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Selective effect of atmospheric non-thermal plasma on resin cement shear bond strength to glass ceramics

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Abstract

Statement of problem The effectiveness of non-thermal plasma (NTP) in improving the bond strength of different resin cements to different glass ceramics under various surface treatment protocols remains unclear. Moreover, the influence of specific plasma devices and the material-dependent response of ceramic–resin cement systems to NTP have not been sufficiently investigated.

Purpose The purpose of this in vitro study was to evaluate the effect of NTP on the shear bond strength of different resin cements to different glass ceramics by comparatively assessing multiple surface treatment protocols.

Materials and methods A total of 240 specimens of each glass ceramic group (IPS e.max CAD (E), Vitamark II (V)) were divided into 24 groups according to the combination of 6 surface treatments ((control), hydrofluoric acid (HF)+ceramic primer (Pr), Pr, HF+plasma (PI) + Pr, PI + Pr, and PI) and two different resin cements (Single Bond+RelyX Ultimate (R) and ZenitCem (Z)). NTP was applied with an AC microsecond pulse power supply (5 kHz, 20 kV, 90 s). Specimens were cemented to composite cylinders. After storage in an oven, SBS was measured. The results were analyzed using three-way ANOVA, post-hoc tests, and targeted pairwise comparisons, with the significance level set at $\alpha = 0.05$.

The effectiveness of NTP is material- and cement-dependent and should be considered as a selective surface modification strategy rather than a universal alternative to conventional surface treatments.

Results The V-PI-Z group showed significantly higher SBS values than the V-Z group, and these values were within the clinically acceptable range ($p < 0.05$). In the V groups treated with HF + Pr and HF + PI+Pr, R demonstrated higher bond strength values than Z. HF surface treatment increased the SBS values for all groups ($p < 0.05$).

Conclusions The effectiveness of NTP is material- and cement-dependent and should be considered as a selective surface modification strategy rather than a universal alternative to conventional surface treatments

Clinical significance This study demonstrates that atmospheric non-thermal plasma does not universally enhance ceramic–resin cement bonding. Its effectiveness depends on the ceramic substrate, resin cement type, and surface treatment protocol. Clinicians should therefore apply plasma selectively.

Keywords Nonthermal plasma, Plasma medicine, Resin, Ceramic, Bond strength

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Introduction

Advances in adhesive dentistry have led to the greater use of all-ceramic restorations because of their improved aesthetic and biocompatibility properties compared with metal-supported restorations [1, 2].

Even though ceramic materials are popular in dental practice [3–8], their clinical performance is limited by their tensile strength [1]. The adhesion potential of resin cements to ceramic restorations and tooth structures is a key factor to improve the performance of dental restorations [9, 10].

An increasing number of different surface treatments have been discussed and studied to enhance dental ceramics' clinical performance [11–12].

Surface treatments with acid etching and silane-coupling agents are commonly used applications prior to cementing ceramic restorations [13].

Hydrofluoric (HF) acid etching is a reliable protocol for the bonding of glass ceramics with resin cements [14, 15]. Some authors, however, state that surface treatment with HF acid negatively affects the mechanical properties of etched dental ceramics because of its potential for creating surface defects [16–19]. This indicates the necessity of innovative strategies to develop bonding procedures [20–22].

Plasma is the fourth state of matter [23, 24]. It is composed of reactive species, ions, electrons, free radicals, and neutrals [24, 25]. Such composition leads to modifications to plasma-treated surfaces, which may result in a reactive surface that increase the surface hydrophilicity and cement wetting capacity, without significantly affecting the bulk properties of dental ceramics [9, 26–33].

Nonthermal plasma (NTP) treatment has been suggested as an alternative to HF acid etching that can improve the adhesion effectiveness and durability between ceramic surfaces and resin cements [6, 26, 34].

In dentistry, NTP treatment is a new technique that is used for inducing the surface modification of titanium implants [35, 36], improving the mechanical properties of fiber-reinforced acrylic resins [37], and improving the adhesion effectiveness and durability between fiber post surfaces and core resins [38] and between resin cements and ceramic surfaces [39].

Previous studies have shown that the effects of non-thermal plasma (NTP) on dental silicate ceramics are influenced by the plasma device, treatment parameters, and surface conditioning protocol [40]. However, studies evaluating a specific atmospheric non-thermal plasma device operating with an AC microsecond-pulsed power supply, while simultaneously comparing multiple surface treatment protocols, different glass ceramics, and different resin cements, are limited. Furthermore, the material- and cement-dependent effectiveness of plasma treatment in comparison with conventional surface treatments has

not been comprehensively investigated. Therefore, the aim of this in vitro study was to evaluate the effect of atmospheric non-thermal plasma surface treatment on the shear bond strength of two different resin cements to two different glass ceramics by comparing various surface treatment combinations.

The null hypothesis of this study was that the effectiveness of non-thermal plasma treatment would not increase bond strength depending on the material, cement, and surface treatment combination.

Materials and methods

In the present study, a $2 \times 6 \times 2$ factorial experimental design was used to evaluate the effects of two glass ceramic materials, six surface treatment protocols and two cement systems on shear bond strength. Accordingly, a total of 24 experimental combinations were generated. Ten specimens were allocated to each experimental combination ($n = 10$), resulting in a total sample size of 240 specimens. The sample size was determined based on an a priori power analysis, assuming a minimum statistical power of 80%, a Cohen's effect size of 0.50, and a Type I error probability of $\alpha = 0.05$.

The materials used in the study are listed in Table 1. A flowchart of the experimental process is given in Fig. 1.

For evaluating shear bond strength (SBS), glass ceramic plates (IPS e.max CAD, Vitamark II; 2 mm in thickness) were obtained using a precision sectioning machine (IsoMet 1000; Buehler Ltd., Lake Bluff, IL, USA). Then samples were embedded in self-curing acrylic resin (SC, Imicryl Dental, Konya, Turkey) to allow the test surfaces to be exposed [6].

These glass ceramic plates were then sequentially polished with 600, 800, and 1200 grit silicon carbide abrasive papers under water cooling to create initial surface roughness standardization.

Then the specimens were washed in an ultrasonic water bath to remove the impurities remaining on the specimen surface followed by air drying.

Two hundred and forty composite resin cylinders were built up in a plastic mold (4 mm in inner diameter and 5 mm in height).

A flowable composite resin (Fusio, Pentron, Wallingford, CT, USA) was used to fill the plastic mold and then it was light polymerized according to the manufacturer's recommendation.

The experimental design was structured to enable a comprehensive evaluation of non-thermal plasma in comparison with conventional and combined surface treatment protocols across different ceramics fabricated using CAD/CAM systems and different resin cement systems.

Glass ceramic specimens obtained from IPS e.max CAD (E) and Vitamark II (V) CAD/CAM blocks were

Table 1 Materials used in the study

Material	Composition	Product Name	Manufacturer	Lot. No.
Feldspathic ceramic	Silicon dioxide 56–64%, Aluminum oxide 20–23%, Sodium oxide 9–11%, Potassium oxide 6–8%, Calcium oxide 0.3–0.6%, Titanium dioxide 0.0–0.1%	Vitablocks Mark II (V)	Vita Zahnfabrik, Bad Säckingen, Germany	
Lithium disilicate ceramic	Quartz, lithium dioxide, phosphoric oxide, alumina, potassium oxide	IPS e.MAX CAD	Ivoclar Vivadent, Liechtenstein	
Self Adhesive Resin	Barium in a bis-GMA based dental resin matrix, pigments, catalysts and additives. Filler content: 69%, weight: 51%, volume. Inorganic filler particle amount: between 0.02 and 3 Mm	Zenitcem	President Dental, Munich, Germany	PD793000
Cement	Surface modification with glass powder, 2 propionic acid, 2 methyl-3- (trimethoxysilyl) propyl ester and phenyltrimethoxy silane; bulk material; 2-propionic acid; 2 methyl-, 1,11- [1- (hydroxymethyl) 1,2-ethanediyl] ester; reaction products with 2-hydroxy-1,3 propanediyl dimethacrylate and phosphorus oxide; TEGDMA; silane treated silica; oxide glass chemicals(non-flbrous); sodium persulfate; TBPIN	RelyX Ultimate Clicker (RXU)	3 M ESPE, Neuss, Germany	670,438
Hydrofluoric acid	9.5% hydrofluoric acid	Porcelain Etchant –9.5%Buffered hydrofluoric Acid Gel	Bisco, Schaumburg, USA	1,800,004,851
Porcelain Silane-Primer	Glycidoxypolytrimethoxysilane, ethyl alcohol	Ceramic primer	B.J.M.Laboratories Ltd., Israel	4572PFXSTR
Adhesive	MDP phosphate monomer, dimethylacrylate resins, HEMA, vitrebond copolymer, filler, ethanol, water, initiators, silane	Single Bond Universal	3 M, Neuss, Germany	669,822
Composite resin	Nano-sized amorphous silica and glass-filled 4-methanyloxy ethyl trimellitic acid	Flowable composite	Fusio, USA	
Acrylic resin	Polymethylmethacrylate Methyl methacrylate	SC Cold Acrylic	Imicryl Dental, Konya, Turkey	

