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Article

Does Silane Application Affect Bond Strength Between Self-Adhesive Resin Cements and Feldspathic Porcelain?

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Abstract: This study aimed to evaluate the shear bond strengths of six self-adhesive resin cements (SACs) on porcelain surfaces and to compare the effectiveness with and without silane application. One hundred and twenty feldspathic porcelain specimens were prepared, etched with 9.5% HF, and divided into two main groups: (i) without silane, and (ii) with silane application. Each main group was further divided into six subgroups, testing six various SACs. Shear bond strength was measured using a universal testing machine, and the de-bonded surfaces were examined with a stereomicroscope. The statistical analysis was tested with two-way ANOVA and post hoc with Tukey's. The results showed that Panavia SA Luting Multi had the highest shear bond strength, especially with silane application, while G-Cem One exhibited the lowest in the absence of silane. The addition of silane application significantly improved the shear bond strengths of G-Cem One, Panavia SA Luting Multi, and RelyX Unicem compared to situations without silane application. The adhesive and mixed failure modes were found to depend on the brand of SACs. No cohesive failure was detected. The study concludes that Panavia SA Luting Multi achieves superior shear bond strength on feldspathic porcelain when used with a separate silane agent. The etched feldspathic porcelain surface primed with silane coupling agent is recommended for optimal bond strength when using with SACs such as G-Cem One, Panavia SA Luting Multi, or RelyX Unicem.

Keywords: bond strength; porcelain; repair; resin cements; silane

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1. Introduction

Restorations with porcelain fused to metal (PFM) have been widely used in clinical treatments and tooth restorations due to their outstanding characteristics, including natural esthetics, durability, wear resistance, and corrosion resistance. The porcelain veneer enhances the appeal of these prostheses with its aesthetic qualities, color stability, biocompatibility, and excellent wear resistance [1].

There are a lot of reports on the chipping of the veneering felspathic porcelain. A long-term clinical study on PFM crowns found that there was 6.25% of porcelain fracture [2], while laboratory studies stated the percentages of successful and damaged PFM restorations were 88% and 12%, respectively. Chipped porcelain veneers comprised 13% of the defects, and c racked porcelain veneers constituted 25% of the defects [3]. Fractured porcelain may result from multifactorial problems, such as the vast differences in moduli between the metal and ceramic materials, repeated stress and strain during chewing, trauma, microcracks, improper porcelain thickness, technical mistakes during porcelain fabrication, improper design of the restoration, and the chemistry of the oral environment [4].

Fractured porcelains will affect the aesthetics and function of the prostheses, which may cause patients to seek immediate treatment [5,6]. Fractures of porcelain may be classified as simple (fracture in porcelain only), mixed (fracture with both porcelain and core material exposure), or complex (fracture with substantial core material exposure) [7,8].

The most effective way to solve the problem is to evaluate the cause of failure. There are several kinds of direct intraoral repairing techniques. First, it is possible to remove the entire restoration and send it to the technician, who will re-veneer and refire it or replace it with a new restoration. In practical terms, the complete removal of a restoration without inflicting any damage to the surrounding portions of the restoration is unattainable [9].

An alternative approach involves conducting an intraoral repair of the ceramic restoration, serving as a temporary yet effective measure. This strategy circumvents the drawbacks associated with removing the restoration, preserving its functionality and preventing the buildup of microorganisms in the damaged area. Three options exist: (i) replace the missing piece of porcelain with composite-based resin, (ii) reattach the broken piece of porcelain with resin cement, or (iii) prepare the restoration for a new porcelain veneer and then securely attach the ceramic veneer to the existing restoration using resin cement [9].

