5.64 (4.13, 7.15)*	
SA+ OST	**WS+ TC ≥10000**	Sakrana et al 2020[113]	60	23.28	5.23	60	17.50	5.00	5.78 (3.95, 7.61)	24.8

(*continued on next page*)

Table 3 (*continued*)

Surface treatment	Aging	Study	Non- aging Total No	Mean	SD	Aging Total No	Mean	SD	Mean difference (95% CI)	% Change
Non-MDP cement + non-MDP primer										
No SA+ NOST	**TC <10000**	Rebholz-Zaribaf et al 2016[85]	15	7.20	2.70	15	9.70	3.40	-2.50 (-4.70, -0.30)	-34.7*
	TC ≥10000	Hallman et al 2016[102]	16	24.55	7.60	16	10.75	6.35	13.80 (8.95, 18.65)	56.2
No SA+ OST	**TC ≥10000**	Hallman et al 2016[102]	56	26.60	7.24	56	12.64	6.59	13.96 (11.39, 16.52)	52.5
MDP cement + non-MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA + NOST	**WS+TC <10000**	Xiong et al 2021[115]	80	10.81	2.22	8	2.52	1.00	8.29 (7.76, 8.82)	76.7
	WS+TC ≥10000	Sakrana et al 2020[113]	30	23.47	6.00	30	13.63	4.20	9.83 (7.21, 12.45)	41.9
SA + OST	**WS+TC ≥10000**	Sakrana et al 2020[113]	60	24.25	4.40	60	19.52	4.65	4.73 (3.11,6.35)	19.5
No SA+ NOST	**WS+TC <10000**	Rebholz-Zaribaf et al 2016[85]	15	4.40	3.80	15	3.30	2.50	1.10 (-1.20, 3.40)	25
TSC + NOST	**TC <10000**	Rebholz-Zaribaf et al 2016[85]	30	12.40	2.60	30	12.45	2.95	-0.05 (-1.46, 1.36)	-0.4*
	TC ≥10000	Ruales-Carrera et al 2019[109]	60	13.26	4.74	60	15.06	3.98	-1.80 (-3.37, -0.23)	-13.2*
MDP cement + MDP primer										
Surface treatment	**Aging**	**Study**	**Non- aging Total No**	**Mean**	**SD**	**Aging Total No**	**Mean**	**SD**	**Mean difference (95% CI)**	**% Change**
SA + NOST	**TC <10000**	Thammajaruk et al 2019 [112]	20	90.88	17.41	20	90.12	8.54	0.76 (-7.74, 9.26)	0.8
	TC ≥10000	Thammajaruk et al 2019 [112]	20	90.88	17.41	20	80.29	23.37	10.59 (-2.18, 23.36)	11.7
	WS+TC<10000	Xiong et al 2021	80	16.27	3.50	80	10.12	2.66	6.15 (5.23, 7.07)	37.8
SA + OST	**TC <10000**	Thammajaruk et al 2019 [112]	20	37.57	9.9	20	24.05	3.06	13.52 (8.98, 18.06)	36
	TC ≥10000	Thammajaruk et al 2019 [112]	20	37.57	9.9	20	13.43	7.93	24.14 (18.58, 29.70)	64.3
No SA+ NOST	**TC <10000**	Yoshida et al 2021[97]	40	23.58	1.92	40	19.52	1.58	4.05 (3.28, 4.82)	17.2
		Rebholz-Zaribaf et al 2016 [85]	45	13.03	3.10	45	12.33	3.40	0.70 (-0.64, 2.04)	5.4
		Pooled Mean Difference (95%CI)							*3.22 (2.55, 3.89)*	

*Negative values means that specimens in non-aging group have lower mean bond strength than those in the aging group.**study is excluded from the pooled mean difference NOST: No Other Surface Treatment, OST: Other Surface Treatment

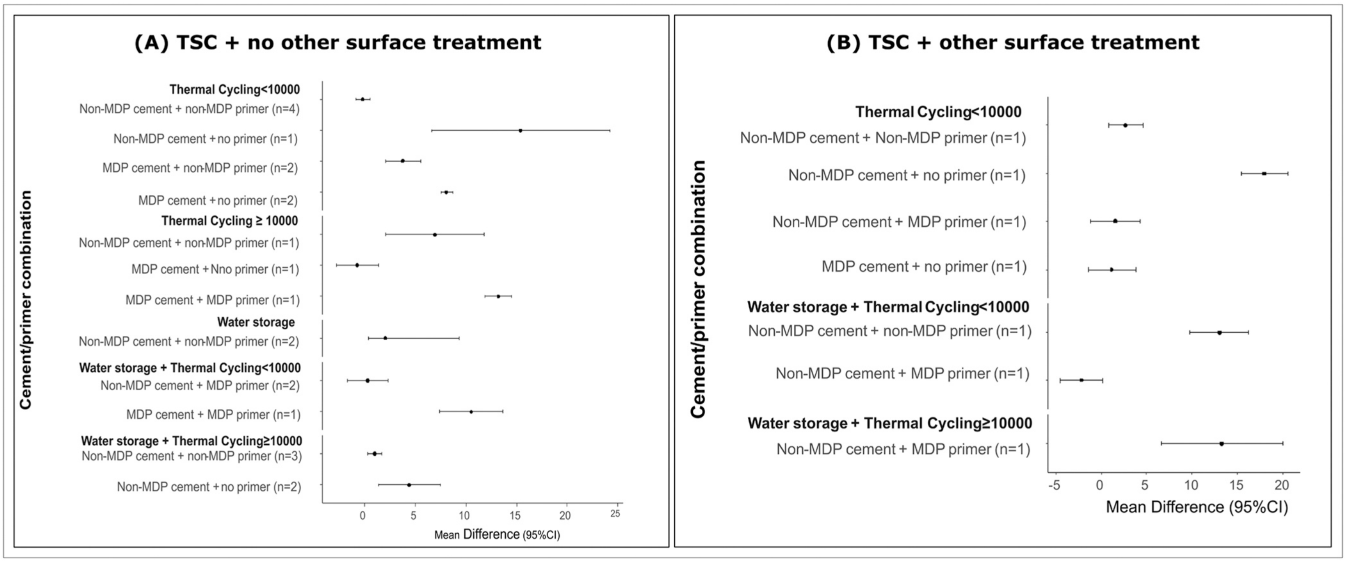

Fig. 3. Mean Difference of bond strength between control group and aging group from studies including shear tests for zirconia-resin bond strength evaluation. Classification was based on whether TSC was applied or not in combination with or without other surface treatments and studies were grouped based on different cement/primer combinations. Error bars represent the 95% confidence intervals of mean difference. (A) TSC + no other surface treatment, (B) TSC + other surface treatment.

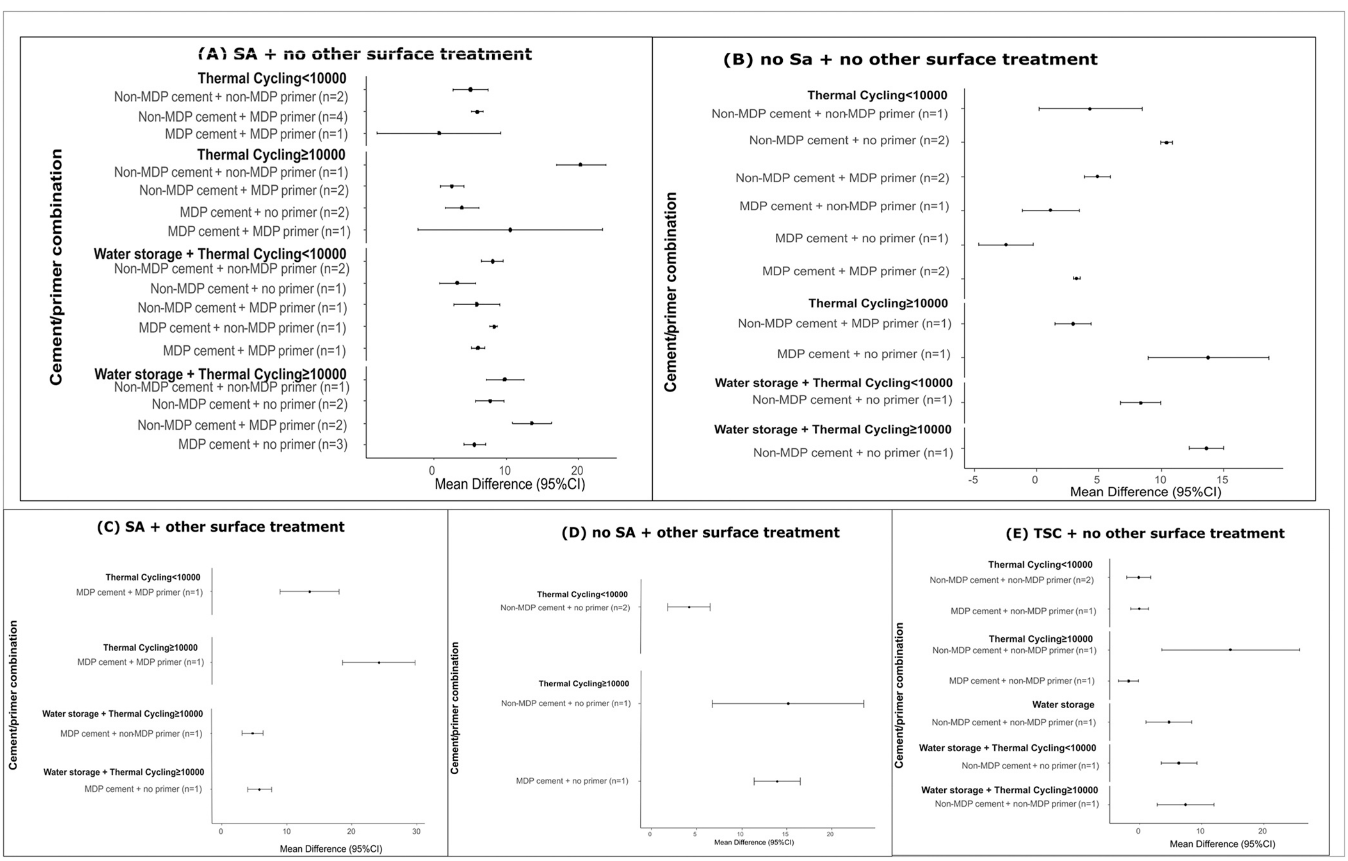

Fig. 4. Mean Difference of bond strength between control group and aging group from studies including tensile tests for zirconia-resin bond strength evaluation. Classification was based on whether SA or TSC was applied or not in combination with or without other surface treatments and studies were grouped based on different cement/primer combinations. Vertical line indicates no difference between the two groups. Error bars represent the 95% confidence intervals of mean difference. (A) SA + no other surface treatment, (B) SA + other surface treatment, C) no SA + no other surface treatment, (D) no SA + other surface treatment, (E) TSC + no other surface treatment.

immersion in Zr/Si suspension and Zr/Si primer resulted in slightly lower decrease, one 33.6[116] by the use of a porous silica-zirconia coating and another 18.6%[149] after in-situ nano-silica deposition and bioglass or alumina abrasion respectively. Regarding TSC, the limited number of studies and the variation among their results does not allow any conclusive result.

