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Evaluation of Shear Bond Strength of Resin Cement on the Surface of a Lithium Disilicate Glass-Ceramic Restorative Material after Various Surface Treatments

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Abstract: With bonded restorations gaining rapid popularity in clinical dentistry, manufacturers have introduced a variety of bonding protocols and materials. These materials, including surface modifiers and cleaning agents, are designed to decontaminate surfaces and enhance bonding effectiveness. In this study, six different combinations of mechanical and chemical modifications were tested on a lithium disilicate surface to determine the combination that offers optimal resistance to shear stresses. The tested surface modifications included 9% hydrofluoric acid, sandblasting with 29 µm aluminum oxide (Al_2O_3) particles, Ivoclean (a recently introduced decontamination agent), Monobond Etch & Prime (a one-stage etching and priming agent for ceramic surfaces), Monobond Plus (a silane agent), and the bonding agent Adhese Universal. Six different sequence combinations were tested and compared to the negative control group. The highest bond strength was achieved using all materials and cleansing methods in a logical order, while the bond strength was lowest in the absence of surface modification (control group). The results indicate a significantly positive influence on bond strength of silane coupling agents present in surface modifiers, including pure forms like Monobond Plus. Potential negative effects of cleansing agents or methods on bond strength were not observed. Multiple and separate stages in the treatment of the lithium disilicate surface positively impact bond strength. Cleansing agents may prove beneficial in clinical conditions, and they do not interfere with bonding.

Keywords: cleansing agents; hydrofluoric acid; lithium disilicate; sandblasting; shear bond strength; silane agents; surface treatments

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1. Introduction

The use of dental ceramics is steadily increasing in clinical dentistry, with the introduction of new products and bonding methods. Ceramics are broadly classified based on their glass content into bonded and non-bonded categories. The two main types are oxide ceramics and glass ceramics. Oxide ceramics, containing less than 15% silica with little or no glass phase, are acid-resistant and considered non-susceptible to bonding [1]. On the other hand, glass ceramics are silica-based, making them acid-sensitive and capable of achieving high adhesion strength [2]. Lithium disilicate, which contains 60 wt% silica, falls under the category of bonded ceramics [2].

Adhesive bonding of ceramic restorations with a resin cement is essential for reinforcement and support, especially without a core or framework [3]. Various studies have demonstrated that resin bonding significantly enhances the fracture resistance of ceramics [4]. This capability is closely related to the resin's elastic modulus and thickness [5]. Resin cement interacts with the defects on the ceramic surface, minimizing any flaws, while polymerization shrinkage creates compressive stresses [4]. Since ceramic materials inherently have brittleness and limited flexural strength, resin cementation is necessary to enhance their fracture toughness [1,6,7] and biaxial flexural strength [1,8].

The key to the clinical success of ceramic restorations lies in the bonding protocol used. During masticatory function, shear stresses can impact the bond strength between restorations and tooth structure. It is widely accepted that alterations in the surface treatment of ceramics affect bond strength. Several studies have explored methods to optimize the bonding protocol for ceramic restorations [9–11]. The most common protocol for surface treatment in glass ceramics involves etching with hydrofluoric acid, followed by the application of a silane coupling agent [9–11]. Some studies also suggest sandblasting followed by tribochemical silica coating or laser etching [12,13].

Oxide ceramics cannot be conditioned through acid etching; their surface can be treated with airborne-particle abrasion or tribochemical silica coating, followed by silanization or 10-MDP (10-methacryloyloxydecyl dihydrogen phosphate) application [2]. Additionally, they can be cemented using various agents such as conventional water-based luting agents like ionomer and zinc phosphate cements, hybrid cements like resin-modified glass-ionomer cements, conventional resin cements, and self-adhesive luting agents [2]. Glass ceramics can be cemented using resin luting cements, which can be light-cured, chemically cured, or dual-cured. Photo-polymerized resin cements offer advantages and higher bond strength compared to dual-polymerized cements, with dual-cured cements being preferable over chemically cured ones [1,9]. Preheated restorative resin composite with high filler content can also be used for glass ceramic cementation [9].