Two strategies comprise the ceramic repair techniques: (i) Micro-mechanical retention is achieved through sandblasting or hydrofluoric (HF) acid etching, creating micropores that enhance surface roughness. These micro-roughened surfaces allow better mechanical retention of the repair material, leading to a stronger bond and (ii) chemical adhesion by functional monomers. Bonding agents, primers, or SACs incorporate these monomers with the intention of chemically interacting with the ceramic surface. The functional groups in the monomers can bond with the silica component in the ceramic, creating a strong chemical link that improves the overall adhesion of the repair material [8,9]. When reattaching the broken piece of porcelain with resin cement, the challenge is to create a strong, mechanochemical bond between the hydrophobic resin-based composite or resin cement and the fractured surface of the restoration. Micromechanical retention is achieved using air abrasion with the intraoral sandblaster or by etching with hydrofluoric acid. However, etching with hydrofluoric acid is preferred because it is easier to perform, well documented in the literature, and less detrimental to silicate ceramic material [10–12]. Etching the fractured ceramic part of a crown with HF, followed by applying a silane, is a well-known and recommended method to improve the attachment of resin composite to ceramic [13,14].

The newest resin cements are self-adhesive dual-cured cements that require no etching, primers, or bonding agents to bond to the tooth surface. Self-adhesive cements (SACs) simplify bonding procedures, saving time, and are designed to reduce the luting step of indirect restorations. The bonding effectiveness of self-adhesive cements is determined by their chemical composition. The matrix of these cements contains molecules with acidic phosphate or carboxylate groups, such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), 4-methacryloyloxyethyl trimelithic acid (4-META), and glycerol phosphate dimethacrylate (GPDM), which contribute to their ability to bond with the substrate chemically [15].

Silane coupling agents are widely recognized as effective promoters of adhesion for silica-based or silica-coated indirect dental restorations. The silane coupling agents enhance the etched ceramic surface by improving its wettability, allowing for more effective infiltration of the resin cements into the etched surface irregularities [16]. Additionally, this establishes a covalent bond that connects the ceramic's inorganic phase with the resin cement's organic phase via siloxane bonds. To achieve strong and long-lasting adhesion between the substrate and resin composite, surface pre-treatment methods such as acid etching for porcelain are employed prior to the application of silane [17]. Tarateeraseth et al. found that the type of silane agent greatly influences the bonding strength between ceramic and resin material, and the bond abilities vary in accordance with the type of silane applied [13].

Recently, there have been no investigations into the efficacy of chairside repairs of chipped porcelain using various SACs. Consequently, the aim of this study was to evaluate the shear bond strengths of SACs when applied to a porcelain surface and to compare these shear bond strengths between applications involving silane and those without it on the porcelain surface. The null hypothesis is that there is no difference in the shear bond strength of different SACs when applied to a porcelain surface with or without a silane agent.

2. Materials and Methods

2.1. Specimen Preparation

The sample size was calculated by G-power software (Version 3.1.9.7, Heinrich-Heine Dusseldorf University, Dusseldorf, Germany) using ANOVA fixed effects, special, and main effects and interactions with 0.05 type I error, 0.95 power, and a degree of freedom of 5. The findings showed an effect size of 0.42 with a total of 119 samples spread over 12 subgroups. Therefore, in this study, 10 specimens per group were used. One hundred and twenty specimens made of feldspathic porcelain (Noritake Super Porcelain Ex-3 (A2 Body), Kuraray Noritake Dental Inc., Tokyo, Japan), each measuring 10 mm in diameter and 4 mm in thickness, were created. The manufacturer's instructions were followed for fabricating the porcelain specimens. Porcelain specimens were embedded in 22 mm diameter polyvinyl chloride (PVC) tubes containing epoxy resin. The specimens were polished using silicon carbide paper of 600-grit (3M Wetordry abrasive sheet, 3M, Maplewood, MN, USA) on an automated polishing device (Nano 2000, PACE Technologies, St. Tucson, NZ, USA) under running water for 120 s. The specimens were cleaned in an ultrasonic cleaner (Branson 5210, Bransonic, Dietzenbach-Steinberg, Germany) with distilled water for 5 min, subjected to oil-free air drying, and stored in a closed plastic container until used.