3.6. MDP cement+ No primer

When MDP cement was used alone without any primer and no SA was applied, the decrease of bond strength ranged from 1.6% to 100% in 19 out of 22 groups using shear test, where 3[85,130,162] reported an increase after aging, while in the tensile group, two study groups presented a 56.2% and a 52.5% decrease respectively [82,102], and another[85] a 34.7% increase (Tables 2 and 3). When only SA was applied (SA+NOST), decrease of bond strength ≤ 45.1% was observed in most of the studies in the shear group, and ≤ 32.9% in all 5 studies in the tensile group, while 3[163,165,166] studies in the shear group presented decrease ranging from 68.8% to 98.9% and 3 studies [137,138,162]an increase ranging from 2.3% to 54.5%. When SA was combined with other surface treatments, a bond strength decrease was observed ranging from 10.1 to 74.9 for both shear and tensile groups. The application of surface treatments other than SA or TSC, could not show a distinct trend, due to large variation in the included studies. When TSC was applied with no other surface treatment (TSC+NOST), 3 studies in the shear group [88,93,162] presented a low decrease (3.2 −8.5%) and one study[93] a 50% decrease.

3.7. MDP cement + non-MDP primer

The combination MDP cement + non-MDP primer was investigated in a few studies conducting shear or tensile tests, with either SA or TSC pre-treatments alone, without being able to yield any conclusive result for the benefit of this specific combination, because a great variation was recorded among the different studies, irrespectively of the aging protocol applied (Tables 2 and 3).

3.8. MDP cement + MDP primer

Ten studies evaluated the combination of MDP cement + MDP primer by shear test, in zirconia specimens after SA and bond strength change varied from − 1.3–87.7% (Table 2). Most studies presented a decrease up to 46%, one study [173] presented a decrease of 87.7% and another study that test a bioactive cement [147] demonstrated an increase of 1.3%. Low values of bond strength decrease were observed for SA in the study of Thammajaruk et al., 2019[112] with tensile test (0.8% after TC < 10,000 cycles and 11.7% after TC ≥10000 cycles) (Table 3). When no SA was applied, great variation was observed in the mean bond strength percentage of change (−98.3 to 88.7%). This cement/primer combination was used with TSC pre-treatment in only 2 studies, showing decrease in bond strength from 52.6% [175]and 73.5% [174].

Regarding the application of OST, different results were observed whether they were combined or no with SA. In the shear sample groups in which an alternative surface treatment was performed alone, samples which were cemented with non-MDP cement and without MDP primer presented a tendency for low percentage of bond strength change (up to 23.7%) or even increase. These surface treatments included silica coating [127,131], silica-zirconia coating [116], in situ silica nanoparticle surface deposition[122], silica surface infiltration[128] and tribochemical glass-ceramic coating[129]. On the other hand, when SA was performed in combination with an alternative surface treatment, the bond strength change was higher when a non-MDP cement and a non-MDP primer were used [118,119] and when a non-MDP cement and no primer were use [119,140,141]. When MDP cement and MDP primer were used, samples did not present any significant difference whether the alternative surface treatment was combined with SA [119,141,150,156,165] or it was performed alone [150,156,157,165,168,174,175]. Data were not as favorable for specimens without SA that were cemented with a non-MDP cement and an MDP primer was used, as other surface treatments did not seem to result in a durable bond [91,128,150,157] Thus, the combination of an alternative surface treatment with non MDP primers and cements seems to provide a more stable bond compared to the use of an MDP primer instead.

In general, the additional zirconia surface treatments were performed uniquely in the individual studies that utilized them, except for selective infiltration etching[144,165], Nd:YAG laser irradiation [166,169] and non-thermal plasma etching[150,168,174] which were utilized in different studies. Additional surface treatments included argon plasma with or without SA[164], ceramic glaze vitrification [156], CO_2 laser [166], immersion in Si/ Zr primer[149], use of a paste liner with or without HF[165] and silica-based epitaxial transition film formation[161]. Experimental silica coated aluminum oxide particles[94], Bioglass 45S5 particles abrasion [149], slurry coating with silica particles 6.5–8.1 mm (at pre-sintered phase) [175], coating with feldspathic ceramic powder and leucite glass ceramic powder of 45 µm[129], zirconia particle abrasion[102], alumina coating through aluminum nitride suspension[111] are some other surface modifications prior to bonding. Er,Cr:YSGG[144] and Er:YAG[88] laser irradiation etching were other laser treatments that were used. Also, TSC 110 µm [118,119,171] and HF[140,158,175] etching were performed additionally to SA. Other treatments included the immersion in different chemical solutions such as Si_3N_4 and Si_3N_4 -NaOH solution [127], 37% H_3PO_4 [125,157], piranha solution (H_2SO_4:H_2O_2 = 3:1)[102], CH_2Cl_2 and hot etching solution 37% HCl[110].

4. Discussion

Based on the correlations established from the present meta-analysis, the null hypothesis has been rejected as there were several statistical associations established between the surface pre-treatment, MDP content of the cement and primer used as well as the level of artificial aging. The study evaluated the mean bond strength change between resin cements and zirconia ceramics after thermal cycling, as derived from in vitro studies. It is important to estimate the bond strength change of zirconia ceramics to resin-based luting cements in water aging environments after the application of different adhesive protocols to verify their efficiency in bond durability. Immediate bond strength evaluation after cementation has limited clinical significance, as the intraoral conditions may lead to debonding of the restoration, if the bonding interface is not able to withstand its integrity in the wet oral environment. In the present review, all studies selected included at least one non-aged control group. Previous reviews have not rejected studies without non-aged control groups [3,6,179].

Studies that performed shear or tensile bond strength testing were considered for inclusion, as these testing methods are the most widely used for bond strength testing [180]. In addition, ISO (Dentistry — Polymer-based luting materials containing adhesive components, TECHNICAL SPECIFICATION ISO/TS 16506) declares that the standard deviation in that type of test is usually high, so we decided to include studies with at least 5 specimens per group to accommodate this issue. The main surface treatments evaluated, were SA and TSC coating since those pre-treatment methods present the highest amount of existing evidence of efficacy, while they are also mostly accessible to clinicians [181]. Other methods that have been evaluated in in vitro studies were classified as additional surface pre-treatments. In the included studies bonding procedures took place either by curing a resin cement cylinder on the zirconia surface, or by cementing a metallic or composite rod on the zirconia surface with the use of a resin cement. Studies that bonded zirconia to human or animal dental tissues were excluded, since cohesive failures of dentin or enamel during bond strength testing have been reported [182].

The included studies in the present review were grouped according to the pre-treatment method applied and the artificial aging protocol. In most of the subgroups the number of the included studies did not lead to conclusive results according to descriptive statistics, due to the small number of studies applying the same protocols. However, the evaluation of pooled mean difference and percentage of change in values implicated a tendency for better results in groups where MDP-containing products were used, as well as TSC when compared to SA. Most of the other various applied pretreatment methods, did not have a significant impact except the different methods that led to the development of a silica layer. This can be attributed to the greater resistance to hydrolysis of siloxane bonds formed between silanol groups of organo-silane and the developed silica layer on zirconia surface[122].

In the shear group, the use of an MDP cement combined with a non-MDP primer followed by surface pre-treatment with either SA or TSC (with no other surface treatment), led to a lower percentage of change in bond strength values after thermal cycling. In the group where no SA was applied, alternative surface treatments or MDP primer application or MDP cement bonding, yielded the lowest percentages of bond strength reduction. Similarly, low percentages of bond strength change were observed in the group where TSC was performed without further surface treatment but following the application of a non-MDP primer and eventually cemented with a non-MDP cement. Thus, it can be assumed that a simplified cementation method where no mechanical surface treatment is used, or alternatively TSC is performed solely, stable bond strength values may be achieved. This is partly in disagreement with the previous meta-analysis of Inokoshi et al.[183] who concluded that the combination of a mechanical surface treatment with chemical steps is of critical value. Nonetheless, the application of TSC prior to cementation with an MDP cement leads to a reduced percentage of change in the bond strength, according to the present study. This is in agreement with the meta-analysis by Thammajaruk et al. [6].

In the tensile group, where SA was performed followed by the application of an MDP primer and cementation with a non-MDP cement, a reduced percentage of bond strength reduction was observed compared to the respective group in which a non-MDP primer was used. The remaining groups of studies were of insufficient number and have not allowed similar observations as in the shear group. In a recent systematic review, Quigley et al. [181] suggested that SA combined with MDP cement should be in the first line of action for zirconia bonding. This is in agreement with the present study, as derived especially from tensile tests, where low percentages of change were observed in all studies (maximum 32.9% in one study) despite the intense and prolonged aging process (either TC≥10000 or WS + TC≥10000). In the tensile group, the bond strength appears to be more severely affected when aging protocol combines WS and TC, compared to TC solely. This should be taken into consideration since restorations have to adequately function in an aqueous milieu in the oral cavity.