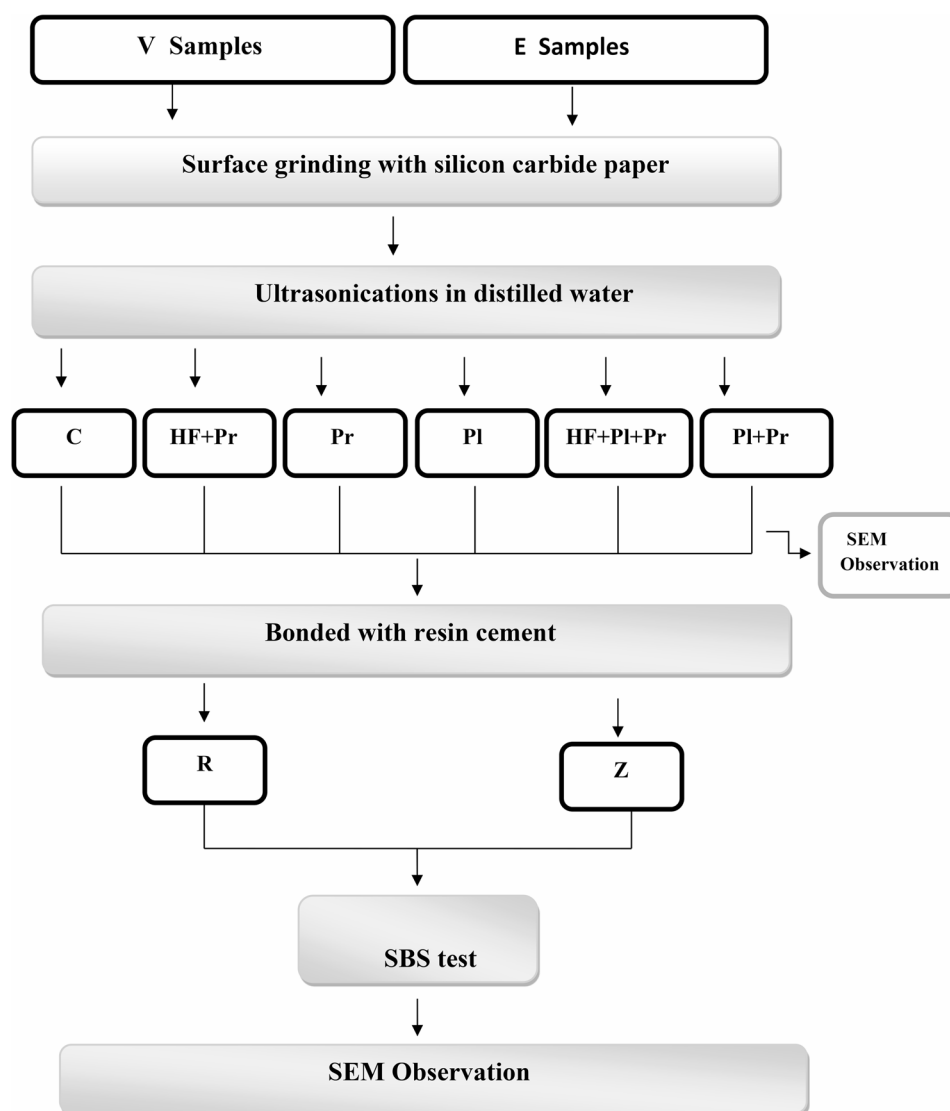


Fig. 1 Flowchart of the experimental process. 6 groups according to the combination of surface treatments; (Hydrofluoric acid etching (HF); Primer application (Pr); Non-thermal Plasma application (Pl). Cements: ((Single Bond + Rely x Ultimate)(R); Zenitcem (Z). Glass ceramic specimens which were obtained from IPS e.max CAD (E) and Vitamark II (V) CAD / CAM blocks

randomized into 6 groups according to the combination of surface treatments: hydrofluoric acid etching (HF), primer application (Pr), and nonthermal plasma application (Pl):

Group 1: Untreated (C)

Group 2: HF + Pr

Group 3: Pr

Group 4: Pl

Group 5: HF + Pl+Pr

Group 6: Pl + Pr

Cements: ((Single Bond + RelyX Ultimate) (R),

ZenitCem (Z)

For the NTP application, an AC microsecond pulse power supply was used. Glass ceramic surfaces were treated with NTP for 90 s. The power supply was operated at 5 kHz frequency and 20 kV voltage by maintaining the discharge gap at 2 mm for the plasma treatment of samples.

Porcelain Etchant Buffered (9.5% hydrofluoric acid) was applied to the IPS e.max CAD (E) substrate surface for 60 s.

Porcelain Etchant Buffered (9.5% hydrofluoric acid) was applied to the Vitamark II (V) substrate surface for 2 min. Following acid etching, the ceramic surfaces were thoroughly rinsed under running water for 60 s to remove residual acid and reaction by-products, and subsequently dried with compressed air.

The ceramic primer was uniformly applied to the ceramic surfaces with a disposable brush applicator and subsequently air-dried for 5 s.

After the surface treatments, composite resin cylinders were cemented to the ceramic samples with ZenitCem or RelyX Ultimate resin cement. For the RelyX Ultimate resin cement groups, Single Bond Universal adhesive was actively applied to the ceramic bonding surface using a disposable microbrush, in accordance with the manufacturer's instructions. The adhesive layer was gently air-thinned to obtain a uniform distribution.

For specimen preparation, all composite resin cylinders were prepared using a plastic mold with a fixed internal diameter of 4 mm and a height of 5 mm, and transparent tapes with a central perforation were placed on the ceramic surfaces to standardize and control the bonding area. Flowable composite resin was carefully placed into the mold to prevent air bubble entrapment, and polymerization was performed using an LED light-curing unit. During cementation, each composite cylinder was centrally positioned on the treated ceramic surface, and the circular interface defined by the perforated tape and mold was considered the standardized bonding area. To prevent uncontrolled enlargement of the bonding interface, excess resin cement around the cylinder margins was carefully removed before polymerization. Light curing was performed for 20 s using an LED curing unit, according to the manufacturer's recommendations.

Before SBS testing, the bonded specimens were inspected to verify proper cylinder positioning, absence of obvious excess cement, and preservation of the standardized bonding diameter. During the same inspection procedure, all ceramic specimens were visually examined under magnification using dental loupes and an LED light source to detect visible defects, including surface cracks, edge chipping, irregularities, or voids within the composite build-up, that could potentially affect bond strength measurements. This procedure was performed to reduce bias related to pre-existing ceramic or composite defects, prevent variability in the bonding interface, and improve specimen standardization among the experimental groups. Specimens showing visible defects, structural irregularities, incorrect cylinder positioning, obvious excess cement, or loss of the standardized bonding diameter were excluded and replaced with new specimens.

Then these samples were stored in an oven (37 °C, 100% humidity, 24 h) before the SBS test.

SBS was measured using a universal testing machine (Shimadzu, AGS-X 5kN, Shimadzu Corporation, Kyoto, Japan). In the SBS test, a knife edge-shaped apparatus was used at a crosshead speed of 1 mm/min until failure occurred. Subsequently, SBS (MPa) was determined by

dividing the ultimate failure load by the bonding interface area.

After SBS testing, the fractured surfaces of all specimens were systematically evaluated to determine the failure mode. Initial examination was performed using a stereomicroscope (Stemi 508; Carl Zeiss Jena GmbH, Jena, Germany) to identify the predominant failure location and the amount and distribution of residual resin cement on the ceramic surface. Failure modes were classified according to predefined criteria as adhesive, cohesive, or mixed failures. Type I failure was defined as adhesive failure, corresponding to separation at the resin cement–ceramic interface, and was recorded when the ceramic surface appeared clean or nearly clean. Type II failure was defined as cohesive failure within the material and was subclassified as cohesive failure within the resin cement, composite resin cylinder, or ceramic substrate. Cohesive failure was recorded when fracture occurred predominantly within one of these materials without complete separation at the bonding interface. Type III failure was defined as mixed failure, in which both adhesive interfacial separation and cohesive fracture areas were observed within the same specimen. The same classification criteria were applied to all specimens to improve consistency. Scanning electron microscopy (SEM; Zeiss, Germany) was used at 100× magnification to further evaluate the failure modes and fracture surface characteristics in greater detail.

The normality of data distribution was assessed using the Shapiro–Wilk test, and the homogeneity of variances was evaluated using Levene's test. A three-way ANOVA with Type III sums of squares was performed to analyze the main effects and all interaction effects. For statistically significant main effects, Tukey's HSD post-hoc test was applied, whereas simple main effects analysis was used for the evaluation of interaction effects. To assess the targeted effect of plasma treatment, pairwise comparisons were performed using either the independent-samples t-test or the Mann–Whitney U test, as appropriate, and Cohen's d effect size was calculated. The clinically relevant threshold was defined as 8–9 MPa, which is widely accepted in the literature. The level of statistical significance was set at $\alpha = 0.05$, and all analyses were performed using IBM SPSS Statistics version 30.

Results

Table 2 shows the mean and standard deviation values for the SBS of composite cylinders with glass ceramic specimens.