2.2. Surface Treatment

All porcelain specimens were etched with 9.5% HF (Bisco Inc., Schaumburg, IL, USA) for 120 s and then rinsed with distilled water and air-dried for 10 s with 40–50 pound/in^2. The porcelain specimens were randomized into two groups of 60 specimens each, as follows: group 1, without silane application, and group 2, with silane application. Each group was randomized into six subgroups of 10 specimens, each according to a type of SACs, as follows: G-Cem One, (GC Corp., Tokyo, Japan), Maxcem Elite Chroma (Kerr Corporation, Brea, CA, USA), Panavia SA Luting Multi (Kuraray Noritake, Tokyo, Japan), RelyX Unicem (3M ESPE, 3M, Maplewood, MN, USA), RelyX U200 (3M ESPE, Maplewood, MN, USA), and RelyX Universal (3M ESPE, Maplewood, MN, USA).

To obtain the maximum SACs bonding area, an adhesive tape (thickness = 50 micron) with an inner circular hole (diameter = 2.38 mm) was prepared by a laser die cutting machine, and an adhesive tape was applied to all specimens; cutting the tape's side produced a circular hole that was easy to remove.

The experimental design is shown in Figure 1, whereas Figure 2 illustrates the stage of specimen preparation and testing.

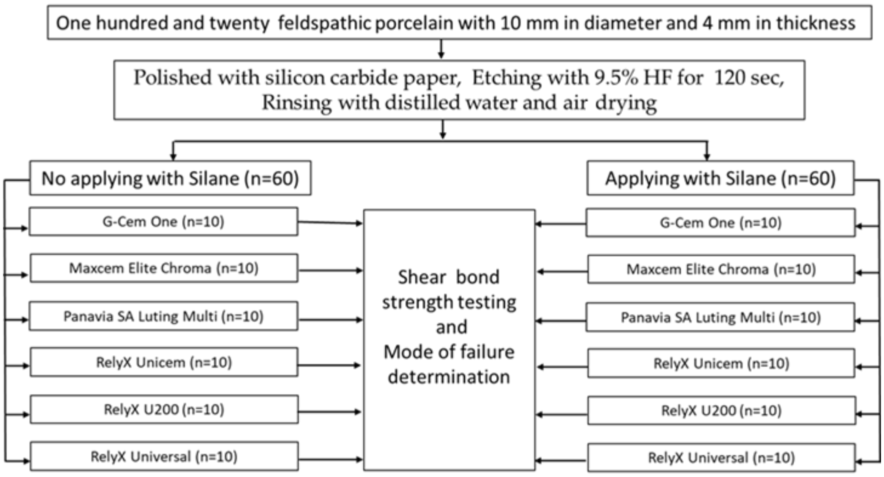

Figure 1. A flowchart of the experimental process for measuring the shear bond strength and determining the mode of failure.