Finally, it should be mentioned that in the present study the tensile and shear bond strength investigations were not divided into micro and macro types of testing as opposed to a recent meta-analysis and authors acknowledge that this remains one of the studies limitations[6]. There is insufficient literature clarifying which surface area may alter the testing type from micro to macro. It has been reported that a decreased bonding area reduces cement defects in the bonded interface and hence ensures a minimum number of pre-test bond failures and this may affect the results of a study depending on the bonded area [184]. Further classification based on micro or macro testing method was abandoned because this would reduce the amount of data available for every individual variable studied, although this parameter could have an impact on the pooled results. In spite of the increased popularity of the “micro” bond strength tests and the criticism endured by the conventional tensile and shear methods, the number of articles using “macro” tests published in recent years remains high, meaning that a lot of the available data on dental adhesion still comes from mechanical tests performed in specimens with large bonded areas. As during chewing, all adhesive interfaces are subjected to both shear and tensile forces, all applied methods can be useful in predicting the bond strength of zirconia to resin.

Clinical studies establish one of the highest levels of scientific evidence. However, it is difficult or impossible to attribute a restoration’s loss of retention solely to its adhesion protocol because other factors such as tooth preparation or chewing forces may significantly affect the restoration’s resistance and retention as well as the magnitude of the forces that tend to displace the restoration [185,186]. The importance of a correct tooth preparation remains fundamental but with a rising predilection of clinicians for less destructive preparations and maximum hard tissue preservation, the importance of factors affecting restoration survival and success leans more towards the adhesive protocol [187,188].

Since zirconia is a pollycrystaline material, the matter of adequate and durable bonding remains unsolved. During the conduction of the present systematic review many different studies were found in literature with regards to the most promising bonding protocol. Investigators have performed various innovative methods – such as piranha solution etching [156], laser pre-treatment[88,144,166,169], silica coating [122,128,131,139], ceramic glaze vitrification[156] – which reveals the ongoing wish of the dental community to answer this crucial scientific question. At the same time, most studies included an artificial aging protocol when testing ceramic materials. However, despite ISO guidelines (ISO 4049:2009, ISO 29022:2013), there is no established aging protocol, which leads to results that cannot be easily compared. In the present study, articles were subgrouped, in order to better analyze the results, in those performing an artificial aging protocol with less than 10.000 thermal cycles or with > 10000 cycles. Gale and Darvell [189] postulated that approximately 10,000 thermal cycles correspond to 1 year of clinical function, so 10.000 cycles can be a convenient threshold based on that. Furthermore, a lot of studies now use a higher number of cycles, and the 10.000 threshold helped to have good homogeneity of the groups. Additionally, control groups included water storage from 0 to 7 days. This selection was based on previous literature. According to the study of Blumer et al. [190], at least 1 day of water storage at 37 °C should be performed prior to TC of resin cements to allow adequate conversion rate and curing. In addition, according to Carek et al. [191], various resin cements present a significant degree of conversion during their first 7 days post-cure and this period seems to be critical to determine their flexural strength and modulus as these properties tend to increase during the first 28 days. Aguiar et al. [192], reported that resin cement micro-hardness increases during the first 7 days following curing, regardless of curing time and conditions. Finally, the classic articles by Mitchell et al. [193], and Knoblock et al. [194], use the 7-day period post-cure as a landmark for the determination of the mechanical properties of resin cements. Thus, in our study we opted to choose the 7-day period following curing of the cements as the baseline period, during which the cements are most likely to have achieved their full mechanical strength. Finally, the cut-off of 6 months was set as there is evidence from literature that after 6 months the hydrolytic stability of MDP-based primer is being significantly reduced [195,196]. Furthermore, alumina sandblasting and tribochemical silica coating remain the pre-treatment methods most widely applied. However, differences in particle size in both treatments may yield different effects on the bond strength. Due to the limited number of studies it was not possible to compare these effects in the present review, suggesting one limitation. Similarly, the aging protocols applied in the included studies varied and involved only thermal cycling, without the effect of mastication loading. Additionally, different types of zirconia ceramics with different composition and crystalline phases, were used in the included studies, a factor that may have influenced bond strength and durability. Thus, the results of this investigation should be considered under those limitations. Power analysis was not performed for the individual studies that fulfilled the inclusion criteria. This parameter determines the statistical reliability of the included study itself, although the majority of the studies do not perform power analysis. Future systematic reviews and meta-analyses should consider this in their inclusion criteria for in-vitro studies.

The use of silane in zirconia bonding protocols that include a silicatization step is fundamental, and not having taken it into consideration in a review dealing with this topic is a limitation. However, the following findings from the present study are clear and should be pointed out in this review. In the shear test group, Campos et al., 2016 [128] compared the use of Monobond Plus and Monobond S, on infiltrated specimens, and found that even though prior to aging Monobond Plus achieved higher bond strength values, following TC of 6000 both primers achieved similar bond strength levels. In the study of Akazawa et al., 2017 [119], a combination of MDP and silane provided the best adhesion values, while zirconia specimens that were submerged in a suspension containing zirconia and silica prior to sintering, presented over 30% higher bond strength values following WS when a silane primer was applied compared to when an MDP primer was applied. In the study of Dal Piva et al., 2019 [91], following TC, MDP primer combined with silane, achieved bond strength values that were at least 3.7 times higher compared to silane primer alone, when these were applied on TSC treated zirconia surface. On the contrary, in the tensile group, no studies were identified that could attribute any similar comparisons between MDP primers and silane primers on TSC treated surfaces.

Finally, studies evaluating the durability of bond strength are the most appropriate when determining the most successful protocol for clinical use. The percentages of bond strength change may be a useful method to compare the effect of aging on bond strength durability. An in-vitro study with a uniform methodology evaluating the different groups of bonding protocols, as they were classified in the present study, may enlighten the question of which bonding protocol offers the most durable bond strength.

5. Conclusions

Within the limitations of the included studies that were not equally distributed to different combinations of surface pre-treatments and cementation protocols, the following conclusions may be drawn: 1. When non-MDP cement and non-MDP primer are used, SA and TSC should be performed, while TSC seems to provide more durable bond compared with SA. 2. The use of MDP primer alone does not seem to provide a clear benefit on the bond durability from in vitro studies, but its combination with SA provides a lower decrease in bond strength after aging. 3. When MDP cement is used alone, a durable bond cannot be guaranteed, unless other surface treatments such as SA or TSC are applied. 4. There is no clear evidence of an additional benefit when combining an MDP cement with an MDP primer. 5. The combination of an MDP cement with TSC may yield more durable results after aging.

Conflict of interest

The authors have no conflicts of interests directly relevant to the content of this article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jdsr.2023.04.002.

References

[1] Denry I, Kelly JR. Emerging ceramic-based materials for dentistry. J Dent Res 2014;93:1235–42. https://doi.org/10.1177/0022034514553627
[2] Pjetursson B.E., Sailer I., Makarov N.A., Zwahlen M., Thoma D.S. Corrigendum to "All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part II: Multiple-unit FDPs" [Dental Materials 31 (6) (2015) 624–639] (S0109564115000627)(10.1016/j.den. Dent Mater 2017;33:e48–51. https://doi.org/10.1016/j.dental.2016.09.033.
[3] Minakuchi S, Meerbeek BVan, Inokoshi M, De Munck J, Minakuchi S, Van Meerbeek B. Meta-analysis of bonding effectiveness to zirconia ceramics. J Dent Res 2014;93:329–34. https://doi.org/10.1177/0022034514524228
[4] Blatz MB, Vonderheide M, Conejo J. The effect of resin bonding on long-term success of high-strength ceramics. J Dent Res 2018;97:132–9. https://doi.org/10.1177/0022034517729134
[5] Tzanakakis E-GGC, Tzoutzas IG, Koidis PT. Is there a potential for durable adhesion to zirconia restorations? A systematic review. J Prosthet Dent 2015;115:9–19. https://doi.org/10.1016/j.prosdent.2015.09.008
[6] Thammajaruk P, Inokoshi M, Chong S, Guazzato M. Bonding of composite cements to zirconia: a systematic review and meta-analysis of in vitro studies. J Mech Behav Biomed Mater 2018;80:258–68. https://doi.org/10.1016/j.jmbbm.2018.02.008
[7] Otani A, Amaral M, May LG, Cesar PF, Valandro LF. A critical evaluation of bond strength tests for the assessment of bonding to Y-TZP. Dent Mater 2015;31:648–56. https://doi.org/10.1016/j.dental.2015.03.002
[8] Ramos NC, Kaizer MR, Campos TMB, Kim J, Zhang Y, Melo RM. Silica-based infiltrations for enhanced zirconia-resin interface toughness. J Dent Res 2019;98:423–9. https://doi.org/10.1177/0022034518819477
[9] da Silva BTF, Trevelin LT, Schroeter AC, Willers AE, Cesar PF, Matos AB. Effect of silica coating and laser treatment on the flexural strength, surface characteristics, and bond strength of a dental zirconia. Eur J Oral Sci 2021;129:1–9. https://doi.org/10.1111/eos.12754
[10] Lima RBW, Barreto SC, Alfrisany NM, Porto TS, De Souza GM, De Goes MF. Effect of silane and MDP-based primers on physico-chemical properties of zirconia and its bond strength to resin cement. Dent Mater 2019;35:1557–67. https://doi.org/10.1016/j.dental.2019.07.008
[11] Chen C, Chen Y, Lu Z, Qian M, Xie H, Tay FR. The effects of water on degradation of the zirconia-resin bond. J Dent 2017;64:23–9. https://doi.org/10.1016/j.jdent.2017.04.004
[12] Aboushelib MN, Ragab H, Arnaot M. Ultrastructural analysis and long-term evaluation of composite-zirconia bond strength. J Adhes Dent 2018;20:33–9. https://doi.org/10.3290/j.jad.a39962
[13] Lima RBW, Barreto SC, Hajhamid B, de Souza GM, de Goes MF. Effect of cleaning protocol on silica deposition and silica-mediated bonding to Y-TZP. Dent Mater 2019;35:1603–13. https://doi.org/10.1016/j.dental.2019.08.099
[14] Zhang X, Liang W, Jiang F, Wang Z, Zhao J, Zhou C, et al. Effects of air-abrasion pressure on mechanical and bonding properties of translucent zirconia. Clin Oral Invest 2020. https://doi.org/10.1007/s00784-020-03506-y
[15] Tzanakakis EG, Dimitriadi M, Tzoutzas I, Koidis P, Zinelis S, Eliades G. Effect of water storage on hardness and interfacial strength of resin composite luting agents bonded to surface-treated monolithic zirconia. Dent J 2021;9(7):78. https://doi.org/10.3390/dj9070078
[16] Müller N, Husain NAH, Chen L, Özcan M. Adhesion of different resin cements to zirconia: effect of incremental versus bulk build up, use of mould and ageing. Materials 2022:15. https://doi.org/10.3390/ma15062186
[17] Yang L, Chen B, Meng H, Zhang H, He F, Xie H, et al. Bond durability when applying phosphate ester monomer–containing primers vs. self-adhesive resin cements to zirconia: Evaluation after different aging conditions. J Prosthodont Res 2020;64:193–201. https://doi.org/10.1016/j.jpor.2019.06.008
[18] Al-Dobaei E, Al-Akhali M, Polonskyi O, Strunskus T, Wille S, Kern M. Influence of cleaning methods on resin bonding to contaminated translucent 3Y-TZP ceramic. J Adhes Dent 2020;22:383–91. https://doi.org/10.3290/j.jad.a44869
[19] Yang L, Xie H, Meng H, Wu X, Chen Y, Zhang H, et al. Effects of luting cements and surface conditioning on composite bonding performance to zirconia. J Adhes Dent 2018;20:549–58. https://doi.org/10.3290/j.jad.a41634
[20] Chen Y, Yao C, Huang C, Wang Y. The effect of monowave and polywave light-polymerization units on the adhesion of resin cements to zirconia. J Prosthet Dent 2019:1–7. https://doi.org/10.1016/j.prosdent.2018.12.010