Monobond Etch & Prime is a recently introduced material for ceramic surface treatment. It serves as a self-etching ceramic primer, containing a water/alcohol solution of tetrabutyl ammonium dihydrogen trifluoride as the etching agent, along with a methacrylate phosphate monomer and a methacrylate functionalized silane as silane components [14]. Additionally, it includes bipodal bis-triethoxysilyl ethane, which simplifies the bonding protocol, requiring fewer steps. Its application creates a smoother ceramic surface with fewer irregularities compared to 9% hydrofluoric acid, and it forms a thin silane layer that chemically bonds to resin [15]. Monobond Etch & Prime is considered a viable alternative, producing bond strengths comparable to conventional hydrofluoric acid treatment [15,16]. However, it necessitates additional silane application [16]. Some studies argue that hydrofluoric acid induces more significant alterations on the ceramic surface, resulting in higher bond strength [15]. According to Al-Harthi et al. [17], the application of hydrofluoric acid, Monobond Etch & Prime, a self-adhesive, and a resin cement combination yields the highest shear bond strength.

During the clinical try-in procedure, the ceramic surface can become contaminated with saliva, blood, or try-in paste [18,19]. Salivary proteins create an acquired pellicle that alters the wettability and surface free energy of the ceramic substrate. This pellicle enhances bacterial adhesion, potentially degrading adhesive bonding [18,19]. These contaminants cannot be removed through water rinsing, requiring proper cleansing before cementation [18–20]. Studies indicate that cleansing the contaminated restoration results in a reliable and durable bond. Among various cleansing methods, the use of Ivoclean paste is considered highly effective [19,21]. Ivoclean contains an alkaline suspension of zirconium oxide particles that bind to salivary phosphate contaminants through adsorption, ensuring a clean ceramic surface [13]. It also includes sodium hydroxide for protein dissolution and exhibits a strong affinity toward the phosphate group, effectively removing saliva contaminants [21].

The aim of this study was to investigate the potential influence on shear bond strength (SBS) of treatment with Monobond Etch & Prime, Ivoclean, and/or sandblasting on lithium disilicate surfaces. The null hypotheses to be tested were as follows: (1) sandblasting does not affect SBS; (2) Ivoclean treatment does not affect SBS; (3) silanization does not affect SBS.

2. Materials and Methods

2.1. Materials

A lithium disilicate glass-ceramic (Vintage LD Press, Shofu, Kyoto, Japan) and a light-cure resin cement (Variolink Esthetic LC, Ivoclar Vivadent, Schaan, Lichtenstein) were tested for shear bond strength in this study. The technical characteristics of all the materials used are shown in Table 1.

Table 1. The technical characteristics of the tested materials according to the manufacturers.

Material	Type	Composition	Manufacturer
Vintage LD Press	Lithium disilicate glass-ceramic	Monoclinic lithium disilicate ($Li_2Si_2O_5$)crystals	Shofu, Kyoto, Japan
Variolink Esthetic LC	Light-cure resin cement	Monomer: UDMA and methacrylate monomers Inorganic fillers: ≅38% by volume of ytterbium trifluoride and spheroid mixed oxide. Particle size is 0.04–0.2 μm	Ivoclar Vivadent, Schaan, Lichtenstein
Monobond Plus	Universal adhesive system	Silane methacrylate, phosphoric methacrylate, and sulfide methacrylate	Ivoclar Vivadent, Schaan, Lichtenstein
Monobond Etch & Prime	Self-etching single-component ceramic primer	Alcoholic-aqueous solution of ammonium polyfluoride, silane methacrylate, and colorant	Ivoclar Vivadent, Schaan, Lichtenstein
AdheSE Universal	Light-curing single-component universal adhesive	10-MDP, MCAP, HEMA, Bis-GMA, D3MA, water, ethanol, highly dispersed silicon dioxide, initiators and stabilizers	Ivoclar Vivadent, Schaan, Lichtenstein
Ivoclean	Universal cleaning paste	Polyethyleneglycol, sodium hydroxide, ZrO_2, water	Ivoclar Vivadent, Schaan, Lichtenstein
AquaAbrasion	Abrasive Al_2O_3 powder	29-μm Al_2O_3 particles	Velopex, Harlesden, UK

Bis-GMA: bis-phenol A diglycidylmethacrylate; D3MA: methyl-D3 methacrylate; HEMA: hydroxyl-ethyl methacrylate; MCAP: methacrylated carboxylic acid poly; UDMA: urethane dimethacrylate; 10-MDP: 10-methacryloyloxydecyl dihydrogen phosphate.