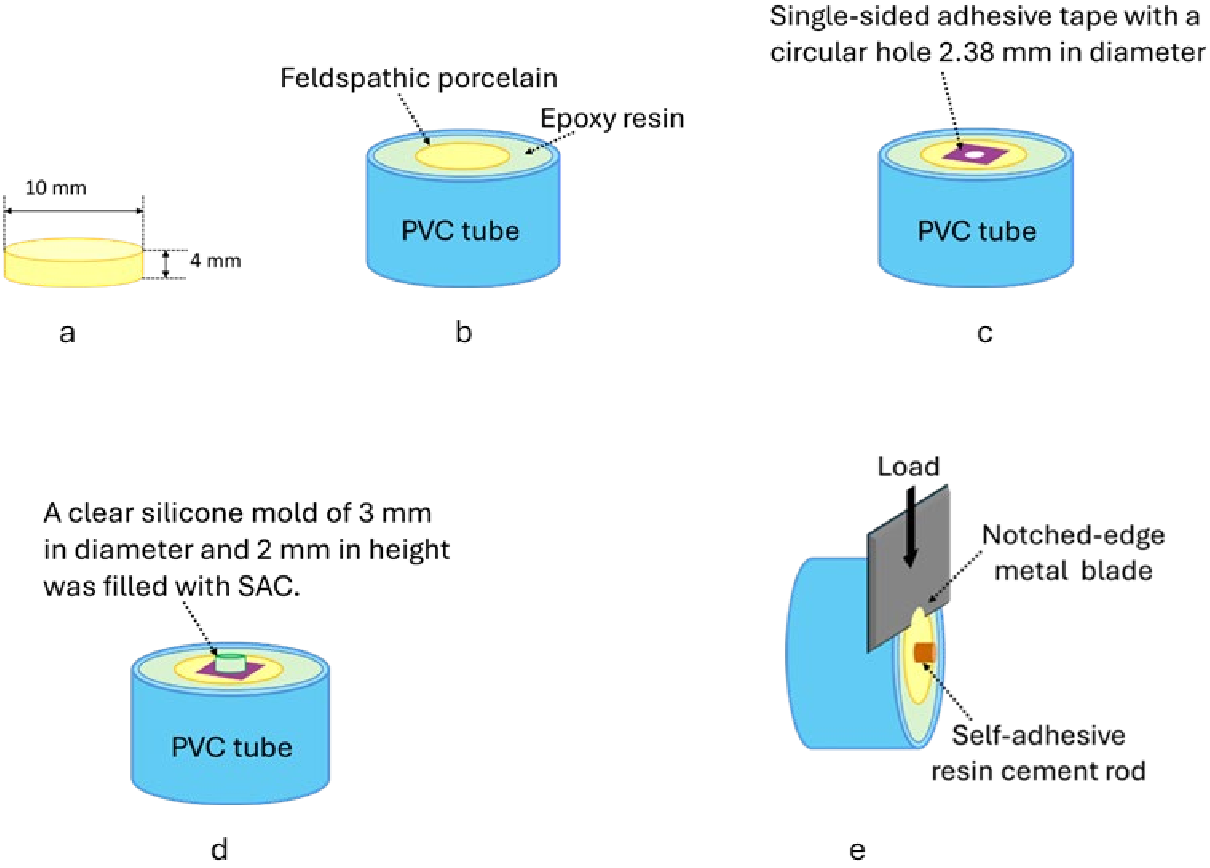

Figure 2. The stage of specimen preparation and testing; (**a**) the dimensions of the feldspathic porcelain sample; (**b**) the sample was embedded using epoxy resin in PVC tube; (**c**) a single-sided adhesive tape with 2.38 mm in diameter was firmly attached on the feldspathic porcelain surface; (**d**) the self-adhesive resin cement was filled into a clear silicone mold; (**e**) the notched-edge shear bond strength testing was performed by using universal testing machine.

2.3. Silane Application

The silane agent (Porcelain primer, Bisco Inc., Schaumburg, IL, USA) was applied onto the porcelain specimens in group 2 with a disposable micro brush (applicator tips, Dentsply DeTrey, Konstanz, Germany). The silane agent was smeared evenly into a thin layer, enabling the silane coupling agent to interact with the porcelain surface. The excess silane agent that built up around the border of the tape loop was blotted off using a new micro brush. After 30 s, oil-free air was blown from a triple syringe until the absence of movement of the silane agent was observed, and it was scorched [13].

2.4. Cementation

The SAC was then poured into the silicone mold (3 mm in diameter, 2 mm in height) until full and then light-cured for 40 s perpendicular to the template and as close as possible using an LED light-curing unit (Demi Plus, Kerr, Brea, CA, USA). The specimens were light-cured for another 40 s perpendicular to the resin cement on each side. All specimens had the adhesive tape removed and were stored in distilled water for 24 h at 37 degrees Celsius. Table 1 indicates the materials and SACs used in this research.

Table 1. Materials, manufacturers, and compositions used in this research.