According to the three-way ANOVA results, the main effect of surface treatment was statistically significant and showed the highest effect size among the tested factors ($F = 22.561$, $p < 0.001$, $\eta^2 p = 0.343$). In addition, the ceramic × surface treatment interaction ($p = 0.013$,

Table 2 Descriptive Statistics of SBS Values by Group

Ceramic	Surface Treatment	Cement	n	Mean ± SD (MPa)	95% CI	Med.	Min–Max
Vitamark II	Primer	RelyX+Bond	10	10,22 ± 3,99	7,37–13,07	10,25	4,19–15,88
Vitamark II	Primer	ZenitCem	10	8,80 ± 2,54	6,98–10,61	8,55	5,56–13,59
Vitamark II	HF+Primer	RelyX+Bond	10	18,56 ± 2,49	16,78–20,33	19,19	14,96–21,61
Vitamark II	HF+Primer	ZenitCem	10	13,77 ± 3,67	11,14–16,40	13,57	6,93–19,41
Vitamark II	Plasma+Primer	RelyX+Bond	10	10,35 ± 3,13	8,11–12,58	9,76	4,22–14,86
Vitamark II	Plasma+Primer	ZenitCem	10	11,90 ± 2,07	10,42–13,38	11,36	8,78–16,22
Vitamark II	HF+Plasma+Primer	RelyX+Bond	10	19,93 ± 2,73	17,97–21,88	19,84	17,13–26,46
Vitamark II	HF+Plasma+Primer	ZenitCem	10	16,01 ± 3,81	13,29–18,74	16,49	8,30–20,88
Vitamark II	Untreated	RelyX+Bond	10	8,00 ± 1,50	6,92–9,07	8,18	5,40–9,74
Vitamark II	Untreated	ZenitCem	10	7,12 ± 2,59	5,27–8,97	6,52	4,41–13,06
Vitamark II	Plasma	RelyX+Bond	10	10,77 ± 3,65	8,15–13,38	11,26	5,09–16,51
Vitamark II	Plasma	ZenitCem	10	10,77 ± 2,33	9,10–12,44	10,48	7,22–14,90
IPS e.max CAD	Primer	RelyX+Bond	10	8,90 ± 2,98	6,77–11,03	8,73	5,08–13,98
IPS e.max CAD	Primer	ZenitCem	10	5,39 ± 2,44	3,64–7,14	4,70	2,54–8,62
IPS e.max CAD	HF+Primer	RelyX+Bond	10	19,59 ± 6,33	15,06–24,12	20,30	9,01–28,78
IPS e.max CAD	HF+Primer	ZenitCem	10	15,60 ± 5,48	11,68–19,52	15,05	4,99–22,90
IPS e.max CAD	Plasma+Primer	RelyX+Bond	10	11,45 ± 3,38	9,03–13,87	11,25	6,75–16,48
IPS e.max CAD	Plasma+Primer	ZenitCem	10	8,11 ± 2,56	6,28–9,95	8,47	3,79–12,36
IPS e.max CAD	HF+Plasma+Primer	RelyX+Bond	10	21,56 ± 3,10	19,34–23,78	21,24	17,30–26,60
IPS e.max CAD	HF+Plasma+Primer	ZenitCem	10	16,71 ± 5,48	12,78–20,63	18,41	9,69–26,66
IPS e.max CAD	Untreated	RelyX+Bond	10	5,33 ± 2,49	3,55–7,11	4,42	2,56–9,59
IPS e.max CAD	Untreated	ZenitCem	10	2,98 ± 0,43	2,67–3,29	2,99	2,25–3,61
IPS e.max CAD	Plasma	RelyX+Bond	10	5,99 ± 2,61	4,12–7,86	5,69	2,63–11,04
IPS e.max CAD	Plasma	ZenitCem	10	4,23 ± 1,22	3,36–5,11	4,27	2,42–6,60

Mean ± SD mean ± standard deviation, CI confidence interval, Med. median, HF hydrofluoric acid, MPa megapascal. Each group included n = 10 specimens. Bold values indicate mean SBS values < 8 MPa, below the clinical threshold

$\eta^2 p = 0.064$) and the surface treatment × cement system interaction ($p = 0.026$, $\eta^2 p = 0.057$) were statistically significant. Figure 2; Table 3.

In the Tukey's HSD post-hoc analysis of the main effect of surface treatment, significant differences were observed among the surface treatment groups. The HF + Pl+Pr and HF + Pr groups showed higher SBS values than most non-HF groups. The Pl + Pr group had significantly higher SBS values than the Pl group (+ 2.51 MPa, $p = 0.045$) and the untreated group (+ 4.596 MPa, $p < 0.001$).

For the V ceramic, the highest mean SBS values were recorded in the HF-containing surface treatment groups for both cement systems. In the R group, the mean SBS values were 19.93 ± 2.73 MPa for HF + Pl+Pr and 18.56 ± 2.49 MPa for HF + Pr. In the Z group, the corresponding values were 16.01 ± 3.81 MPa and 13.77 ± 3.67 MPa, respectively. Among the V combinations, the mean SBS value of the untreated Z group was below the clinical threshold of 8 MPa (7.12 ± 2.59 MPa). For the E ceramic, the highest mean SBS values were also recorded in the HF-containing surface treatment groups. In the R group, the mean SBS values were 21.56 ± 3.10 MPa for HF + Pl+Pr and 19.59 ± 6.33 MPa for HF + Pr. In the Z group, the corresponding values were 16.71 ± 5.48 MPa and 15.60 ± 5.48 MPa, respectively.

In the E–R combinations, the mean SBS values of the untreated group (5.33 ± 2.49 MPa) and the Pl group (5.99 ± 2.61 MPa) were below the clinical threshold of 8 MPa. In the E–Z combinations, the mean SBS values of the untreated group (2.98 ± 0.43 MPa), Pl group (4.23 ± 1.22 MPa), and Pr group (5.39 ± 2.44 MPa) were below the clinical threshold of 8 MPa Fig. 3.

In the Mann–Whitney U comparison, plasma-treated groups showed higher mean SBS values than non-plasma-treated groups. The difference was significant in the Z groups (+ 2.35 MPa, $p = 0.012$), but not in the R groups (+ 1.57 MPa, $p = 0.110$). Significant differences were also observed for V + Z (+ 3.80 MPa, $p = 0.001$) and E + Z (+ 5.09 MPa, $p < 0.001$). After HF etching, the additional effect of plasma treatment was not statistically significant Table 4.

In the targeted comparisons of plasma effect, at level A (untreated vs. Pl), statistically significant differences were observed in the V + R group (+ 2.77 MPa, $p = 0.040$) and in both Z ceramic groups. In the E + Z group, the Plasma group showed a statistically significant increase compared with the untreated group ($p < 0.01$); however, the absolute mean SBS value remained below the clinical threshold. At level B (Pr vs. Pl + Pr), statistically significant differences were observed in the Z groups. The mean SBS value was higher in the Pl + Pr group than in

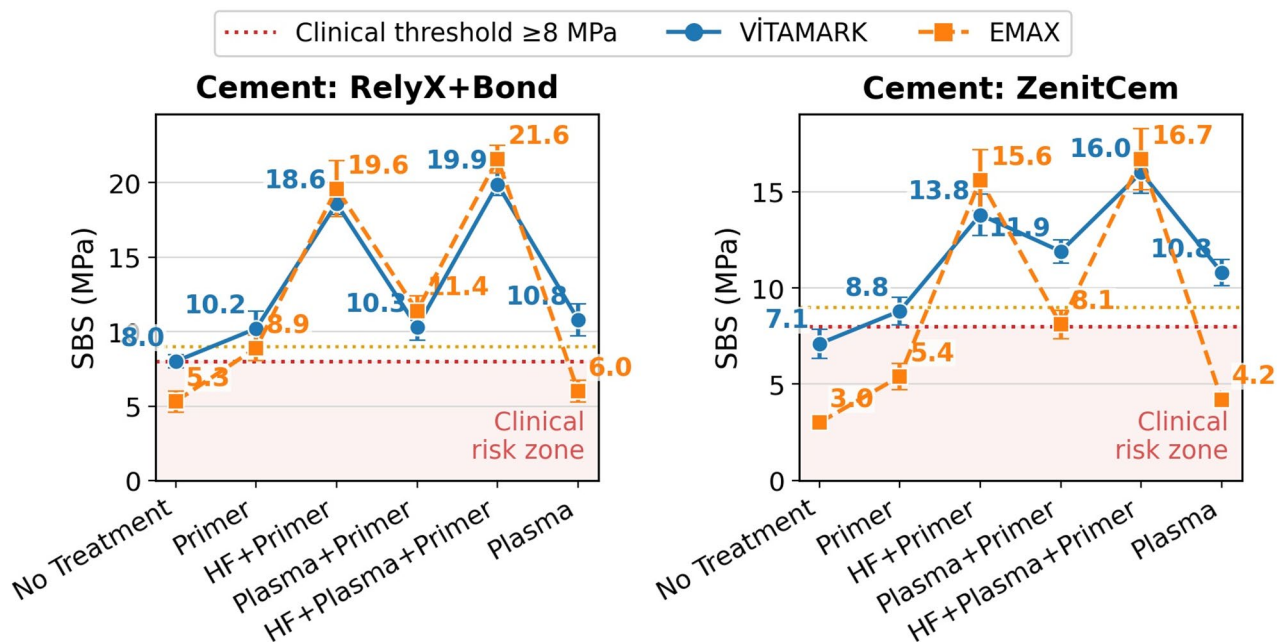


Fig. 2 Ceramic Material $\times$ Surface Treatment Interaction Plot (Mean $\pm$ SEM). The red dashed lines indicate the 8–9 MPa clinical threshold. Left: RelyX+Bond; Right: ZenitCem

Table 3 Three-Way ANOVA Results (Type III Sum of Squares)

Effect	SS	df	F	<i>p</i>	η^2p
Ceramic (C)	8,738	1	0,797	0,373	0,004
Surface Treatment (S)	1236,286	5	22,561	<0,001	0,343
Primer/Cement System (P)	10,153	1	0,926	0,337	0,004
C $\times$ S Interaction	162,290	5	2,962	0,013	0,064
C $\times$ P Interaction	10,858	1	0,991	0,321	0,005
S $\times$ P Interaction	143,061	5	2,611	0,026	0,057
C $\times$ S $\times$ P Interaction	42,949	5	0,784	0,562	0,018
Error	2367,220	216	–	–	–

SS sum of squares, *df* degrees of freedom, η^2p partial eta squared. $\eta^2p \leq 0.06$ indicates a small effect, 0.06–0.14 indicates a medium effect, and ≥ 0.14 indicates a large effect. *p*-values are presented in italics; statistically significant *p*-values ($p < 0.05$) are presented in bold italics

the Pr group for both V + Z (+3.10 MPa, $p = 0.008$) and E + Z (+2.72 MPa, $p = 0.026$). In the R groups, the difference between Pr and Pl+Pr was not statistically significant. At level C (HF+Pr vs. HF+Pl+Pr), no statistically significant differences were observed in any ceramic–cement combination Fig. 4.