[21] Vechiato-Filho AJ, Matos AO, Landers R, Goiato MC, Rangel EC, De Souza GM, et al. Surface analysis and shear bond strength of zirconia on resin cements after non-thermal plasma treatment and/or primer application for metallic alloys. Mater Sci Eng C 2017;72:284–92. https://doi.org/10.1016/j.msec.2016.11.033

[22] Xie H, Li Q, Zhang F, Lu Y, Tay FR, Qian M, et al. Comparison of resin bonding improvements to zirconia between one-bottle universal adhesives and tribochemical silica coating, which is better. Dent Mater 2016;32:403–11. https://doi.org/10.1016/j.dental.2015.12.014

[23] Yu M-K, Oh E-J, Lim M-J, Lee K-W. Change of phase transformation and bond strength of Y-TZP with various hydrofluoric acid etching. Restor Dent Endod 2021:46. https://doi.org/10.5395/rde.2021.46.e54

[24] Bielen V, Inokoshi M, De Munck J, Zhang F, Vanmeensel K, Minakuchi S, et al. Bonding effectiveness to differently sandblasted dental zirconia. J Adhes Dent 2015;17:235–42. https://doi.org/10.3290/j.jad.a34401

[25] Kim DS, Ahn JJ, Bae E, Bin, Kim GC, Jeong CM, Huh JB, et al. Influence of non-thermal atmospheric pressure plasma treatment on shear bond strength between Y-TZP and self-adhesive resin cement. Materials 2019:12. https://doi.org/10.3390/ma12203321

[26] Piest C, Wille S, Strunskus T, Polonskyi O, Kern M. Efficacy of plasma treatment for decontaminating zirconia. J Adhes Dent 2018;20:289–97. https://doi.org/10.3290/j.jad.a40986

[27] Aggarwal A, De Souza GM. The role of a MDP/VBATDT-primer composition on resin bonding to Zirconia. Metals 2018:8. https://doi.org/10.3390/met8040247

[28] Tsujimoto A, Barkmeier WW, Takamizawa T, Wilwerding TM, Latta MA, Miyazaki M. Interfacial characteristics and bond durability of universal adhesive to various substrates. Oper Dent 2017;42:e59–70. https://doi.org/10.2341/15-353-L

[29] Khanlar LN, Takagaki T, Abdou A, Inokoshi M, Ikeda M, Takahashi A, et al. Effect of air-particle abrasion protocol and primer on the topography and bond strength of a high-translucent zirconia ceramic. J Prosthodont 2022;31:228–38. https://doi.org/10.1111/jopr.13372

[30] Khanlar LN, Abdou A, Takagaki T, Mori S, Ikeda M, Nikaido T, et al. The effects of different silicatization and silanization protocols on the bond durability of resin cements to new high-translucent zirconia. Clin Oral Invest 2022;26(4):3547–61. https://doi.org/10.1007/s00784-021-04323-7

[31] Garcia I, Soto-Montero J, Collares F, Giannini M. Bonding of resin cements to ultra-translucent zirconia after aging for 24 hours and 1 year. Int J Prosthodont 2022;35:460–8. https://doi.org/10.11607/ijp.7703

[32] Steiner R, Heiss-Kisielewsky I1, Schwarz V, Schnabl D, Dumfahrt H, Laimer J, et al. Zirconia primers improve the shear bond strength of dental zirconia. J Prosthodont 2019. https://doi.org/10.1111/jopr.13013

[33] Yenisey M, Dede DÖ, Rona N. Effect of surface treatments on the bond strength between resin cement and differently sintered zirconium-oxide ceramics. J Prosthodont Res 2016;60:36–46. https://doi.org/10.1016/j.jpor.2015.09.001

[34] Al-Harbi FA, Ayad NM, Khan ZA, Mahrous AA, Morgano SM. In vitro shear bond strength of Y-TZP ceramics to different core materials with the use of three primer/resin cement systems. J Prosthet Dent 2016;115:84–9. https://doi.org/10.1016/j.prosdent.2015.07.002

[35] De Sousa R.S., Campos F., Sarmento H.R., Alves M.L.L., Dal Piva AMDO, Gondim L.D., et al. Surface roughness and bond strength between Y-TZP and self-adhesive resin 6] Lümkemann N, Schönhoff LM, Buser R, Stawarczyk B. Effect of cleaning protocol on bond strength between resin composite cement and three different CAD/CAM materials. Materials (Basel) 2020;13:1–12. https://doi.org/10.3390/ma13184150.

[36] Lümkemann N, Schönhoff LM, Buser R, Stawarczyk B. Effect of Cleaning Protocol on Bond Strength between Resin Composite Cement and Three Different CAD/CAM Materials. Materials (Basel) 2020;13(18):4150.

[37] Lümkemann N, Eichberger M, Stawarczyk B. Different surface modifications combined with universal adhesives: the impact on the bonding properties of zirconia to composite resin cement. Clin Oral Invest 2019;23:3941–50. https://doi.org/10.1007/s00784-019-02825-z

[38] Pozzobona JL, Missaua T, Drucka CC, Özcanb M, Valandroa LF. Effects of different particle deposition parameters on adhesion of resin cement to zirconium dioxide and phase transformation. J Adhes Sci Technol 2016;30:412–21. https://doi.org/10.1080/01694243.2015.1101189

[39] Liebermann A, Detzer J, Stawarczyk B. Impact of recently developed universal adhesives on tensile bond strength to computer-aided design/manufacturing ceramics. Oper Dent 2019;44:386–95. https://doi.org/10.2341/18-017-L

[40] Kim DH, Son JS, Jeong SH, Kim YK, Kim KH, Kwon TY. Efficacy of various cleaning solutions on saliva-contaminated zirconia for improved resin bonding. J Adv Prosthodont 2015;7:85–92. https://doi.org/10.4047/jap.2015.7.2.85

[41] Vicente M, Gomes AL, Montero J, Rosel E, Seoane V, Albaladejo A. Influence of cyclic loading on the adhesive effectiveness of resin-zirconia interface after femtosecond laser irradiation and conventional surface treatments. Lasers Surg Med 2016;48:36–44. https://doi.org/10.1002/lsm.22442

[42] Alnassar T, Ozer F, Chiche G, Blatz MB. Effect of different ceramic primers on shear bond strength of resin-modified glass ionomer cement to zirconia. J Adhes Sci Technol 2016;30:2429–38. https://doi.org/10.1080/01694243.2016.1184404

[43] Alnassar T. Effect of surface treatments and aging solutions on the repair bond strength of composite resin to zirconia. J Biomater Tissue Eng 2017;7:1045–50. https://doi.org/10.1166/jbt.2017.1666

[44] Kaimal A, Ramdev P, Shruthi CS. Evaluation of effect of zirconia surface treatment, using plasma of argon and silane, on the shear bond strength of two composite resin cements. ZC39–43 J Clin Diagn Res 2017;11. https://doi.org/10.7860/JCDR/2017/27426.10372

[45] Fernandes Neto C, Narimatsu MH, Magão PH, da Costa RM, Pfeifer CS, Furuse AY. Physical-chemical characterization and bond strength to zirconia of dental adhesives with different monomer mixtures and photoinitiator systems light-activated with poly and monowave devices. Biomater Invest Dent 2022;9:20–32. https://doi.org/10.1080/26415275.2022.2064289

[46] Sriamporn T, Thamrongananskul N, Klaisiri A. The effectiveness of various functional monomers in self-Adhesive resin cements on prosthetic materials. J Int Soc Prev Community Dent 2022;12:332–5. https://doi.org/10.4103/jispcd.JISPCD_50_22

[47] Shafiei F, Fattah Z, Kiomarsi N, Dashti MH. Influence of primers and additional resin layer on zirconia repair bond strength. J Prosthodont 2019;28:826–32. https://doi.org/10.1111/jopr.13011

[48] Byeon SM, Lee MH, Bae TS. Shear bond strength of Al2O3 sandblasted Y-TZP ceramic to the orthodontic metal bracket. Materials 2017;10:1–14. https://doi.org/10.3390/ma10020148