Type	Material (Lot No.)	Code	Compositions
Self-adhesive resin cements (SACs)	G-Cem One (GC Corp., Tokyo, Japan) (2101271)	GC	Paste A: fluoroaluminosilicate glass, UDMA, dimethacrylate, initiator, stabilizer, pigment, silicon dioxide, and 10-MDP. Paste B: SiO_2, trimethoxysilane, UDMA,2-hydroxy-1,3 dimethacryloxypropane, 10-MDP, 6-tert-butyl-2,4-xylenol, 2,6-di-tert-butyl-p-cresol, EDTA, disodium salt dehydrate, vanadyl acetylacetonate, TPO, ascorbic acid, camphorquinone, and MgO.
	Maxcem Elite Chroma (Kerr Corporation, CA, USA) (10156938)	MX	Methacrylate ester monomers, GPDM, proprietary self-curing redox activator, camphorquinone, fluoraluminosilicate glass filler, silica, barium glass filler, activators, and stabilizers.
	Panavia SA Luting Multi (Kuraray Noritake, Tokyo, Japan) (3P0169)	PS	10-MDP, Bis-GMA, TEGDMA, hydrophobic aromaticdimethacrylate, hydrophobic aliphatic dimethacrylate, long carbon chain silane, di-camphorquinone, benzoyl peroxide, Initiator, silanated colloidal silica, silanated barium glass filler, accelerators, surface-treated sodium fluoride, and pigments.
	Rely X Unicem (3M ESPE, Maplewood, MN, USA) (9737626)	RUN	Phosphoric acid-modified methacrylate monomers, bifunctional methacrylate, silanated fillers, initiator components, stabilizers, methacrylate monomers, alkaline fillers, and pigments.
	Rely X U200 (3M ESPE Maplewood, MN, USA) (10376045)	RU2	Silane-treated glass powder, substituted dimethacrylate, 1-benzyl-5-phenyl-barbic-acid, calcium salt, silane-treated silica, sodium p-toluenesulfinate, 1,12-dodecane dimethycrylate, calcium hydroxide, methacrylated aliphatic amine, and titanium dioxide.
	Rely X Universal (3M ESPE Maplewood, MN, USA) (10195470)	RUS	BPA derivative-free dimethacrylate monomers and phosphorylated dimethacrylate adhesion monomers. Photoinitiator system, novel amphiphilic redox initiator system, radiopaque fillers, and rheological additives.
Etchant	Porcelain etchant (Bisco Inc., Schaumburg, IL, USA) (2200000962)	HF	9.5% hydrofluoric acid.
Silane	Porcelain primer (Bisco Inc., Schaumburg, IL, USA) (2100008801)	PP	Acetone, ethanol, and silane.

Abbreviations: UDMA, urethane dimethacrylate; 10-MDP, 10-methacryloyloxydecyl dihydrogen phosphate; EDTA, ethylenediaminetetraacetic acid; TPO, diphenyl (2,4,6-trimethylbenzoyl)phosphine oxide; GPDM, glycerol phosphate dimethacrylate; Bis-GMA, bisphenol A-glycidyl methacrylate; TEGDMA, triethylene glycol dimethacrylate; BPA, bisphenol A.

2.5. Shear Bond Strength Testing

A universal testing device (AGS-X 500N, Shimadzu Corporation, Kyoto, Japan) was used to evaluate the shear bond strength of the specimens (shear notch). The shearing blade was positioned parallel to the intersection of the porcelain and SACs. A shear pressure of 0.5 mm per min was set until fracture occurred. The shear bond strength in MPa was calculated by the maximum shear bond strength divided by the surface region of the bonding interface.

2.6. Failure Evaluation

The fractured surface of the porcelain specimen was examined using a stereomicroscope at a magnification of 40× (ML9300, Meiji Techno Co., Ltd., Saitama, Japan) to determine the mode of failure, which was divided into three categories [13,14]: (i) Adhesive failure happens when porcelain and SACs fail to adhere to one another. This occurs when the excess 80% porcelain surface has no SACs. (ii) Cohesive failure happens when the failure occurs within the SACs. This occurs when the excess 80% of the surface of porcelain is coated with SACs. (iii) Mixed failure happens when adhesive and cohesive failures occur together. This happens when a remnant of SACs remains adhered to the porcelain surface or to the dislodged part of the porcelain.

2.7. Statistical Analysis

IBM SPSS Statistics 25.0 (SPSS Inc., Chicago, IL, USA) was used to determine the quantitative data from 12 independent groups. Descriptive analyses are reported as mean and standard deviation. The Shapiro–Wilk test was used to determine normality, and the homogeneity of variance was determined by Levene's test. Two-way ANOVA followed by Tukey's post hoc analysis was used to assess the effect of resin cements, silanization protocols, and their interactions on shear bond strength values. All tests were conducted at a significant level of $p < 0.05$.