The SBS values of the two ceramic groups were compared within the same surface treatments and cement types. For Z cement type in the Pl, control, Pr, and Pl+Pr surface treatments groups, V samples showed significantly higher SBS values when compared with the E samples ($p < 0.05$).

When the SBS values of different cement types were compared within the same surface treatment and glass ceramic groups, significant differences were determined ($p < 0.05$). For V ceramic groups receiving the HF+Pr and HF+Pl+Pr surface treatments, R showed

significantly higher SBS values when compared with Z ($p < 0.05$).

Morphological changes on the CAD/CAM block surfaces resulting from different surface treatments were evaluated by SEM (AxioCam ERc 5s, Zeiss, Germany). The SEM images were obtained at 100 $\times$ and 500 $\times$ magnification and then micrographs were compared with each other.

Considering the SEM micrographs (Fig. 5), alterations and micro-retentive areas were more clearly visible on the surfaces of the HF samples compared with the untreated samples. HF acid etching surface treatment increased the surface area on all the CAD/CAM block (E, V) surfaces. However, small changes, mostly the same surface characteristics, were observed between HF and HF+Pl samples. There were no large morphological differences between HF and HF+Pl samples for all materials.

The SBS values of HF+Pl samples and HF samples were similar as observed in the SEM micrographs for those samples. The untreated samples exhibited a significantly lower bond strength value when compared with HF+Pl and HF samples ($p < 0.05$).

Figure 6 shows the failure modes of all the glass ceramic groups. In the specimens that received Pl surface treatment, mix/cohesive failure was observed rather than adhesive failure. Representative micrographs of different failure modes were obtained by SEM (Zeiss, Germany) (Fig. 7).

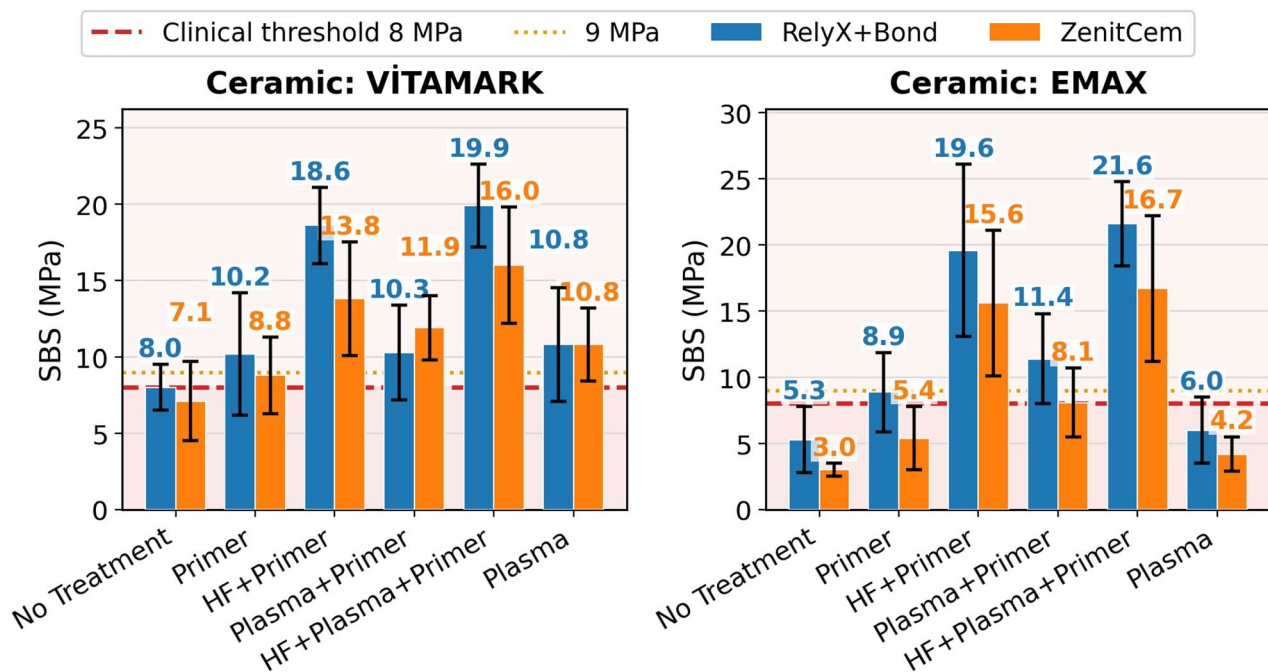


Fig. 3 SBS Values According to Surface Treatment and Cement System (Mean $\pm$ SD). The red dashed line indicates the 8 MPa clinical threshold. Numbers indicate the mean SBS values. Left: VITAMARK II; Right: E-MAX

Table 4 Overall Comparison Between Plasma-Treated and Non-Plasma-Treated Groups (Mann–Whitney U Test)

Group	Plasma-treated Mean $\pm$ SD (MPa)	Non-plasma-treated Mean $\pm$ SD (MPa)	Difference (MPa)	Test	<i>p</i>
All groups	12,31 $\pm$ 5,92	10,35 $\pm$ 6,11	+ 1,96	MWU	0,004 *
VITAMARK II	13,29 $\pm$ 4,59	11,08 $\pm$ 4,87	+ 2,21	MWU	0,006 *
E-MAX	11,34 $\pm$ 6,92	9,63 $\pm$ 7,11	+ 1,71	MWU	0,062 ns
RelyX+Bond	13,34 $\pm$ 6,33	11,77 $\pm$ 6,45	+ 1,57	MWU	0,110 ns
ZenitCem	11,29 $\pm$ 5,34	8,94 $\pm$ 5,46	+ 2,35	MWU	0,012 *
VITAMARK II+ ZenitCem	12,15 $\pm$ 3,47	8,35 $\pm$ 4,25	+ 3,80	MWU	0,001 **
E-MAX + ZenitCem	9,68 $\pm$ 6,55	4,59 $\pm$ 4,26	+ 5,09	MWU	< 0,001 ***

Plasma-treated groups: Plasma+Primer, HF+Plasma+Primer, and Plasma. Non-plasma-treated groups: Primer, HF+Primer, and Untreated. Additional rows were included for the VITAMARK+ZenitCem and EMAX+ZenitCem combinations. $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns: not significant. *p*-values are presented in italics; statistically significant *p*-values ($p < 0.05$) are presented in bold italics

Discussion

In the present study, atmospheric-pressure dielectric barrier discharge (DBD) plasma was applied to the surfaces of feldspathic and lithium disilicate CAD/CAM ceramics in ambient air without the use of an additional process gas.

The null hypothesis of this study was that the effectiveness of non-thermal plasma treatment would not increase bond strength depending on the material, cement, and surface treatment combination. Based on the obtained results, the null hypothesis was rejected.

An important finding of the present study was the material-, cement-, and surface treatment-dependent effect of atmospheric non-thermal plasma application. The effect of plasma treatment appeared to be more evident in the ZenitCem cement system ($p = 0.012$), particularly on surfaces that did not receive HF etching. The V + Z combination was among the groups in which

plasma treatment showed a more pronounced and statistically significant effect. In the E + Z group, plasma treatment resulted in a statistically significant increase in SBS compared with the untreated condition; however, the absolute SBS value remained below the clinical threshold. In contrast, hydrofluoric acid-based surface treatments consistently yielded higher bond strength values regardless of the ceramic type. These findings indicate that non-thermal plasma does not provide a universal bonding improvement, but may be more effective in specific ceramic–resin cement combinations and under certain surface conditioning protocols. Considering the limited number of studies evaluating this specific plasma device and the comparative assessment of multiple surface treatments, the present study provides novel and clinically relevant insights into the selective effectiveness of atmospheric non-thermal plasma.