[49] Chen Y, Lu Z, Qian M, Zhang H, Chen C, Xie H, et al. Chemical affinity of 10-methacryloyloxydecyl dihydrogen phosphate to dental zirconia: Effects of molecular structure and solvents. Dent Mater 2017;33:e415–27. https://doi.org/10.1016/j.dental.2017.09.013

[50] Yu M-K, Lim M-J, Na N-R, Lee K-W. Effect of hydrofluoric acid-based etchant at an elevated temperature on the bond strength and surface topography of Y-TZP ceramics. Restor Dent Endod 2020;45:4–11. https://doi.org/10.5395/rde.2020.45.e6

[51] Murakami T, Takemoto S, Nishiyama N, Aida M. Zirconia surface modification by a novel zirconia bonding system and its adhesion mechanism. Dent Mater 2017;33:1371–80. https://doi.org/10.1016/j.dental.2017.09.001

[52] Şanli S, Çömlekoılu MD, Çömlekoılu E, Sonugelen M, Pamir T, Darvell BW. Influence of surface treatment on the resin-bonding of zirconia. Dent Mater 2015;31:657–68. https://doi.org/10.1016/j.dental.2015.03.004

[53] Noro A, Kameyama A, Haruyama A, Takahashi T. Influence of hydrophilic pre-treatment on resin bonding to zirconia ceramics. Bull Tokyo Dent Coll 2015;56:33–9. https://doi.org/10.2209/tdcpublication.56.33

[54] Qian M, Lu Z, Chen C, Zhang H, Xie H. Alkaline nanoparticle coatings improve resin bonding of 10-methacryloyloxydecyldihydrogenphosphate-conditioned zirconia. Int J Nanomed 2016;11:5057–66. https://doi.org/10.2147/IJN.S116006

[55] Takahashi A., Takagaki T., Wada T., Uo M., Nikaido T., Tagami J. The effect of different cleaning agents on saliva contamination for bonding performance of zirconia ceramics 2018. https://doi.org/10.4012/dmj.2017–376.

[56] Özdemir H, Yanikoğlu N, Sağsöz N. Effect of MDP-based silane and different surface conditioner methods on bonding of resin cements to zirconium framework. J Prosthodont 2019;28:79–84. https://doi.org/10.1111/jopr.12650

[57] Llerena-Icochea AE, Costa RM, Borges AFS, Bombonatti JFS, Furuse AY. Bonding polycrystalline zirconia with 10-MDP-containing adhesives. Oper Dent 2017;42:335–41. https://doi.org/10.2341/16-156-L

[58] Park C, Yoo S-H, Park S-W, Yun K-D, Ji M-K, Shin J-H, et al. The effect of plasma on shear bond strength between resin cement and colored zirconia. J Adv Prosthodont 2017:9. https://doi.org/10.4047/jap.2017.9.2.118

[59] Nagaoka N, Yoshihara K, Feitosa VP, Tamada Y, Irie M, Yoshida Y, et al. Chemical interaction mechanism of 10-MDP with zirconia. Sci Rep 2017:7. https://doi.org/10.1038/srep45563

[60] Cho JH, Kim SJ, Shim JS, Lee K-W. Effect of zirconia surface treatment using nitric acid-hydrofluoric acid on the shear bond strengths of resin cements. J Adv Prosthodont 2017;9:77. https://doi.org/10.4047/jap.2017.9.2.77

[61] Chen Y, Tay FR, Lu Z, Chen C, Qian M, Zhang H, et al. Dipentaerythritol penta-acrylate phosphate - an alternative phosphate ester monomer for bonding of methacrylates to zirconia. Sci Rep 2016;6:1–8. https://doi.org/10.1038/srep39542

[62] Wei Z, Farooq A, Wangping W, Dejun K. Production of alumina micro abrasives coated with nano-silica for bonding improvements to zirconia. J Exp Nanosci 2018;13:212–20. https://doi.org/10.1080/17458080.2018.1502478

[63] Kim SH, Cho SC, Lee MH, Kim HJ, Oh NS. Effect of 9% hydrofluoric acid gel hot-etching surface treatment on shear bond strength of resin cements to zirconia ceramics. Med 2022:58. https://doi.org/10.3390/medicina58101469

[64] Kim JE, Kim JH, Shim JS, Roh BD, Shin Y. Effect of surface treatment on shear bond strength between resin cement and Ce-TZP/Al2O3. Biomed Res Int 2016:2016. https://doi.org/10.1155/2016/7576942

[65] Samran A, Al-Ammari A, El Bahra S, Halboub E, Wille S, Kern M. Bond strength durability of self-adhesive resin cements to zirconia ceramic: An in vitro study. J Prosthet Dent 2019;121:477–84. https://doi.org/10.1016/j.prosdent.2018.03.026

[66] Bömicke W, Schürz A, Krisam J, Rammelsberg P, Rues S. Durability of resin-zirconia bonds produced using methods available in dental practice. J Adhes Dent 2016;18:17–27. https://doi.org/10.3290/j.jad.a35517

[67] Sawada T, Spintzyk S, Schille C, Zöldföldi J, Paterakis A, Schweizer E, et al. Influence of pre-sintered zirconia surface conditioning on shear bond strength to resin cement. Materials 2016;9:1–14. https://doi.org/10.3390/ma9070518

[68] Diniz V, Monteiro JB, Rodrigues JVM. Impact of acid concentration and firing on the long-term bond strength of a zirconia-lithium silicate ceramic following adhesive cementation. J Adhes Dent 2019;21:355–63. https://doi.org/10.3290/j.jad.a42998

[69] Malgaj T, Kocjan A, Jevnikar P. The effect of firing protocols on the resin-bond strength to alumina-coated zirconia ceramics. Adv Appl Ceram 2020;119:267–75. https://doi.org/10.1080/17436753.2019.1651503