2.2. Preparation of the Specimens

Experimental surfaces were obtained by sectioning blocks of lithium disilicate glass ceramic (Vintage LD, Shofu). Cylinders were cut using a low-speed precision cutting machine (Buehler Isomet, Leinfelden-Echterdingen, Germany) equipped with a diamond saw, resulting in a thickness of 2 mm and a diameter of 8 mm. Each disk was then divided into four equal parts using the same cutting device. Subsequently, each part was securely embedded in self-curing acrylic resin material (NT Newton Aycliffe Cold Repair/Self Curing Acrylic, Toros Dental, Antalya, Turkey) inside plastic cylinders precisely matching the shear-testing machine's slot (OM100, Odeme Dental Research, Luzerna, SA, Brazil), with an external diameter of 20 mm. The exposed surfaces of each specimen were meticulously cleaned and polished using a rotational polishing machine (Jean Wirtz TG 250, Dusseldorf, Germany) at 200 rpm, employing 600-grit carbide abrasive papers (Apex S system, Buehler, Lake Bluff, IL, USA) and a continuous water supply (50 mL/min) for 20 s to ensure uniformity across all surfaces.

2.3. Experimental Groups

Sixty slabs of the lithium disilicate glass ceramic were randomly distributed to six groups (n = 10). Each group received one of the treatments that are shown in Table 2 on their polished surface. Specifically, in positive control group specimens, which received all the treatments, for sandblasting (SB), an intraoral sandblasting device (AquaCare Single Dental Air Abrasion and Polishing Unit, Velopex, Harlesden, UK) loaded with 29-µm aluminum oxide particles was used. The nozzle was fixed vertically at a distance of 10 mm from the ceramic surface, with a pressure set at 4 bars. Each sample underwent sandblasting for 15 s, followed by thorough rinsing under running water to remove all particle remnants, and subsequent air drying. Monobond Etch & Prime (MEP) was applied with agitation for 20 s and allowed to react for 40 s before being rinsed off with a water spray and air dried for 10 s. Ivoclean (IC) was applied and left to react for 20 s, followed by rinsing and air drying. Monobond Plus (MP) was applied in a thin coat, left to react for 60 s, and gently air-dried. AdheSE Universal (AU) was applied and left for 20 s to react, after which the solvent was evaporated with air until no movement was detectable on the ceramic surface.

Table 2. The experimental groups in the study.

Group	Abbreviations	Surface Treatments
A	Negative control	No treatment
B	SB + MEP + AU	Sandblasting + Monobond Etch & Prime + AdheSE Universal
C	SB + IC + MEP + AU	Sandblasting + Ivoclean +Monobond Etch & Prime + AdheSE Universal
D	IC + MEP + AU	Ivoclean + Monobond Etch & Prime + AdheSE Universal
E	MEP + AU	Monobond Etch & Prime + AdheSE Universal
F	SB + MEP + IC + MP + AU (Positive control)	Sandblasting + Monobond Etch & Prime + Ivoclean + Monobond Plus + AdheSE Universal

2.4. Bonding Procedure

Teflon molds were utilized to create cylinders using light-cure luting resin cement (Variolink Esthetic LC), which were then bonded to treated surfaces of lithium disilicate specimens. The resin cement was injected into the cylindrical mold, filling a space of 2 mm in height and 3 mm in diameter. It was then light-cured using an LED light-curing unit (Bluephase Style, IvoclarVivadent, Schaan, Liechtenstein) operating at 1100 mW/cm^2 for 20 s. Subsequently, the mold was carefully removed, and all the samples were stored in the dark in distilled water for 24 h before testing.

2.5. Shear Bond Strength Test

Shear bond strength was assessed using an OM100 shear-testing machine (Odeme Dental Research, Luzerna, SA, Brazil) equipped with a load cell of 500 N with the horizontal shaft working at a crosshead speed of 1 mm/min until failure. Each specimen was adapted to the SBS layout using a loop-shaped stainless steel orthodontic wire of 0.15 mm diameter placed in contact with the ceramic restorative/resin cement bonding interface. The peak load at failure was recorded in Newtons (N) and divided by the contact area (mm^2) to calculate the value in MPa. The contact surface of each sample was verified using a digital caliper at three different diameters. The workflow of the experimental part of the study is illustrated in Figure 1.