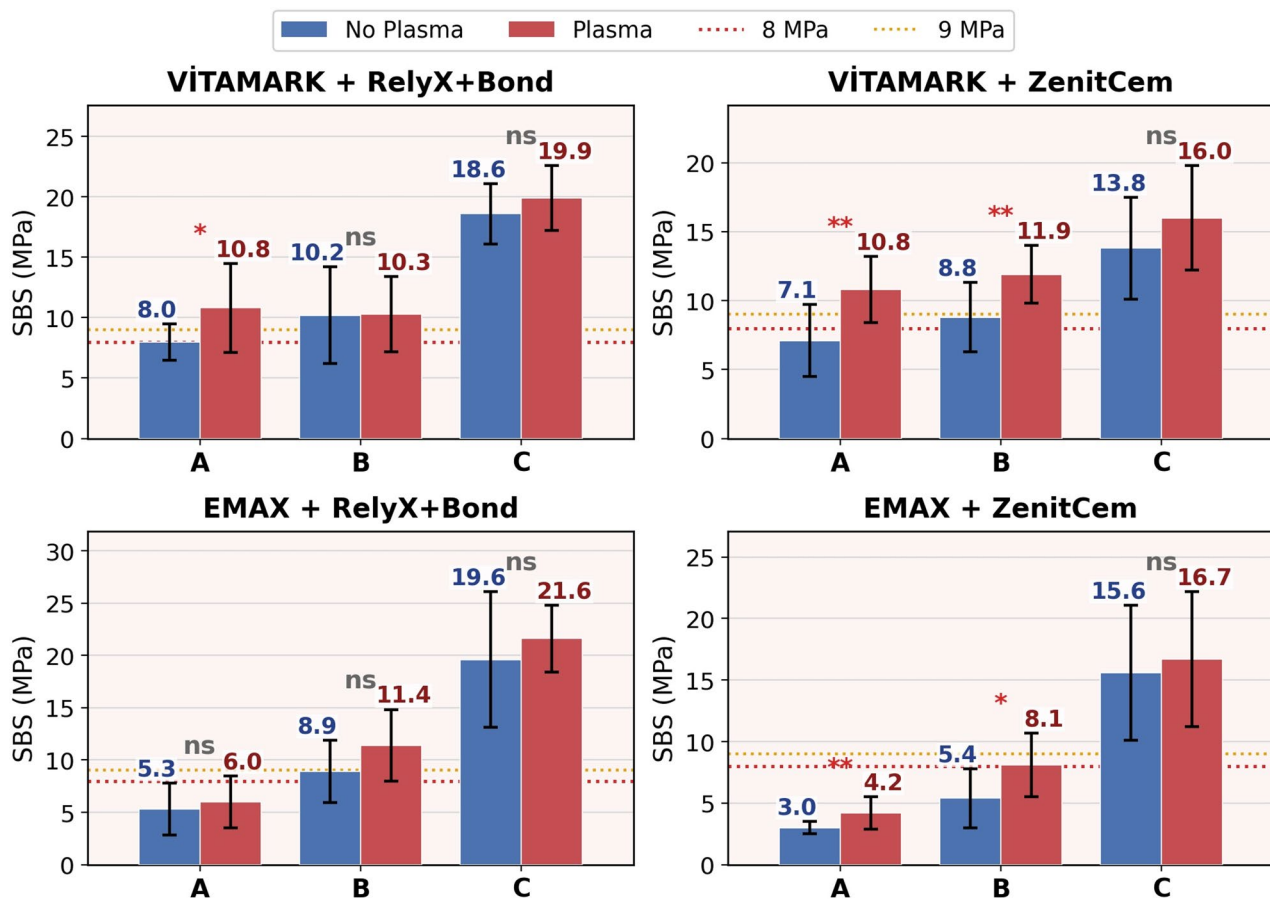


Fig. 4 Targeted Comparisons of Plasma Effect. **A** Untreated vs. Plasma; **B** Primer vs. Plasma+Primer; **C** HF+Primer vs. HF+Plasma+Primer). Numbers indicate the mean SBS values. The red line indicates the 8 MPa clinical threshold. $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

According to Borges and colleagues, cementation plays an important role in the clinical success of ceramics [2]. Some authors suggest that strong resin bonding depends on the composition of the ceramic material and the surface treatment [41].

Airborne particle abrasion is a well-known technique for increasing the surface roughness of ceramics. However, it is not recommended for cementing silica-based ceramics as it may lead to cracks and a high loss of porcelain material [42].

Together with micromechanical interlocking, chemical bonding helps to increase bond strength. For glass ceramics, surface roughening and chemical bonding are achieved via HF acid etching and silane treatment [43].

Although HF acid etching is a generally accepted application for strong resin bonding with glass ceramics, some researchers state that HF may affect ceramic strength negatively since it may lead to cracks [44]. Furthermore, numerous authors still recommend eliminating HF from the etching procedure [21, 22].

The effects of NTP surface treatments on different materials have been investigated in dentistry [13–16].

According to some studies, NTP surface treatment appears to be a promising alternative for improving the surface wettability of ceramics [45–47].

HF etching mainly enhances bonding by dissolving the glassy phase of the ceramic matrix, increasing surface roughness, and promoting micromechanical interlocking between the ceramic and resin cement [48]. In contrast, atmospheric plasma primarily acts through surface activation rather than pronounced micromechanical roughening. Plasma treatment may generate polar functional groups, such as carboxyl groups, on the outermost surface layer, thereby increasing wettability and potentially improving chemical interaction with the adhesive [49–51]. NTP has been used to chemically modify the ceramic surface without negatively affecting ceramic strength [9, 47].

According to Han and colleagues, nonthermal atmospheric pressure plasma surface treatment improved the wettability of feldspathic ceramic surfaces. Moreover, plasma surface treatment increased ceramic bonding by producing carboxyl groups [46].

In a study by Lanza et al. investigating the effects of novel surface treatments on the shear bond strength of

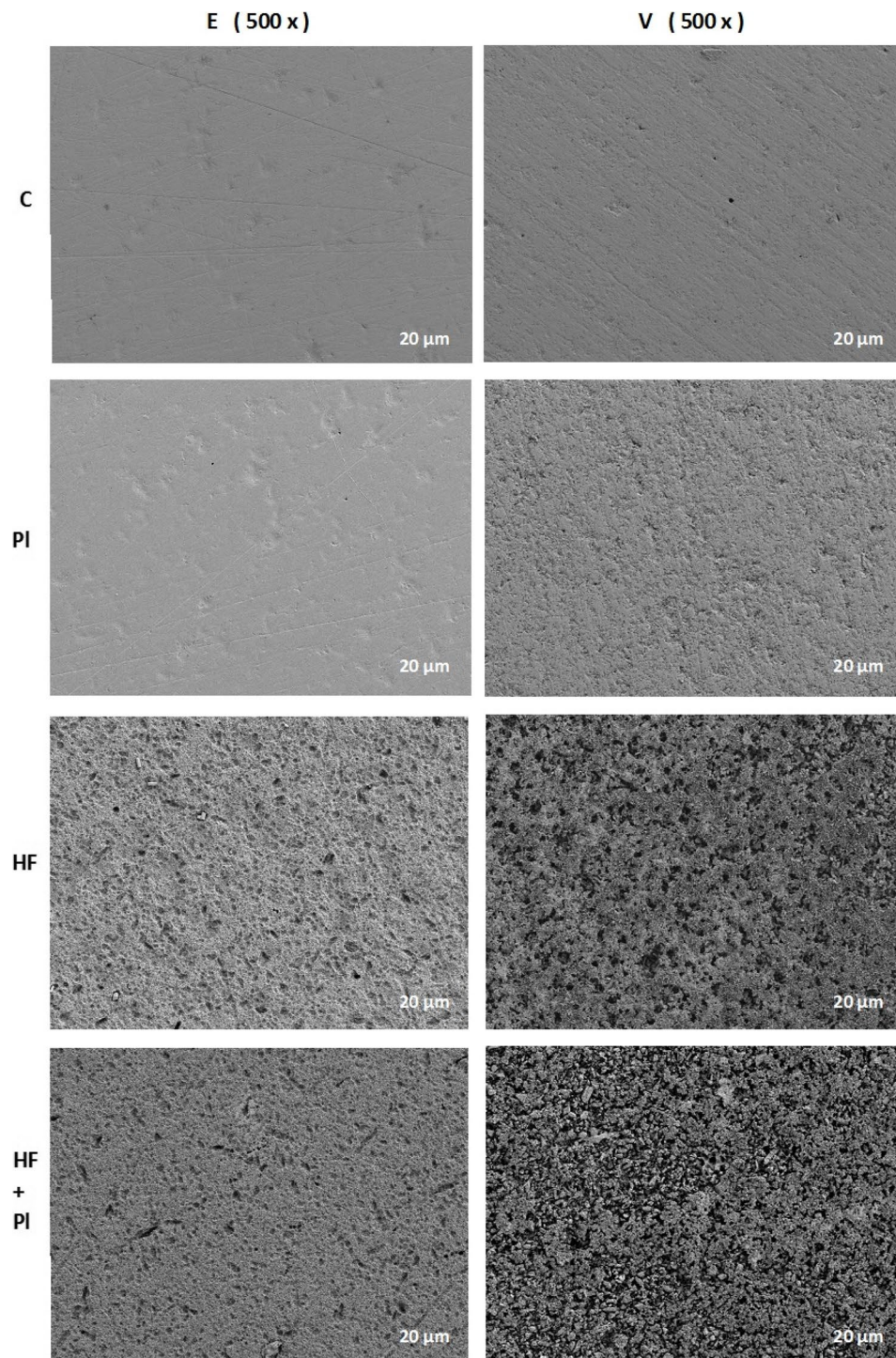


Fig. 5 FE-SEM micrographs of various CAD/CAM materials after different surface treatments. (at 500 x magnification, scale bar indicates 20 µm)

a self-adhesive resin cement to lithium disilicate glass ceramic, the combined application of hydrofluoric acid and non-thermal plasma (NTP) was reported to yield the highest overall bond strength among the evaluated surface pretreatment protocols [52].