[70] Sathish S, Lakshmi S, Patel P, Annapoorni H. Effect of thermocycling on the micro-tensile bond strength between self-adhesive resin cement and non-phosphate monomer cements on zirconium-oxide ceramics. Indian J Dent Res 2019;30:73–9. https://doi.org/10.4103/ijdr.IJDR_361_17
[71] de Araújo Neto VG, Soto-Montero J, de Castro EF, Feitosa VP, Rueggeberg FA, Giannini M. Effects of shades of a multilayered zirconia on light transmission, monomer conversion, and bond strength of resin cement. J Esthet Restor Dent 2022;34:412–22. https://doi.org/10.1111/jerd.12821
[72] Malgaj T, Mirt T, Kocjan A, Jevnikar P. The influence of nanostructured alumina coating on bonding and optical properties of translucent zirconia ceramics: In vitro evaluation. Coatings 2021:11. https://doi.org/10.3390/coatings11091126
[73] Liu T, Hong L, Hottel T, Dong X, Yu Q, Chen M. Non-thermal plasma enhanced bonding of resin cement to zirconia ceramic. Clin Plasma Med 2016;4:50–5. https://doi.org/10.1016/j.cpme.2016.08.002
[74] Thammajaruk P, Buranadham S, Guazzato M, Wang Y. Shear bond strength of composite cement to lithium-disilicate glass-coated zirconia versus alumina air-abraded zirconia. J Adhes Dent 2021;23:267–75. https://doi.org/10.3290/j.jad.b1367913
[75] Scribante A, Contreras-Bulnes R, Montasser MA, Vallittu PK. Orthodontics: bracket materials, adhesives systems, and their bond strength. Biomed Res Int 2016;2016:10–2. https://doi.org/10.1155/2016/1329814
[76] Akay C, Çakırbay Tanış M, Şen M, Akkaş Kavaklı P. Strengthen adhesion between zirconia and resin cement using different surface modifications. Int J Appl Ceram Technol 2019;16:917–22. https://doi.org/10.1111/ijac.13168
[77] Lee M-H, Kwon T-Y, Kim I-H, Kim YK. Effect of incorporating a dimethacrylate monomer on the shear bond strength of two adhesive resin cements to zirconia ceramic. J Nanosci Nanotechnol 2021;21:4046–50. https://doi.org/10.1166/jnn.2021.19166
[78] Gutierrez MF, Perdigao J, Malaquias P, Cardenas AM, Siqueira F, Hass V, et al. Effect of methacryloyloxydecyl dihydrogen phosphate-containing silane and adhesive used alone or in combination on the bond strength and chemical interaction with zirconia ceramics under thermal aging. Oper Dent 2020;45:516–27. https://doi.org/10.2341/18-093-L
[79] Silva GAF, Da Luz EC, Dos Reis Goyatá F, Da Silva Concilio LR, Neves ACC, Vitti RP, et al. Influence of surface treatments on topography and bond strength of densely-sintered zirconium-oxide ceramic. Ceram Int 2016;42:8136–9. https://doi.org/10.1016/j.ceramint.2016.02.019
[80] Sarfaraz H, Rasheed MN, Shetty SK, Prabhu UM, Fernandes K, Mohandas S. Comparison of the bond strength of composite resin to zirconia and composite resin to polyether ether ketone: an in vitro study. J Pharm Bioallied Sci 2020;12:S504–9. https://doi.org/10.4103/jpbs.JPBS_147_20
[81] li R, Wang C, Ma SQ, Liu ZH, Zang CC, Zhang WY, et al. High bonding strength between zirconia and composite resin based on combined surface treatment for dental restorations. J Appl Biomater Funct Mater 2020:18. https://doi.org/10.1177/2280800020928655
[82] Ataol AS, Ergun G. Effects of surface treatments on repair bond strength of a new CAD/CAM ZLS glass ceramic and two different types of CAD/CAM ceramics. J Oral Sci 2018;60:201–11. https://doi.org/10.2334/josnusd.17-0109
[83] Moqbel NM, Al-Akhali M, Wille S, Kern M. Influence of aging and surface treatment on the composite bond strength to translucent 3Y-TZP zirconia. J Adhes Dent 2022 18;24(1):375–84. https://doi.org/10.3290/j.jad.b3500591
[84] Rui L, Ma SQ, Liu ZH, Chen ML, Liu J, Wu J, et al. High shear bond strength between zirconia ceramic and resin cement via surface treatment and cleaning. Mater Res Express 2021:8. https://doi.org/10.1088/2053-1591/ac2bd1
[85] Rebholz-Zaribaf N, Özcan M. Adhesion to zirconia as a function of primers/silane coupling agents, luting cement types, aging and test methods. J Adhes Sci Technol 2017;31:1408–21. https://doi.org/10.1080/01694243.2016.1259727
[86] Lopes GC, Spohr AM, de Souza GM. Different Strategies to Bond bis-GMA-based resin cement to zirconia. J Adhes Dent 2016;18:239–46. https://doi.org/10.3290/j.jad.a36137
[87] Seo SH, Kim JE, Nam NE, Moon HS. Effect of air abrasion, acid etching, and aging on the shear bond strength with resin cement to 3Y-TZP zirconia. J Mech Behav Biomed Mater 2022:134. https://doi.org/10.1016/j.jmbbm.2022.105348
[88] Gomes AL, Ramos JC, Santos-del Riego S, Montero J, Albaladejo A. Thermocycling effect on microshear bond strength to zirconia ceramic using Er:YAG and tribochemical silica coating as surface conditioning. Lasers Med Sci 2015;30:787–95. https://doi.org/10.1007/s10103-013-1433-z
[89] Kang LL, Chuang SF, Li CL, Lin JC, Lai TW, Wang CC. Enhancing resin cement adhesion to zirconia by oxygen plasma-aided silicatization. Materials 2022:15. https://doi.org/10.3390/ma15165568
[90] Negreiros WM, Ambrosano GMB, Giannini M. Effect of cleaning agent, primer application and their combination on the bond strength of a resin cement to two yttrium-tetragonal zirconia polycrystal zirconia ceramics. Eur J Dent 2017;11:6–11. https://doi.org/10.4103/ejd.ejd_276_16
[91] Dal Piva AMO, Carvalho RLA, Lima AL, Bottino MA, Melo RM, Valandro LF. Silica coating followed by heat-treatment of MDP-primer for resin bond stability to yttria-stabilized zirconia polycrystals. J Biomed Mater Res - Part B Appl Biomater 2019:33–5. https://doi.org/10.1002/jbm.b.34100
[92] Kim JH, Chae SY, Lee Y, Han GJ, Cho BH. Effects of multipurpose, universal adhesives on resin bonding to zirconia ceramic. Oper Dent 2015;40:55–62. https://doi.org/10.2341/13-303-L
[93] Re D, Augusti G, Merlati G, Giannì AB, Augusti D. Effect of thermal cycling and low pressure sandblasting on the bond strength of a self-adhesive cement to Y-TZP zirconia. J Adhes Sci Technol 2015;29:1745–57. https://doi.org/10.1080/01694243.2015.1046729
[94] Cadore-Rodrigues AC, Prochnow C, Burgo TAL, Oliveira JS, Jahn SL, Foletto EL, et al. Stable resin bonding to Y-TZP ceramic with air abrasion by alumina particles containing 7% silica. J Adhes Dent 2020;22:149–59. https://doi.org/10.3290/j.jad.a44151
[95] Silveira MPM, Ramos N, de C, Lopes G, da RS, Tribst JPM, et al. Bond strength between different zirconia-based ceramics and resin cement before and after aging. Coatings 2022:12. https://doi.org/10.3390/coatings12101601
[96] Wille S, Lehmann F, Kern M. Durability of resin bonding to lithium disilicate and zirconia ceramic using a self-etching primer. J Adhes Dent 2017;19:491–6. https://doi.org/10.3290/j.jad.a39545
[97] Elsayed A, Younes F, Lehmann F, Kern M. Tensile bond strength of so-called universal primers and universal multimode adhesives to zirconia and lithium disilicate ceramics. J Adhes Dent 2017;19:221–8. https://doi.org/10.3290/j.jad.a38436
[98] Koko M, Takagaki T, Abdou A, Inokoshi M, Ikeda M, Wada T, et al. Effects of the ratio of silane to 10-methacryloyloxydecyl dihydrogenphosphate (MDP) in primer on bonding performance of silica-based and zirconia ceramics. J Mech Behav Biomed Mater 2020;112:1–8. https://doi.org/10.1016/j.jmbbm.2020.104026
[99] Hallmann L, Ulmer P, Lehmann F, Wille S, Polonskyi O, Johannes M, et al. Effect of surface modifications on the bond strength of zirconia ceramic with resin cement resin. Dent Mater 2016;32:631–9. https://doi.org/10.1016/j.dental.2016.02.001
[100] Yoshida K. Influence of alumina air-abrasion for highly translucent partially stabilized zirconia on flexural strength, surface properties, and bond strength of resin cement. J Appl Oral Sci 2020:28. https://doi.org/10.1590/1678-7757-2019-0371
[101] Passia N, Mitsias M, Lehmann F, Kern M. Short communication Bond strength of a new generation of universal bonding systems to zirconia ceramic. J Mech Behav Biomed Mater 2016;62:268–74. https://doi.org/10.1016/j.jmbbm.2016.04.045
[102] Ebeid K, Wille S, Salah T, Wahsh M, Zohdy M, Kern M. Bond strength of resin cement to zirconia treated in pre-sintered stage. J Mech Behav Biomed Mater 2018;86:84–8. https://doi.org/10.1016/j.jmbbm.2018.06.027
[103] Al-Akhali M, Al-Dobaei E, Wille S, Mourshed B, Kern M. Influence of elapsed time between airborne-particle abrasion and bonding to zirconia bond strength. Dent Mater 2021;37:516–22. https://doi.org/10.1016/j.dental.2020.12.010
[104] Luz Madrigal E, Tichy A, Hosaka K, Ikeda M, Nakajima M, Tagami J. The effect of curing mode of dual-cure resin cements on bonding performance of universal adhesives to enamel, dentin and various restorative materials. Dent Mater J 2021;40:446–54. https://doi.org/10.4012/dmj.2020-077
[105] Yoshida K. Effect of 10-methacryloyloxydecyl dihydrogen phosphate concentrations in primers on bonding resin cements to zirconia. J Prosthodont 2021;30:356–62. https://doi.org/10.1111/jopr.13255
[106] Güers P, Wille S, Strunskus T, Polonskyi O, Kern M. Durability of resin bonding to zirconia ceramic after contamination and the use of various cleaning methods. Dent Mater 2019;35:1388–96. https://doi.org/10.1016/j.dental.2019.07.027
[107] Xiong Y, Zhao P, Jin C, Wang J, Arola D, Gao S. Effect of airborne-particle abrasion protocols and MDP-based Primer on the bond strength of highly translucent zirconia. J Adhes Dent 2021;23:437–46.
[108] Abu Ruja M, De Souza GM, Finer Y. Ultrashort-pulse laser as a surface treatment for bonding between zirconia and resin cement. Dent Mater 2019;35:1545–56. https://doi.org/10.1016/j.dental.2019.07.009
[109] Ruales-Carrera E, Cesar PF, Henriques B, Fredel MC, Özcan M, Volpato CAM. Adhesion behavior of conventional and high-translucent zirconia: effect of surface conditioning methods and aging using an experimental methodology. J Esthet Restor Dent 2019:1–10. https://doi.org/10.1111/jerd.12490
[110] Sakrana AA, Özcan M. Effect of chemical etching solutions versus air abrasion on the adhesion of self-adhesive resin cement to IPS e.max ZirCAD with and without aging. Int J Esthet Dent 2017;12:72–85.
[111] Thammajaruk P, Thanatvarakorn O. Influence of nano-structured alumina coating on composite-zirconia bonding and its characterization. J Adhes Dent 2018;20:233–43. https://doi.org/10.3290/j.jad.a40512
[112] Thammajaruk P, Buranadham S, Thanatvarakorn O, Ferrari M, Guazzato M. Influence of glass-ceramic coating on composite zirconia bonding and its characterization. Dent Mater 2019;35:105–13. https://doi.org/10.1016/j.dental.2018.11.001
[113] Sakrana AA. Bond strength durability of adhesive cements to translucent zirconia. Eff Surf Cond 2020:161–71. https://doi.org/10.1922/EJPRD
[114] Lenz U, Alessandretti R, Della Bona A. Resin bond strength to translucent zirconia: a 2-year follow-up. Int J Adhes Adhes 2021:110. https://doi.org/10.1016/j.ijadhadh.2021.102930
[115] Xiong Y, Zhao P, Jin C, Wang J, Arola D, Gao S. Effect of airborne-particle abrasion protocols and mdp-based primer on the bond strength of highly translucent zirconia. J Adhes Dent 2021;23:437–46.
[116] Su Z, Li M, Zhang L, Wang C, Zhang L, Xu J, et al. A novel porous silica-zirconia coating for improving bond performance of dental zirconia. J Zhejiang Univ Sci B 2021;22:214–22. https://doi.org/10.1631/jzus.B2000448
[117] Chuang SF, Kang LL, Liu YC, Lin JC, Wang CC, Chen HM, et al. Effects of silane- and MDP-based primers application orders on zirconia–resin adhesion—A ToF-SIMS study. Dent Mater 2017;33:923–33. https://doi.org/10.1016/j.dental.2017.04.027