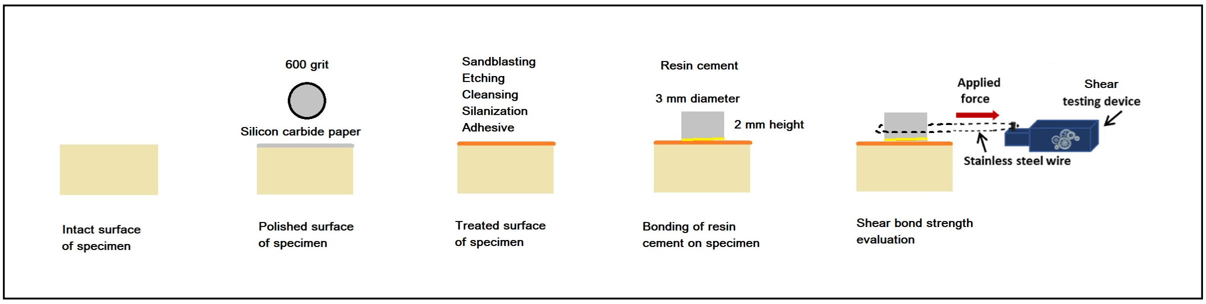

Figure 1. The workflow of the experimental part of the study.

2.6. Failure Mode Analysis

Failures were evaluated under a stereomicroscope at 20× magnification to identify the type of failure mode. The failure modes were classified as (a) adhesive failure between ceramic and resin cement, (b) cohesive failure in the resin cement, (c) cohesive failure in the ceramic bulk, or (d) mixed failure, including both adhesive and cohesive failure in the restorative material and/or resin cement.

2.7. Statistical Analysis

For statistical analysis of the data SPSS 24.0 software (SPSS, Inc., Chicago, IL, USA) was used. The sample size was determined to detect a minimum of 60% difference between any two groups with a power of 80% at a significance level of 5%. Normality distribution was examined using Kolmogorov–Smirnov test and a Q–Q plot to determine if a parametric or non-parametric test would be needed. All tests showed that the groups' distributions were normal-like and, thus, pairwise one-way ANOVA was used to evaluate the relationship between treatment methods and SBS values ($\alpha = 0.05$) and then the Tukey test for post hoc comparisons (Bonferroni corrected) was performed. Failure mode analysis was conducted using Pearson's chi-squared (χ^2) test ($\alpha = 0.05$).

3. Results

3.1. Shear Bond Strength Outcomes

The mean SBS values and standard deviations in MPa for each experimental group are presented in Table 3. All specimens of the untreated specimens of lithium disilicate restorative failed before shear bond strength test, so they were not included in the statistical analysis. The highest SBS values were observed for Group F (positive control group), followed by Group B, while the lowest values were observed for Group D. However, one-way ANOVA indicated no statistically significant differences among groups B, C, D and E ($p > 0.05$), while Group F was significantly different only from Group D ($p = 0.026$), as can be seen in Table 4.

Table 3. Means and standard deviations of shear bond strength (MPa) of the experimental groups in the study. AU: AdheSE Universal; IC: Ivoclean; MEP: Monobond Etch & Prime; MP: Monobond Plus; SB: sandblasting with 29 µm Al_2O_3 particles.

Experimental Groups	N	Abbreviations	Shear Bond Strength (MPa)
A	10	Negative control	N/A *
B	10	SB + MEP + AU	$10.70 \pm 2.40^{a,b}$
C	10	SB + IC + MEP + AU	$10.04 \pm 3.18^{a,b}$
D	10	IC + MEP + AU	9.34 ± 3.46^{a}
E	10	MEP + AU	$10.42 \pm 2.17^{a,b}$
F	10	SB + MEP + IC + MP + AU (Positive control)	12.94 ± 3.17^{b}

Same lowercase superscripts in the column indicate no statistically significant difference ($p > 0.05$). * N/A: not applicable (all the specimens failed before shear bond strength test).

Table 4. One-way ANOVA pairwise comparisons of *p*-values of the experimental groups in the study. Values with asterisk indicate statistically significant differences ($p < 0.05$).