Liao et al. investigated the effects of atmospheric non-thermal argon plasma (NTP) treatment on enhancing the micro-shear bond strength (μ SBS) of lithium disilicate (LD) to dental resin cements and concluded that NTP surface treatment represents a promising technology for

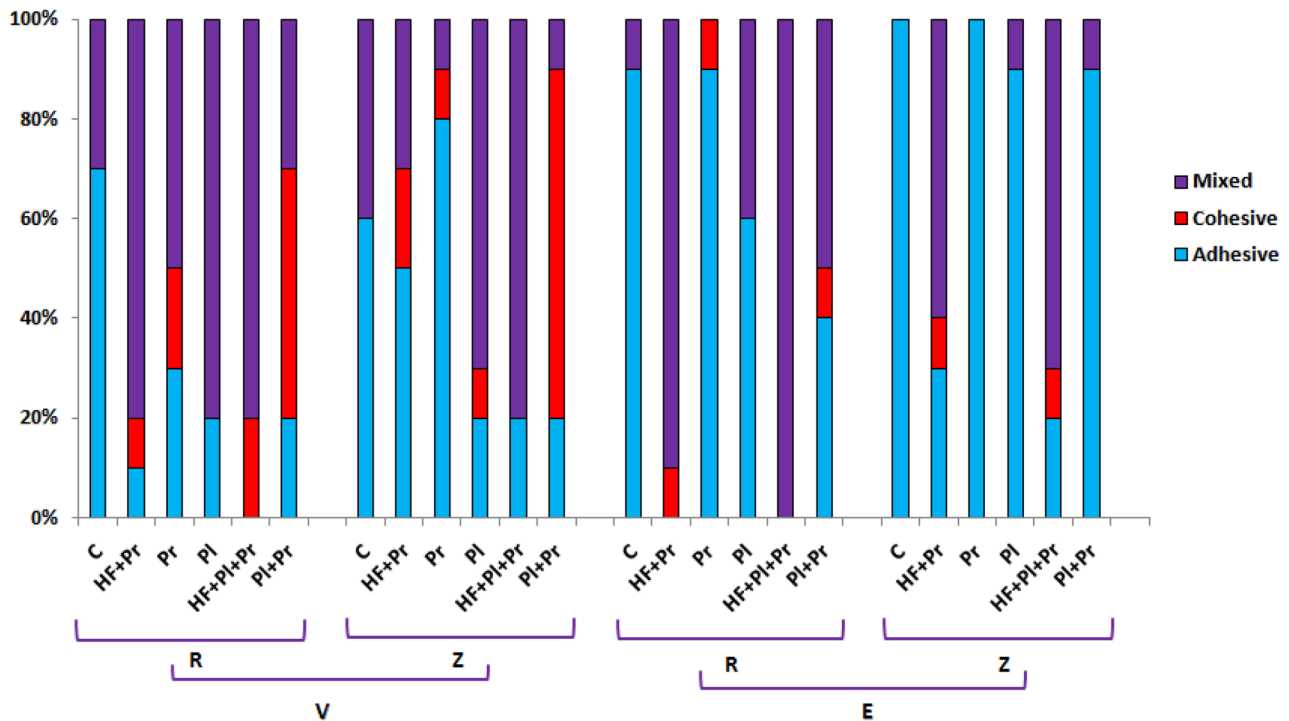


Fig. 6 Failure mode distribution for all groups after the SBS test. 6 groups according to the combination of surface treatments ; (Hydrofluoric acid etching (HF); Primer application (Pr); Non-thermal Plasma application (Pl). Cements: ((Single Bond + Rely x Ultimate)(R); b, Zenitcem (Z). Glass ceramic specimens which were obtained from IPS e.max CAD (E) and Vitamark II (V) CAD / CAM blocks

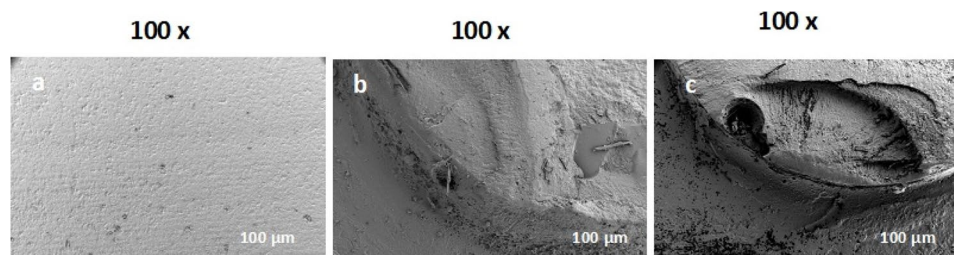


Fig. 7 FE-SEM micrographs of debonded specimens. **a** adhesive failure. **b** cohesive failure. **c** mixed failure. (100x magnification)

improving the short- and long-term micro-shear bond strength of LD bonded to dental resin cements [53].

In a study evaluating the effects of surface modification of feldspathic porcelain by corona discharge on bonding to resin cement, it was reported that the shear bond strength (SBS) values of corona-discharge-treated porcelain were comparable to those obtained with conventionally hydrofluoric acid (HF)-etched porcelain [54].

Non-thermal plasma protocols reported in the literature show substantial variability in gas type, exposure time, treatment power, operating pressure, and source-to-specimen distance. In most dental ceramic studies, plasma treatment times have generally ranged from 10 to 90 s, whereas longer activation periods, including 5–15 min, 30 min, and 60 min, have been used only in limited studies [40]. Treatment power and working distance also vary considerably among protocols, indicating

that there is no standardized NTP application protocol [40]. Previous studies have further suggested that longer treatment times or higher NTP power may result in more pronounced changes in ceramic surface roughness and wettability [46, 55]. In the present study, a 90-s exposure time and a 2-mm discharge gap were selected based on previous evidence identifying this duration as optimal for achieving the highest wettability under similar conditions, as well as on preliminary observations showing comparable surface responses. The 5 kHz frequency and 20 kV voltage were used as device-specific parameters that provided stable plasma discharge, and all plasma settings were kept constant throughout the experiment to ensure reproducibility.

In our previous study the effects of NTP surface treatment on the wettability and surface roughness of different CAD/CAM blocks as well as the bond strength of

dual-cure composite resin cements were investigated. In accordance with the results of that previous study, while 30-s NTP treatment caused an increase in the wettability of the feldspathic ceramic-based CAD/CAM materials, extension of NTP treatment time to 90 s caused an increase in surface roughness. The SBS of feldspathic ceramic-based CAD/CAM materials and the resin cement was also increased after 90 s of NTP treatment. Similarly, in the present study, plasma surface treatment appeared to increase the bond strength values of both Z and R in V specimens when compared with the untreated group.

Plasma treatment may modify material surfaces through various surface-related effects, including cleaning, activation, etching, and coating [56]. Plasma surface treatment is thought to improve bonding mainly through surface activation, increased surface energy, and enhanced wettability [57, 58]. During plasma exposure, reactive species or functional groups such as OH, O₃, H₂O₂, and NO may be generated on the treated surface without substantial structural alteration [59]. This effect may also be accompanied by surface cleaning [60]. Accordingly, these surface modifications may promote adhesive spreading and interfacial interaction, contributing to higher bond strength.

The clinically acceptable minimum bond strength reported in the literature varies widely, ranging from 8 to 30 MPa [61–64]. Kalra *et al.* suggested that, considering the masticatory forces acting on anterior and posterior teeth and the relationship in which strength is directly proportional to force and inversely proportional to bonding area ($\text{Strength} = F/A$), a minimum bond strength of approximately 8–9 MPa may be regarded as clinically acceptable [61]. Based on this threshold, the present findings indicate that the statistically significant effect of plasma treatment may have clinical relevance only in selected material–cement combinations. Specifically, among the plasma-treated and non-plasma-treated surface protocols, the V-R and V-Z groups showed bond strength values within the clinically acceptable range, whereas the E-Z group remained below the clinical threshold. For the Pl + Pr surface treatment protocol, clinically acceptable values were also obtained in the Z group.

The SBS values of the HF + Pl + Pr samples were not significantly different from those of the HF + Pr samples. Another result of our study was that regardless of the cement type, HF surface treatment was a more effective pretreatment than Pl.

Previous studies have shown that bond strength values obtained after cementation following plasma treatments are generally lower than those achieved with conventional hydrofluoric acid (HF) etching [40]. Similar findings were also observed in the present study, which

supports the existing literature. Furthermore, similar results were obtained from the comparison of surface characterization of selected samples. SEM evaluations confirmed that when comparing the HF and HF + Pl treated samples, large morphological surface changes were not observed between these samples. This finding is clinically relevant, as it suggests that the strong effect of hydrofluoric acid etching may overshadow the potential benefits of plasma treatment, emphasizing the importance of selecting appropriate surface treatment strategies rather than applying plasma indiscriminately.

According to Graiff and colleagues [65], the application of HF etching and silane surface treatments to the ceramic surface improved bond strength. Similarly, the SBS of the HF + Pl + Pr treatment was significantly greater than that of the Pl + Pr treatment for all groups. Regardless of ceramic and cement type, HF + Pr exhibited significantly higher values than silane alone. This result is consistent with those of previous studies, as HF acid etching was shown to improve the SBS of ceramics with resin cements when compared with other surface treatments [66–68]. In addition, all surface treatment protocols involving HF etching provided bond strength values exceeding the clinically acceptable threshold for both ceramic materials and both resin cement systems.

The significantly higher SBS values observed for Vita-mark II compared with IPS e.max CAD in the control, plasma, primer, and plasma+primer groups when using the self-adhesive resin cement indicate that the bonding performance is strongly influenced by the ceramic substrate. The higher glass phase content and more homogeneous amorphous structure of feldspathic ceramics may facilitate improved surface wettability and interaction with self-adhesive resin cements following surface energy-modifying treatments. In contrast, the higher crystalline content of lithium disilicate glass ceramics may limit the effectiveness of plasma and primer applications alone, resulting in lower bond strength values in the absence of hydrofluoric acid etching.

The selective response observed after plasma treatment indicates that its effect was not uniform across all experimental groups, but was dependent on the material type and resin cement system. In particular, the effect appeared to be more pronounced in the V material. Vita-mark II and IPS e.max CAD ceramics differ in their crystalline phase content, silica content, and aluminum oxide composition [69], which may contribute to their different responses to surface modification. Accordingly, the effect of plasma surface treatment on different glass-ceramic surfaces may not be identical and may be influenced not only by the chemical composition of the ceramic but also by its microstructural organization and molecular arrangement. The SEM findings, showing different surface modification patterns on glass-ceramic surfaces with

distinct structural characteristics, further support this explanation.