[118] Lee JJ, Kang CK, Oh JW, Seo JM, Park JM. Evaluation of shear bond strength between dual cure resin cement and zirconia ceramic after thermocycling treatment. J Adv Prosthodont 2015;7:1–7. https://doi.org/10.4047/jap.2015.7.1.1
[119] Akazawa N, Koizumi H, Nogawa H, Nakayama D, Kodaira A, Matsumura H. Effect of mechanochemical surface preparation on bonding to zirconia of a trin-butylborane initiated resin. Dent Mater J 2017;36:19–26. https://doi.org/10.4012/dmj.2016-099
[120] Yagawa S, Komine F, Fushiki R, Kubochi K, Kimura F, Matsumura H. Effect of priming agents on shear bond strengths of resin-based luting agents to a translucent zirconia material. J Prosthodont Res 2017. https://doi.org/10.1016/j.jpor.2017.08.011
[121] Ramos NC, Alves LMM, Ricco P, Santos GMAS, Bottino MA, Campos TMB, et al. Strength and bondability of a dental Y-TZP after silica sol-gel infiltrations. Ceram Int 2020;46:17018–24. https://doi.org/10.1016/j.ceramint.2020.03.288
[122] Oliveira-Ogliari A, Collares FM, Feitosa VP, Sauro S, Ogliari FA, Moraes RR. Methacrylate bonding to zirconia by in situ silica nanoparticle surface deposition. Dent Mater 2015;31:68–76. https://doi.org/10.1016/j.dental.2014.11.011
[123] Pott PC, Stiesch M, Eisenburger M. Influence of artificial aging on the shear bond strength of zirconia - composite interfaces after pretreatment with new 10 - MDP adhesive systems. Jdmt 2016;5:1–10.
[124] Zhao M, Zheng Y, Zhang J-F, Ou X, Gao X, Zhang B, et al. The effect of adhesive surface with porcelain sintering and two silane coupling agents on the adhesive properties of zirconia. 87–87 Ann Transl Med 2022;10. https://doi.org/10.21037/atm-22-72
[125] Noda Y, Nakajima M, Takahashi M, Mamanee T, Hosaka K, Takagaki T, et al. The effect of five kinds of surface treatment agents on the bond strength to various ceramics with thermocycle aging. Dent Mater J 2017;36:755–61. https://doi.org/10.4012/dmj.2016-383
[126] Alegría-Acevedo LF, Gutiérrez MF, Perdigão J, Núñez A, Méndez-Bauer L, Dávila-Sanchez A, et al. In vitro performance of different universal adhesive systems on several CAD/CAM restorative materials after thermal aging. Oper Dent 2022;47:107–20. https://doi.org/10.2341/20-203-L
[127] Lung CYK, Liu D, Matinlinna JP. Silica coating of zirconia by silicon nitride hydrolysis on adhesion promotion of resin to zirconia. Mater Sci Eng C 2015;46:103–10. https://doi.org/10.1016/j.msec.2014.10.029
[128] Campos TMB, Ramos NC, MacHado JPB, Bottino MA, Souza ROA, Melo RM. A new silica-infiltrated Y-TZP obtained by the sol-gel method. J Dent 2016;48:55–61. https://doi.org/10.1016/j.jdent.2016.03.004
[129] Wandscher VF, Fraga S, Pozzobon JL, Soares FZM, Foletto EL, May LG, et al. Tribochemical glass ceramic coating as a new approach for resin adhesion to zirconia. J Adhes Dent 2016;18:435–41. https://doi.org/10.3290/j.jad.a36892
[130] Thammajaruk P, Blatz MB, Buranadham S, Guazzato M, Wang Y. Shear bond strength of composite cement to alumina-coated versus tribochemical silica-treated zirconia. J Mech Behav Biomed Mater 2020;105:103710.
[131] Abdalla MM, Lung CYK, Tsoi JKH, Matinlinna JP. Dental resin-zirconia bonding promotion using high-silica PVD coating with high ionization sputtering processing. Coatings 2019:9. https://doi.org/10.3390/COATINGS9030182
[132] Chen B, Yan Y, Xie H, Meng H, Zhang H, Chen C. Effects of tribochemical silica coating and alumina-particle air abrasion on 3Y-TZP and 5Y-TZP: Evaluation of surface hardness, roughness, bonding, and phase transformation. J Adhes Dent 2020;22:373–82. https://doi.org/10.3290/j.jad.a44868
[133] Qeblawi DM, Campillo-Funollet M, Muñoz CA. In vitro shear bond strength of two self-adhesive resin cements to zirconia. J Prosthet Dent 2015;113:122–7. https://doi.org/10.1016/j.prosdent.2014.08.006
[134] Feitosa SA, Patel D, Borges ALS, Alsheeri EZ, Bottino MA, Özcan M, et al. Effect of cleansing methods on saliva-contaminated zirconia- an evaluation of resin bond durability. Oper Dent 2015;40:163–71. https://doi.org/10.2341/13-323-L
[135] Maño EP, Algarra RM, Fawzy A, Leitune VCB, Collares FM, Feitosa V, et al. In vitro bonding performance of modern self-adhesive resin cements and conventional resin-modified glass ionomer cements to prosthetic substrates. Appl Sci 2020;10:1–15. https://doi.org/10.3390/app10228157
[136] Yang L. Durability of Resin Bonding to Zirconia Using Products Containing 10-Methacryloyloxydecyl Dihydrogen 2018;20:279–287. https://doi.org/10.3290/j.jad.a40989.
[137] Pitta J, Branco TC, Portugal J. Effect of saliva contamination and artificial aging on different primer/cement systems bonded to zirconia. J Prosthet Dent 2018;119:833–9. https://doi.org/10.1016/j.prosdent.2017.07.006
[138] Soto-Montero J, Missiato AV, Dias CT, dos S, Giannini M. Effect of airborne particle abrasion and primer application on the surface wettability and bond strength of resin cements to translucent zirconia. J Adhes Sci Technol 2022. https://doi.org/10.1080/01694243.2022.2079326
[139] Liu X, Jiang X, Xu T, Zhao Q, Zhu S. Investigating the shear bond strength of five resin-based luting agents to zirconia ceramics. J Oral Sci 2020;62:84–8. https://doi.org/10.2334/josnusd.18-0480
[140] Lee MH, Son JS, Kim KH, Kwon TY. Improved resin-zirconia bonding by room temperature hydrofluoric acid etching. Materials 2015;8:850–66.
[141] Sanal FA, Kilinc H. Do different sintering conditions influence bond strength between the resin cements and a currently used esthetic zirconia. J Adhes Sci Technol 2020;34:1809–22. https://doi.org/10.1080/01694243.2020.1783773
[142] Lee SE, Bae JH, Choi JW, Jeon YC, Jeong CM, Yoon MJ, et al. Comparative shear-bond strength of six dental self-adhesive resin cements to zirconia. Materials 2015;8:3306–15. https://doi.org/10.3390/ma8063306
[143] Zhao L, Jian YT, Wang XD, Zhao K. Bond strength of primer/cement systems to zirconia subjected to artificial aging. J Prosthet Dent 2016;116:790–6. https://doi.org/10.1016/j.prosdent.2016.03.020
[144] Saade J, Skienhe H, Ounsi HF, Matinlinna JP, Salameh Z. Evaluation of the effect of different surface treatments, aging and enzymatic degradation on zirconia-resin micro-shear bond strength. Clin Cosmet Invest Dent 2020;12:1–8. https://doi.org/10.2147/CCIDE.S219705
[145] Druck CC, Pozzobon JL, Callegari GL, Dorneles LS, Valandro LF. Adhesion to Y-TZP ceramic: study of silica nanofilm coating on the surface of Y-TZP. J Biomed Mater Res - Part B Appl Biomater 2015;103:143–50. https://doi.org/10.1002/jbm.b.33184
[146] Salem R, Ozkurt-Kayahan Z, Kazazoglu E. In vitro evaluation of shear bond strength of three primer/resin cement systems to monolithic zirconia. Int J Prosthodont 2019;32:519–25. https://doi.org/10.11607/ijp.6258
[147] Elgendy M, Mosleh I, Zaghloul H. Micro-shear bond strength of bioactive cement to translucent zirconia after thermocycyling: a comparative in-vitro study. Braz Dent Sci 2020:23. https://doi.org/10.14295/bds.2020.v23i1.1830
[148] Yoshida K. Influence of cleaning methods on resin bonding to saliva-contaminated zirconia. J Esthet Restor Dent 2018;30:259–64. https://doi.org/10.1111/jerd.12369
[149] Darvizeh A, Luzi A, Amin AA, Oliveira-Ogliari A, Ogliari FA, Feitosa VP, et al. In-situ nano-silica deposition and air-abrasion with Bioglass 45S5 or aluminium oxide: Effects on methacrylate bonding to yttria-tetragonal zirconia polycrystal. Int J Adhes Adhes 2015;62:32–9. https://doi.org/10.1016/j.ijadhadh.2015.06.008
[150] Ahn JJ, Kim DS, Bae E, Bin, Kim GC, Jeong CM, Huh JB, et al. Effect of non-thermal atmospheric pressure plasma (NTP) and zirconia primer treatment on shear bond strength between Y-TZP and resin cement. Materials 2020:13. https://doi.org/10.3390/MA13183934.
[151] Ishii R, Tsujimoto A, Takamizawa T, Tsubota K, Suzuki T, Shimamura Y, et al. Influence of surface treatment of contaminated zirconia on surface free energy and resin cement bonding. Dent Mater J 2015;34:91–7. https://doi.org/10.4012/dmj.2014-066
[152] Rohr N, Märtin S, Zitzmann NU, Fischer J. A comprehensive in vitro study on the performance of two different strategies to simplify adhesive bonding. J Esthet Restor Dent 2022;34:833–42. https://doi.org/10.1111/jerd.12903
[153] Awad MM, Alhalabi F, Alzahrani KM, Almutiri M, Alqanawi F, Albdiri L, et al. 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP)-containing cleaner improves bond strength to contaminated monolithic zirconia: an in-vitro study. Materials 2022;15:1023.
[154] Yan Y, Zhang H, Yang J, Chen C. Evaluating the bonding performance of a novel dual-curing composite cement to zirconia. J Adhes Dent 2021;23:569–78. https://doi.org/10.3290/j.jad.b2288181
[155] El-Wassefy NAM, Özcan M, El-Farag SAA. Effect of simultaneous sintering of bioglass to a zirconia core on properties and bond strength. Materials 2021:14. https://doi.org/10.3390/ma14237107
[156] Feitosa SA, Lima NB, Yoshito WK, Campos F, Bottino MA, Valandro LF, et al. Bonding strategies to full-contour zirconia: zirconia pretreatment with piranha solution, glaze and airborne-particle abrasion. Int J Adhes Adhes 2017;77:151–6. https://doi.org/10.1016/j.ijadhadh.2017.05.007
[157] Mangione E, Özcan M. Adhesion of resin cements to contaminated zirconia resin cements on zirconia: effect saliva-contamination and surface conditioning. J Adhes Sci Technol 2019;33:1572–83. https://doi.org/10.1080/01694243.2019.1602903
[158] LE M, LARSSON C, PAPIA E. Bond strength between MDP-based cement and translucent zirconia. Dent Mater J 2019;38:480–9. https://doi.org/10.4012/dmj.2018-194
[159] Moon JE, Kim SH, Lee JB, Han JS, Yeo IS, Ha SR. Effects of airborne-particle abrasion protocol choice on the surface characteristics of monolithic zirconia materials and the shear bond strength of resin cement. Ceram Int 2016;42:1552–62. https://doi.org/10.1016/j.ceramint.2015.09.104
[160] Kwon SM, Min BK, Kim YK, Kwon TY. Influence of sandblasting particle size and pressure on resin bonding durability to zirconia: a residual stress study. Materials 2020;13:1–12. https://doi.org/10.3390/ma13245629
[161] Liu X, Wang H, Yu S, Zhao Q, Shi Z, Cui Z, et al. Construction of a silicate-based epitaxial transition film on a zirconia ceramic surface to improve the bonding quality of zirconia restorations. RSC Adv 2020;10:32476–84. https://doi.org/10.1039/d0ra04735j
[162] Pardo NP, Araya PL, Pardo MP. Effect of different surface treatments on the bonds strength of a resin cement in zirconia frameworks. J Int Dent Med Res 2016;9:1–5.
[163] Franco-Tabares S, Stenport VF, Hjalmarsson L, Tam PL, Johansson CB. Chemical bonding to novel translucent zirconias: a mechanical and molecular investigation. J Adhes Dent 2019;21:107–16. https://doi.org/10.3290/j.jad.a42361
[164] de Mendonça BC, Negreiros WM, Giannini M. Effect of aluminum oxide sandblasting, plasma application and their combination on the bond strength of resin cement to zirconia ceramics. Braz Dent Sci 2019;22:275–80. https://doi.org/10.14295/bds.2019.v22i2.1721
[165] Cheung GJK, Botelho MG. Zirconia surface treatments for resin bonding. J Adhes Dent 2015;17:551–8. https://doi.org/10.3290/j.jad.a35249
[166] Kasraei S, Rezaei-Soufi L, Yarmohamadi E, Shabani A. Effect of CO_2 and Nd:YAG lasers on shear bond strength of resin cement to zirconia ceramic. J Dent 2015;12:686–94.
[167] Petkosit P, Sanohkan S. The effect of curing pressure on shear bond strength of zirconia to resin cement. Open Dent J 2022;15:410–6. https://doi.org/10.2174/1874210602115010410
[168] Negreiros W. Adhesion of resin cement to zirconia using argon plasma and primer. Int J Prosthodont 2021:1–16. https://doi.org/10.11607/ijp.7118