Groups	A	B	C	D	E	F
A	-	-	-	-	-	-
B	-	-	0.607	0.321	0.787	0.091
C	-	0.607	-	0.643	0.759	0.055
D	-	0.321	0.643	-	0.415	0.026 *
E	-	0.787	0.759	0.415	-	0.052
F	-	0.091	0.055	0.026 *	0.052	-

3.2. Failure Mode Distribution

For the classification of failure types, a quantitative method was chosen over qualitative estimation. All fractured interfaces were examined and photographed under a stereomicroscope at 20× magnification to inspect the bond failure type. The percentage of the resin composite area that remained bonded to the ceramic surface versus areas where cohesive failure occurred within the ceramic bulk were calculated for each specimen using image editing software (GIMP-GNU 2.10.18 Image Manipulation Program). Specimens that exhibited debonding in more than 75% of the total surface were classified as adhesive failures, while those showing cohesive failure in more than 75% of the composite bulk area (no cohesive failures were observed in the ceramic bulk) were classified as cohesive failures. Samples with areas of debonding representing between 25% and 75% of the total sample surface were classified as mixed failures.

The frequency of the mode of failure is presented in Table 5, and representative images under the microscope are shown in Figure 2. Considering the significances of Pearson's chi-squared (χ^2) test it can be assumed that there was a relationship between "Treatment" and "Failure type" ($p < 0.05$). Mixed failures were the most common failure type across all groups. In total, 12 (24%) specimens exhibited adhesive failure, 12 (24%) had cohesive failure in the resin bulk, and 26 (52%) specimens demonstrated mixed failure types. Group B predominantly displayed mixed failure types, while the addition of Ivoclean to the bonding protocol, regardless of whether sandblasting was performed (groups C and D), increased the frequency of cohesive failures due to enhanced bond stability. Interestingly, in Group F, where bond strength was the highest, failure types were primarily mixed as well. This was likely related to the distribution of forces during testing.

Table 5. Distribution of failure mode after shear bond strength test. (a) Adhesive: failure between ceramic and resin cement; (b) Cohesive in resin bulk: failure in the resin cement; (c) Cohesive in ceramic bulk: failure in the ceramic bulk; and (d) Mixed: failure including both adhesive and cohesive failure in the restorative material and/or resin cement.

Groups	Surface Treatment	Adhesive	Cohesive in Resin Bulk	Cohesive in Ceramic Bulk	Mixed
A	None	-	-	-	-
B	SB + MEP + AU	2	0	0	8
C	SB + IC + MEP + AU	3	4	0	3
D	IC + MEP + AU	3	3	0	4
E	MEP + AU	1	4	0	5
F	SB + MEP + IC + MP + AU	3	1	0	6

Figure 2. Representative optical microscope images (15× magnification) for each category of failure mode observed in the study. (**a**) Adhesive; (**b**) Cohesive in resin bulk; and (**d**) Mixed. White arrows indicate the adhesive agent and black arrows the resin cement.

4. Discussion

The bonding of ceramics to hard tissues relies on micro-retention of irregularities created on their surface through different modification techniques. Acid-etching protocols described in the literature vary in terms of application time, the agents used, and acid concentration. Some authors recommend applying 9.5–10% hydrofluoric acid for 20 s [22,23] to 60 s [24], while others prefer 4.9% hydrofluoric acid for 2 min [25]. Hydrofluoric acid reacts with silicon dioxide, dissolving the ceramic glassy matrix, and generates micro-irregularities and pits, enhancing roughness and facilitating micromechanical interlocking with the resin cement. A similar effect can be achieved through mechanical treatments, such as sandblasting with alumina particles, creating an irregular wavy surface without visible cracks [4,26]. Irregularities can also be produced with diamond burs [2] or laser treatments [27]. In more recent protocols, the application of 37% orthophosphoric acid after hydrofluoric acid treatment is suggested to remove inorganic remnants without affecting surface morphology [1,13]. A silane coupling agent (3-methacryloxypropyltrimethoxysilane) can then be used to induce chemical bonding between the organic resin matrix and the ceramic inorganic phase [1,10,11]. According to Magne et al. [11], optimal adhesion is achieved through airborne-particle abrasion, followed by etching with 9% hydrofluoric acid for 90 s, then applying 37.5% phosphoric acid for 1 min for post-etching cleaning, and finally, applying silane that dries in 5 min at 100 °C. In this study, two recently introduced materials were tested in various combinations with mechanical and chemical surface modifiers to investigate their influence on bond strength and propose an optimal usage protocol. Monobond Etch & Prime, as per the manufacturer, can simultaneously be used for acid-etching and silanizing the ceramic surface, while Ivoclean is a universal cleaner made by the same manufacturer.