Etch-and-rinse adhesive resin systems are generally considered to result in higher bond strengths when compared with self-adhesive and self-etch resin cements on glass ceramic surfaces [70]. In the present study, within the V ceramic groups, the HF + Pr and HF + Pl+Pr surface treatments resulted in significantly higher SBS values with R than with Z. It is possible that R, which has an adhesive agent, reacts more to the HF-treated glass ceramic surface than Z, which is a self-adhesive resin cement and used single step and alone [35]. This result was supported by previous studies in which the self-adhesive resin cement bond strength exhibited a significantly lower bond strength value when compared with etch-and-rinse procedure resin cements [70–72]. Chen et al. have reported that the weaker physical properties of self-adhesive cements than traditional resin cements could be considered a reason for this behavior [71, 72].

Taken together, the bonding performance of plasma-treated ceramics appears to be governed by both surface treatment–cement and surface treatment–material interactions. The response to atmospheric nonthermal plasma may therefore depend on the microstructural characteristics of the ceramic substrate, the physicochemical properties of the resin cement system, and the specific surface treatment protocol used. Accordingly, plasma treatment should not be considered merely as a surface roughening method, but rather as a multifactorial interfacial phenomenon involving surface activation, wettability enhancement, and material- and cement-dependent bonding mechanisms. In light of these selective effects, atmospheric nonthermal plasma should not be regarded as a direct substitute for HF etching; instead, it may be evaluated as a potential alternative for selected material–cement–surface treatment combinations.

The present study has several limitations. First, although the shear bond strength (SBS) test is one of the most commonly used methods for evaluating bond strength in resin-bonded restorations [73], it has inherent methodological limitations. The complex stress distribution generated during loading may result in cohesive bulk fractures within the material rather than failure occurring exclusively at the bonded interface [73]. Second, thermocycling was not performed; therefore, the durability of the adhesive interface after artificial aging and the influence of long-term factors, such as material aging, on bond strength could not be assessed. This limits the clinical interpretation of the findings and restricts the ability to make direct clinical recommendations. Third, the effectiveness of NTP treatment may vary considerably depending on the plasma system, gas type, exposure time, power, source-to-specimen distance, restorative material, surface treatment combination, resin cement system,

and subsequent adhesive protocol. Accordingly, since the effect of plasma treatment cannot be generalized based on a single application protocol, further studies evaluating different plasma parameters in combination with various adhesive systems and ceramic substrates are needed. Finally, because of the *in vitro* design of this study, intraoral conditions could not be fully reproduced. Moreover, future studies are required to evaluate clinically applicable intraoral versions of plasma treatment and to determine their safety, feasibility, and effectiveness under real oral conditions. Further experimental and clinical studies are therefore needed to validate the routine applicability of NTP treatment as a surface pretreatment method in clinical practice.

Conclusions

Within the limitations of this *in vitro* study, NTP surface treatment selectively improved the SBS of self-adhesive resin cement to feldspathic glass ceramic, reaching a clinically acceptable and statistically significant level in the Vitamark II–ZenitCem combination without HF etching. However, HF etching remained the most effective surface treatment and produced clinically acceptable bond strength values in all HF-containing groups. The bonding effectiveness of NTP was dependent on the ceramic substrate, resin cement type, and surface treatment protocol. Therefore, NTP should be considered a selective surface modification strategy rather than a universal alternative to conventional HF-based surface treatments.

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Authors' contributions

Emine Mustafaoğlu wrote the main manuscript text and prepared figures. Bora Bağış, Gizem Dilara Özdemir, Utku Kürşat Ercan, Emine Mustafaoğlu reviewed the manuscript.

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Data availability

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

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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References

- Saygili G, Şahmali S. Effect of ceramic surface treatment on the shear bond strengths of two resin luting agents to all-ceramic materials. *J Oral Rehabil*. 2003;30:758–64. <https://doi.org/10.1046/j.1365-2842.2003.01027.x>.
- Borges GA, Sophr AM, De Goes MF, et al. Effect of etching and airborne particle abrasion on the microstructure of different dental ceramics. *J Prosthet Dent*. 2003;89:479–88.
- Sulaiman TA, Delgado AJ, Donovan TE. Survival rate of lithium disilicate restorations at 4 years: a retrospective study. *J Prosthet Dent*. 2015;114:364–6.
- Noro A, Kaneko M, Murata I, Yoshinari M. Influence of surface topography and surface physicochemistry on wettability of zirconia (tetragonal zirconia polycrystal). *J Biomed Mater Res B Appl Biomater*. 2013;101:355–63.
- Beier US, Kapferer I, Burtscher D, Dumfahrt H. Clinical performance of porcelain laminate veneers for up to 20 years. *Int J Prosthodont*. 2012;25:79–85.
- Derand T, Molin M, Kvam K. Bond strength of composite luting cement to zirconia ceramic surfaces. *Dent Mater*. 2005;21:1158–62.
- Brunot-Gohin C, Duval JL, Azogui EE, et al. Soft tissue adhesion of polished versus glazed lithium disilicate ceramic for dental applications. *Dent Mater*. 2013;29:e205–12.
- Della Bona A, Corazza PH, Zhang Y. Characterization of a polymer infiltrated ceramic-network material. *Dent Mater*. 2014;30:564–9.
- Valverde GB, Coelho PG, Janal MN, et al. Surface characterization and bonding of Y-TZP following non-thermal plasma treatment. *J Dent*. 2013;41:51–9.
- Silva NR, Coelho PG, Valverde GB, et al. Surface characterization of Ti and Y-TZP following non-thermal plasma exposure. *J Biomed Mater Res B Appl Biomater*. 2011;99:199–206.
- Blatz MB, Conejo J, Alammari A, Ayub J. Current protocols for resin-bonded dental ceramics. *Dent Clin North Am*. 2022;66(4):603–25. <https://doi.org/10.1016/j.cden.2022.05.008>.
- Sen D, et al. Shear bond strength of resin luting cement to glass-infiltrated porous aluminum oxide cores. *J Prosthet Dent*. 2000;83:210–5.
- Santos GC Jr, Santos MJMC, Rizkalla AS. Adhesive cementation of etchable ceramic esthetic restorations. *J Can Dent Assoc*. 2009;75:379–84.
- Beier US, Kapferer I, Burtscher D, et al. Clinical performance of porcelain laminate veneers for up to 20 years. *Int J Prosthodont*. 2012;25:79–85.
- Dumfahrt H, Schaffer H. Porcelain laminate veneers. A retrospective evaluation after 1 to 10 years of service, part II: clinical results. *Int J Prosthodont*. 2000;13:9–18.
- Addison O, Marquis PM, Fleming GJP. The impact of hydrofluoric acid surface treatments on the performance of a porcelain laminate restorative material. *Dent Mater*. 2007;23:461–8.
- Menees TS, Lawson NC, Beck PR, Burgess JO. Influence of particle abrasion or hydrofluoric acid etching on lithium disilicate flexural strength. *J Prosthet Dent*. 2014;112:1164–70.
- Swain MV. Impact of oral fluids on dental ceramics: what is the clinical relevance. *Dent Mater*. 2014;30:33–42.
- Aladağ A, Elter B, Çömlekoğlu E, et al. Effect of different cleaning regimens on the adhesion of resin to saliva contaminated ceramics. *J Prosthodont*. 2014;23:1–10.
- Della Bona A. Bonding to ceramics: scientific evidences for clinical dentistry. São Paulo: Artes Médicas. 2009;91–132.
- Fabianelli A, Pollington S, Papacchini F, et al. The effect of different surface treatments on bond strength between leucite reinforced feldspathic ceramic and composite resin. *J Dent*. 2010;38:39–43.
- Queiroz JR, Benetti P, Özcan M, et al. Surface characterization of feldspathic ceramic using ATR FT-IR and ellipsometry after various silanization protocols. *Dent Mater*. 2012;28:189–96.
- Fernandes VBB Jr, Dantas DCB, Bresciani E, et al. Evaluation of the bond strength and characteristics of zirconia after different surface treatments. *J Prosthet Dent*. 2018;120:955–9.
- Chen M, Zhang Y, Sky Driver M, et al. Surface modification of several dental substrates by non-thermal, atmospheric plasma brush. *Dent Mater*. 2013;29:871–80.
- Da Silva BTF, Trevelin LT, Teixeira FDS, et al. Non-thermal plasma increase bond strength of zirconia to a resin cement. *Braz Dent Sci*. 2018;21:210–19.
- Han GJ, Chung SN, Chun BH, et al. Effect of the applied power of atmospheric pressure plasma on the adhesion of composite resin to dental ceramic. *J Adhes Dent*. 2012;14:461–9.
- Vechiato Filho AJ, dos Santos DM, Goiato MC, et al. Surface characterization of lithium disilicate ceramic after nonthermal plasma treatment. *J Prosthet Dent*. 2014;112:1156–63.
- Fracassi F, d'Agostino R, Palumbo F, et al. Application of plasma deposited organosilicon thin films for the corrosion protection of metals. *Surf Coat Technol*. 2003;174–175:107–11.
- Rangel RCC, Pompeu TC, Barros JLS Jr, et al. Improvement of the corrosion resistance of carbon steel by plasma deposited thin films. *Recent Researches in Corrosion Evaluation and Protection*. Croatia: InTech; 2012. pp. 91–116.
- Wang Y, Yin S, Ren L, Zhao L. Surface characterization of the chitosan membrane after oxygen plasma treatment and its aging effect. *Biomed Mater*. 2009;4:035003.
- Wan Y, Qu X, Lu J, et al. Characterization of surface property of poly(lactide-co-glycolide) after oxygen plasma treatment. *Biomaterials*. 2004;25:4777–83.
- Liu YC, Hsieh JP, Chen YC, et al. Promoting porcelain-zirconia bonding using different atmospheric pressure gas plasmas. *Dent Mater*. 2018;34:1188–98.
- Vechiato-Filho AJ, Matos AO, Landers R, 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 Mater Biol Appl*. 2017;72:284–92.
- Della Bona A, Shen C, Anusavice KJ. Work adhesion of resin on treated lithia disilicate-based ceramic. *Dent Mater*. 2004;20:338–44.
- Hayakawa T, Yoshinari M, Nemoto K. Characterization and protein-adsorption behavior of deposited organic thin film onto titanium by plasma polymerization with hexamethyldisiloxane. *Biomaterials*. 2004;25(1):119–27.
- Puleo DA, Kissling RA, Sheu MS. A technique to immobilize bioactive proteins, including bone morphogenetic protein-4 (BMP-4), on titanium alloy. *Biomaterials*. 2002;23(9):2079–87.
- Çökeller D, Erkut S, Zemek J, Biederman H, Mutlu M. Modification of glass fibers to improve reinforcement: a plasma polymerization technique. *Dent Mater*. 2007;23(3):335–42.
- Yavirach P, Chaijareenont P, Boonyawan D, et al. Effects of plasma treatment on the shear bond strength between fiber-reinforced composite posts and resin composite for core build-up. *Dent Mater J*. 2009;28(6):686–92.
- Derand T, Molin M, Kvam K. Bond strength of a composite luting agent to alumina ceramic surfaces. *Acta Odontol Scand*. 2006;64(4):227–30.
- Birk L, Luka M, et al. Surface modification of dental silicate ceramics using nonthermal plasma: A systematic review. *Dent Mater*. 2024;40(3):531–45.
- Clelland NL, Warchol N, Kerby RE, et al. Influence of interface surface conditions on indentation failure of simulated bonded ceramic onlays. *Dent Mater*. 2006;22:99–106.
- Blatz MB, Vonderheide M, Conejo J. The Effect of Resin Bonding on Long-Term Success of High-Strength Ceramics. *J Dent Res*. 2018;97(2):132–9. <https://doi.org/10.1177/0022034517729134>.
- Blatz MB, Sadan A, Kern M. Resin-ceramic bonding: a review of the literature. *J Prosthet Dent*. 2003;89:268–74.
- Zhang Y, Sailer I, Lawn BR. Fatigue of dental ceramics. *J Dent*. 2013;41:1135–47.
- Sevilla P, Lopez-Suarez C, Pelaez J, Tobar C, Rodriguez-Alonso V, Suarez MJ. Influence of low-pressure plasma on the surface properties of CAD-CAM leucite-reinforced feldspar and resin matrix ceramics. *Appl Sci*. 2020;10. <https://doi.org/10.3390/app10248856>.
- Han GJ, Chun SN, Chun BH, et al. Effect of the applied power of atmospheric pressure plasma on the adhesion of composite resin to dental ceramic. *J Adhes Dent*. 2012;14:461–9.
- Foest R, Kindel E, Ohl A, et al. Non-thermal atmospheric pressure discharges for surface modification. *Plasma Phys Control Fusion*. 2005;47:B525–36.
- Kurtulmus-Yilmaz S, et al. The effect of surface treatments on the mechanical and optical behaviors of CAD/CAM restorative materials. *J Prosthodont*. 2019;28(2):e496–503. <https://doi.org/10.1111/jopr.12749>.