[169] Liu L, Liu S, Song X, Zhu Q, Zhang W. Effect of Nd: YAG laser irradiation on surface properties and bond strength of zirconia ceramics. Lasers Med Sci 2015;30:627–34. https://doi.org/10.1007/s10103-013-1381-7
[170] Paschoalino M., Paschoalino J., Carvalho L.A. De. Effect of different air-abrasion protocols on topography, surface wettability and adhesion of MDP monomer-based resin cement to zirconia Effect of different air-abrasion protocols on topography, surface wettability and adhesion of MDP monomer-based resi 2019;33:1948–58.
[171] Zaia WLS, de Figueiredo JLG, Leite LM, Satake A, Medeiros IS. Bond strenght of zirconia submitted to different surface treatments. Pesqui Bras Odontopediatria Clin Integr 2015;15:387–98. https://doi.org/10.4034/PBOCI.2015.151.41
[172] Cao Y, Zhang J-F, Ou X, Zhang B, Chen L, Deng X-H. The effects of four primers and two cement types on the bonding strength of zirconia. 248–248 Ann Transl Med 2022;10. https://doi.org/10.21037/atm-21-4909
[173] Hjerppe J, Perea-Lowery L, Lassila LVJ, Vallittu PK. Effect of potassium hydrogen difluoride in zirconia-to-resin bonding. Dent Mater J 2021;40:245–52. https://doi.org/10.4012/dmj.2019-389
[174] Nogueira Alvim HC, Silva-Concilio LR, da, Cavalcanti de Queiroz JR, Amaral M, Vitti RP, Claro Neves AC. Influence of plasma-based dry etching on the bond strength of Y-TZP ceramic. Gen Dent 2018;66:e11–5.
[175] Liu D, Tsoi JKH, Matinlinna JP, Wong HM. Effects of some chemical surface modifications on resin zirconia adhesion. J Mech Behav Biomed Mater 2015;46:23–30. https://doi.org/10.1016/j.jmbbm.2015.02.015
[176] Emamieh S, Elahi M, Ghasemi A. Effect of two universal adhesives on micro-shear bond strength of resin cement to zirconia. Dent Med Probl 2019;56:245–9. https://doi.org/10.17219/dmp/109349
[177] Renata Vasconcelos Monteiro. Effect of Universal Adhesives on Long-term Bond Strength to Zirconia. J Adhes n.d. https://doi.org/10.3290/j.jad.b3512333.
[178] Thammajaruk P, Buranadham S, Thanatvarakorn O, Ferrari M, Guazzato M. Influence of glass-ceramic coating on composite zirconia bonding and its characterization. Dent Mater 2019;35:105–13. https://doi.org/10.1016/j.dental.2018.11.001
[179] Gresnigt MMM, Cune MS, de Roos JG, Özcan M. Effect of immediate and delayed dentin sealing on the fracture strength, failure type and Weilbull characteristics of lithiumdisilicate laminate veneers. Dent Mater 2015. https://doi.org/10.1016/j.dental.2016.01.001
[180] Scherrer SS, Swain MV, CPF, Scherrer SS, Cesar PF, Swain MV. Direct comparison of the bond strength results of the different test methods: a critical literature review. Dent Mater 2010;26:e78–93. https://doi.org/10.1016/j.dental.2009.12.002
[181] Quigley NP, Loo DSS, Choy C, Ha WN. Clinical efficacy of methods for bonding to zirconia: a systematic review. J Prosthet Dent 2021;125:231–40. https://doi.org/10.1016/j.prosdent.2019.12.017
[182] Armstrong S, Geraldeli S, Maia R, Raposo LHA, Soares CJ, Yamagawa J. Adhesion to tooth structure: a critical review of "micro" bond strength test methods. Dent Mater 2010;26:50–62. https://doi.org/10.1016/j.dental.2009.11.155
[183] Inokoshi M, Kameyama A, De Munck J, Minakuchi S, Van Meerbeek B. Durable bonding to mechanically and/or chemically pre-treated dental zirconia. J Dent 2013;41:170–9. https://doi.org/10.1016/j.jdent.2012.10.017
[184] Otani A, Amaral M, May LG, Cesar PF, Valandro LF. A critical evaluation of bond strength tests for the assessment of bonding to Y-TZP. Dent Mater 2015;31:648–56. https://doi.org/10.1016/j.dental.2015.03.002
[185] Tiu J, Al-Amleh B, Waddell JN, Duncan WJ. Clinical tooth preparations and associated measuring methods: a systematic review. J Prosthet Dent 2015;113:175–84. https://doi.org/10.1016/j.prosdent.2014.09.007
[186] Parker MH. Resistance form in tooth preparation. Dent Clin North Am 2004;48:387–96. https://doi.org/10.1016/j.cden.2003.12.009
[187] Kern M. Bonding to oxide ceramics-Laboratory testing versus clinical outcome. Dent Mater 2014;31:1–7. https://doi.org/10.1016/j.dental.2014.06.007
[188] Shahdad S, Cattell MJ, Cano-Ruiz J, Gamble EGA. Clinical evaluation of all ceramic zirconia framework resin bonded bridges. Eur J Prosthodont Restor Dent 2018:203–11. https://doi.org/10.1922/EJPRD
[189] Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent 1999;27:89–99.
[190] Blumer L, Schmidli F, Weiger R, Fischer J. A systematic approach to standardize artificial aging of resin composite cements. Dent Mater 2015;31:855–63. https://doi.org/10.1016/j.dental.2015.04.015
[191] Carek A., Dukaric K., Miler H., Marovic D., Tarle Z., Par M. Post-Cure Development of the Degree of Conversion and Mechanical Properties of Dual-Curing Resin Cements. Polymers (Basel). 2022;14:3649. doi: 10.3390/polym14173649. PMID: 36080725; PMCID: PMC9460751.
[192] Aguiar TC, Saad JRC, Pinto SCS, Calixto LR, Lima DM, Silva MAS, et al. The effects of exposure time on the surface microhardness of three dual-cured dental resin cements. Polymers 2011;3:998–1005. https://doi.org/10.3390/polym3030998
[193] Mitchell CA, Douglas WH, Cheng YS. Fracture toughness of conventional, resin-modified glass-ionomer and composite luting cements. Dent Mater 1999;15:7–13. https://doi.org/10.1016/s0109-5641(99)90024-6
[194] Knobloch LA, Kerby RE, Seghi R, Berlin JS, Lee JS. Fracture toughness of resin-based luting cements. J Prosthet Dent 2000;83:204–9. https://doi.org/10.1016/s0022-3913(00)80013-x
[195] Saade J, Skienhe H, Ounsi HF, Matinlinna JP, Salameh Z. Evaluation of the effect of different surface treatments, aging and enzymatic degradation on zirconia-resin micro-shear bond strength. Clin Cosmet Invest Dent 2020;12:1–8. https://doi.org/10.2147/CCIDE.S219705
[196] da Silva EM, Miragaya L, Sabrosa CE, Maia LC. Stability of the bond between two resin cements and an yttria-stabilized zirconia ceramic after six months of aging in water. J Prosthet Dent 2014;112:568–75. https://doi.org/10.1016/j.prosdent.2013.12.003