Applying Ivoclean has been suggested as a cleaning method for the extraoral application of ceramic and metal surfaces that may be contaminated during intraoral try-ins [28,29]. It contains an alkaline suspension of zirconium oxide particles (10–15%), water (65–80%), polyethylene glycol (8–10%), sodium hydroxide (<1%), and pigments and additives (4–5%) [29,30]. The removal of residual organic contaminants from the surface of restorations is achieved through the alkalinity or acidity of cleansing agents. Acidity is provided by the contained hydrofluoric acid (HF) and phosphoric acid (H_3PO_4), while alkalinity primarily comes from sodium hydroxide (NaOH) solutions. The alkalinity of Ivoclean results in a strong affinity toward the phosphate group of saliva [21]. Phosphate contaminants are absorbed by Ivoclean, leaving a clean zirconium oxide surface [31]. Despite available data on the immediate bond strength of surfaces treated with Ivoclean, the long-term in vivo effects of this treatment method are still unknown [32]. Nejatidanesh et al. [32] emphasized the safety of Ivoclean for surface conditioning due to its ease of application and removal, as well as its lack of toxicity. Kim et al. [33] acknowledged its effectiveness in removing saliva contaminants and providing a clean surface for improved resin bonding, while several authors found higher shear bond strength (SBS) when Ivoclean was applied prior to air–water spray and acid treatment [34–36].

Both Ivoclean application and sandblasting are used to remove contaminants from surfaces before applying bonding agents. Groups B and D in the present study followed the same bonding protocol but differed in their cleaning approach. Thus, the cleaning effectiveness of sandblasting was compared to that of the Ivoclean method. Results indicated that both cleaning methods were equally effective in terms of shear bond strength. Furthermore, when both cleansing methods were applied (Group C), the results remained within the same SBS range. It appeared that the cleaning agents did not produce any significant effects on the ceramic surface under in vitro conditions, supporting the acceptance of the first null hypothesis. However, it should be noted that these results cannot be directly extrapolated for in vivo applications, as the laboratory conditions for this specific experiment did not include intraoral contaminants. Therefore, ceramic surfaces were treated as "clean" and not "cleaned". Some studies claimed that sandblasting as the sole surface treatment does not yield adequate bond strength [37–40], while others argue that a sandblasted surface may initially achieve high SBS, but this strength significantly decreases after artificial aging [41].

Samples in Group E underwent the same surface modifications as those in Group D, with the additional Ivoclean treatment in the latter. However, this addition did not appear to influence bond strength values. This result was expected since the experiment was conducted in the absence of intraoral contaminants. It is essential to note that there might still be potential negative effects or interference in bonding when using Ivoclean. According to the results of the current study, the influence of Ivoclean was neither positive nor negative regarding SBS. Therefore, the second null hypothesis should also be accepted. In similar publications, Aladag et al. [29] compared the influence of cleansing methods on saliva-contaminated ceramic surfaces in terms of micro-SBS. However, they tested the cleaning effect in cases where contamination followed sandblasting and/or acid etching. They concluded that, for lithium disilicate surfaces, Ivoclean or 0.5% sodium hypochlorite did not completely restore bond strength compared to their effect on non-contaminated surfaces. Lapinska et al. [19] tested the same sequence of post-modification contamination and argued that the best practice for lithium disilicate surfaces is re-etching with HF acid for contaminated surfaces, when compared to water-spray rinsing and Ivoclean application. The same results were also presented by Charasseangpaisarn et al. [21], who found HF to provide the best post-contamination SBS values when compared to Ivoclean, phosphoric acid, sodium hypochlorite solution, and restorative cleansing agents, although the authors did not consider this a clinically important difference. However, Borges et al. [34] claimed that HF-etched lithium disilicate surfaces perform better in bond strength after contamination when treated with Ivoclean in comparison to water-spray, phosphoric acid, and isopropanol cleaning. According to the authors, this difference becomes more prominent after the samples are aged through thermocycling, providing evidence of the higher stability of the bond. This stability is associated with the observed rounded zirconia particles on the ceramic surface after treatment with Ivoclean [34].