49. Seker E, et al. Effect of atmospheric plasma versus conventional surface treatments on the adhesion capability between self-adhesive resin cement and titanium surface. *J Adv Prosthodont*. 2015;7(3):249–56. <https://doi.org/10.4047/jap.2015.7.3.249>.
50. Seker E, et al. Non-thermal atmospheric plasma: can it be taken as a common solution for the surface treatment of dental materials? *Plasma Sci Technol*. 2016;18(4):417. <https://doi.org/10.1088/1009-0630/18/4/15>.
51. Liu T, et al. Non-thermal plasma enhanced bonding of resin cement to zirconia ceramic. *Clin Plasma Med*. 2016;4(2):50. <https://doi.org/10.1016/j.cpm.2016.08.002>.
52. Lanza MDS, Lanza FJSR, Manso AP, Matinlinna JP, Carvalho RM. Innovative surface treatments for improved ceramic bonding: Lithium disilicate glass ceramic. *Int J Adhes Adhes*. 2018;82:60–6.
53. Liao Y, Lombardo SJ, Yu Q. Argon plasma treatment effects on the micro-shear bond strength of lithium disilicate with dental resin cements. *Mater (Basel)*. 2023;16(15):5376.
54. Komagata Y, Ikeda H, Fujio Y, Nagamatsu Y, Shimizu H. Surface modification of feldspar porcelain by corona discharge and its effect on bonding to resin cement with silane coupling agent. *J Mech Behav Biomed Mater*. 2020;105:103708.
55. Han G-JJ, Chung S-NN, Chun B-HH, Kim C-KK, Oh KHH, Cho B-HH. 1,3-butadiene as an adhesion promoter between composite resin and dental ceramic in a dielectric barrier discharge jet. *Plasma Chem Plasma Process*. 2013;33:539–51. <https://doi.org/10.1007/s11090-013-9437-9>.
56. Bonitz M, Lopez J, Becker KH, Thomsen H. *Complex Plasmas: Scientific Challenges and Technological Opportunities*. Basel, Switzerland: Springer; 2014. pp. 455–85. [Google Scholar].
57. Valverde GB, Coelho PG, Janal MN, Lorenzoni FC, Carvalho RM, Thompson VP, Weltemann K-D, Silva NR. Surface characterisation and bonding of Y-TZP following non-thermal plasma treatment. *J Dent*. 2013;41:51–9. [Google Scholar] [CrossRef].
58. Tabari K, Hosseinpour S, Mohammad-Rahimi H. The Impact of Plasma Treatment of Cercon Zirconia Ceramics on Adhesion to Resin Composite Cements and Surface Properties. *J Lasers Med Sci*. 2017;8(Suppl S1):S56–61. [Google Scholar] [CrossRef].
59. Heinlin J, Isbary G, Stolz W, Morfill G, Landthaler M, Shimizu T, Steffes B, Nosenko T, Zimmermann J, Karrer S. Plasma applications in medicine with a special focus on dermatology. *J Eur Acad Dermatol Venereol*. 2011;25:1–11. [Google Scholar] [CrossRef].
60. Silva NR, Coelho PG, Valverde GB, Becker K, Ihrke R, Quade A, Thompson VP. Surface characterization of Ti and Y-TZP following non-thermal plasma exposure. *J Biomed Mater Res B Appl Biomater*. 2011;99:199–206. [Google Scholar] [CrossRef].
61. Kalra A, Mohan MS, Gowda EM. Comparison of shear bond strength of two porcelain repair systems after different surface treatment. *Contemp Clin Dent*. 2015;6(2):196–200.
62. Luthy H, Loeffel O, Hammerle CHF. Termosiklin zirkonya seramiğe ile seyrec çimentolarının bağlanma dayanıklılığı üzerindeki etkisi. *Dent Mater*. 2006;22:195–200.
63. Hannig C, Laubach S, Hahn P, Attin T. Shear bond strength of repaired adhesive filling materials using different repair procedures. *J Adhes Dent*. 2006;8:35–40. <https://doi.org/10.3290/jjad.a10897>.
64. Senawongse P, Sattabanasuk V, Shimada Y, Otsuki M, Tagami J. Bond strengths of current adhesive systems on intact and ground enamel. *J Esthet Restor Dent*. 2004;16:107–15.
65. Graiff L, Piovani C, Vigolo P, et al. Shear bond strength between feldspathic CAD/CAM ceramic and human dentine for two adhesive cements. *J Prosthodont*. 2008;17:294–9.
66. Brum R, Mazur R, Almeida J, et al. The influence of surface standardization of lithium disilicate glass ceramic on bond strength to a dual resin cement. *Oper Dent*. 2011;36:478–85.
67. Panah FG, Rezai SM, Ahmadian L. The influence of ceramic surface treatments on the micro-shear bond strength of composite resin to IPS Empress 2. *J Prosthodont*. 2008;17:409–14.
68. Nagai T, Kawamoto Y, Kakehashi Y, et al. Adhesive bonding of a lithium disilicate ceramic material with resin-based luting agents. *J Oral Rehabil*. 2005;32:598–605.
69. Bajraktarova-Valjakova E, Grozdanov A, Guguvcevski L, Korunoska-Stevkovska V, Kapusevska B, Gigovski N, et al. Acid etching as surface treatment method for luting of glass-ceramic restorations, part 1: Acids, application protocol and etching effectiveness. *Open Access Maced J Med Sci*. 2018;6(3):568–73. <https://doi.org/10.3889/oamjms.2018.147>.
70. D'Arcangelo C, De Angelis F, D'Amario M, et al. The influence of luting systems on the micro-tensile bond strength of dentin to indirect resin-based composite and ceramic restorations. *Oper Dent*. 2009;34:328–36.
71. Luhrs AK, Guhr S, Gunay H, et al. Shear bond strength of self-adhesive resins compared to resin cements with etch and rinse adhesives to enamel and dentin in vitro. *Clin Oral Investig*. 2010;14:193–9.
72. Hooshmand T, Rostami G, Behroozibakhsh M, et al. Interfacial fracture toughness of different resin cements bonded to a lithium disilicate glass ceramic. *J Dent*. 2012;40:139–45. <https://doi.org/10.1016/j.jdent.2011.12.005>.
73. El Zohairy AA, De Gee AJ, Mohsen MM, Feilzer AJ. Microtensile bond strength testing of luting cements to prefabricated CAD/CAM ceramic and composite blocks. *Dent Mater*. 2003;19:575–83.

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