Surfaces in Group E received no other treatment than application of Monobond Etch & Prime. This alone was adequate for the SBS of this group to outperform that of the negative control group, it having non-treated surfaces in which only pre-testing failures were experienced. In fact, the SBS for this group reached comparable values to those of groups with surface pre-treatment values. This suggests that, for application to clean surfaces, a single-bottle agent that modifies and silanizes ceramic surfaces provides a reliable alternative in terms of SBS. Consequently, the third null hypothesis of the study, stating that surface silanization does not have a significant effect on SBS, was rejected. These results are also supported by various previous studies examining different lithium disilicate surface treatments with and without silane application. Several reports concluded that silane treatment, in a separate stage and prior to the application of a universal adhesive, significantly improved bond strength [10,13,42–46].

Regarding the content of silane within the composition of universal adhesives, the literature indicated that it is not of importance, and results showed the same bond strength and quality between silane and silane-free adhesives [44–46]. As far as it concerns the intention of the acid-etching stage, Roman-Rodriguez et al. [47] claimed that the sole application of Monobond Etch & Prime provides comparable SBS values to those with a separate HF-acid-etching stage, while Lopes et al. [48] argued that the exclusion of the acid-treatment stage before silane application results in lower μ-SBS values.

In the positive control group F, all tested materials and surface treatments were sequentially implemented in a logical order. As expected, this resulted in the highest SBS values measured in this study. It could be assumed that any potential voids or imperfections in the silane monolayer formation on the ceramic surface left by Monobond Etch & Prime are filled or repaired by the application of pure silane solutions, such as Monobond Plus, and the possible addition of silane-containing universal adhesives. This way, the multiple silanization stages may complement each other, enhancing bonding.

In this study, the influence of two recently introduced materials from the same manufacturer, Ivoclean and Monobond Etch & Prime, was evaluated in an in-vitro experimental environment. Ivoclean is meant to be applied on the ceramic surface after the try-in of the restoration and contamination by saliva. Most relevant published work focused on contaminated ceramic surfaces to evaluate the decontamination potential of the material [19,21,29,34]. In this experiment, the research question was whether there was any influence, either positive or negative, on bond strength of possible surface modification or Ivoclean remnants that was not linked to cleaning ability or residual contaminants. The findings of the study did not indicate any positive or negative effect on SBS values of Ivoclean treatment. Demonstrating a potential negative influence on bond strength would raise skepticism regarding its use in clinical conditions. In such cases, the cumulative result should be taken into consideration. Hence, it could be assumed that the results of the current study are in agreement with those studies that demonstrated a positive influence of Ivoclean on SBS after contamination. For Monobond Etch & Prime, the main outcome arising from these results was that it significantly improved bond strength, even if used in a single-step treatment on the ceramic surface.

The present study, like all in vitro studies, has its limitations. In this context, to draw conclusions applicable to clinical scenarios, clinical trials and retrospective studies are necessary. The absence of contaminants in this experiment provides a repeatable experimental protocol with reliable results; however, it overlooks the influence of ceramic surface contamination, a crucial factor that may affect clinical outcomes. Using a rubber dam and sandblasting prior to try-in might reduce ceramic surface contamination. Alternatively, cleaning agents seem to offer a reliable surface decontamination treatment. Another limitation of the current study is that SBS values were obtained 24 h after bonding procedures. Artificial aging in such cases may provide more information on the bond between the restorative material and the resin cement. Additionally, more restorative materials and resin cements should be investigated in future studies to enrich data on the behavior of these materials during bonding procedures.

5. Conclusions

Within the limitations of this in vitro study, it could be deduced that surface modifications of a lithium disilicate glass-ceramic restorative are essential for bonding procedures using resin cements. The modifications to the lithium disilicate surface for bonding purposes should focus on promoting micro-retention, potentially inducing chemical interactions, and preventing contamination. In cases of contamination, cleansing methods should be implemented to re-expose the surface to bonding agents. Protocols involving etching, silanization, and decontamination are crucial for achieving stable and repeatable results. The use of cleansing agents is recommended as a reliable alternative for treating a contaminated surface. Further studies are necessary to confirm the findings of this research and especially to evaluate the restorations in vivo.

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Conflicts of Interest: The authors declare no conflict of interest.

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