3. Results

Prior to measuring the shear bond strength in this investigation, no debonded specimens were present. The samples were divided into two silanization protocols: one without silane application and one with it. Furthermore, each protocol was divided into six smaller groups using six different SACs: GC, MX, PS, RU2, RUN, and RUS. The descriptive analyses of mean shear bond strength and standard deviation (MPa) of all groups are shown in Table 2.

Table 2. Mean shear bond strength and standard deviation (MPa).

Type of SACs	Without Silane	With Silane
GC	$12.68 \pm 1.92^{(A,1)}$	$36.77 \pm 3.15^{(B,1)}$
MX	$29.77 \pm 2.44^{(A,2,3)}$	$29.36 \pm 4.74^{(A,2)}$
PS	$25.72 \pm 2.50^{(A,2)}$	$56.09 \pm 1.82^{(B,3)}$
RU2	$42.04 \pm 2.47^{(A,4)}$	$40.45 \pm 4.65^{(A,1)}$
RUN	$35.36 \pm 3.07^{(A,3)}$	$50.57 \pm 5.77^{(B,3)}$
RUS	$27.06 \pm 1.82^{(A,2)}$	$29.69 \pm 2.92^{(A,2)}$

The same upper-case superscript letter (in rows) indicates mean values without statistically significant differences among silanization (without silane and with silane). The same number (in columns) indicates mean values without statistically significant differences among of SACs. Abbreviations: SACs, self-adhesive resin cements; GC, G-Cem One; MX, Maxcem Elite Chroma; PS, Panavia SA Luting Multi; RU2, Rely X U200; RUN, Rely X Unicem; RUS, Rely X Universal.

In the subgroup where silane was not used, the SACs are arranged in a way that shows their shear bond strengths in a certain order. The order starts with GC and goes through PS, RUS, MX, RUN, and finally RU2. This sequence represents a gradation from the lowest to the highest shear bond strength observed among these materials. We observed that GC exhibited the lowest shear bond strength, while RU2 demonstrated the highest shear bond strength. This difference was significant compared to all other groups, and a *p*-value less than 0.05 indicated the statistical significance. We observed no significant difference in shear bond strength between PS, RUS, and MX or between MX and RUN, with a *p*-value more than 0.05 indicating statistical significance.

The SACs in the silane application subgroup are organized analytically to show a logical order based on their shear bond strengths. The order starts with MX and goes through RUS, GC, RU2, RUN, and PS. This sequence illustrates a spectrum of shear bond strengths from the lowest to the highest observed among these materials. MX demonstrated the lowest shear bond strength, showing a significant difference from GC, RU2, RUN, and PS, as evidenced by a *p*-value less than 0.05. Therefore, it did not significantly differ from RUS. On the other hand, PS demonstrated the highest shear bond strength, showing a significant difference from MX, RUS, GC, and RU2, as evidenced by a *p*-value less than 0.05. Therefore, it did not significantly differ from RUN.

We observed significant differences among GC, PS, and RUN within the category of SACs. We discovered that adding silane made the shear bond strengths of GC, PS, and RUN better than when silane was not added ($p < 0.05$). Regardless of silane application, we observed no statistically significant difference in the shear bond strengths of RU2, MX, and RUS ($p > 0.05$).

Table 3 presents the results of the failure mode analysis for SACs. In the groups without silane, testing the shear bond strength showed that the failure modes were mostly adhesive or mixed. Specifically, RU2 and RUN showed a consistent pattern of failure, with all specimens (100%) exhibiting mixed failure. RUS displayed an equitable distribution of failure modes, with an equal split (50%) between adhesive and mixed failures. MX and PS primarily exhibited adhesive failures at rates of 70% and 60%, respectively. Finally, all specimens of GC showed adhesive failure. Figure 3 displays stereomicroscope pictures of the failure mode analysis for SACs without silane.

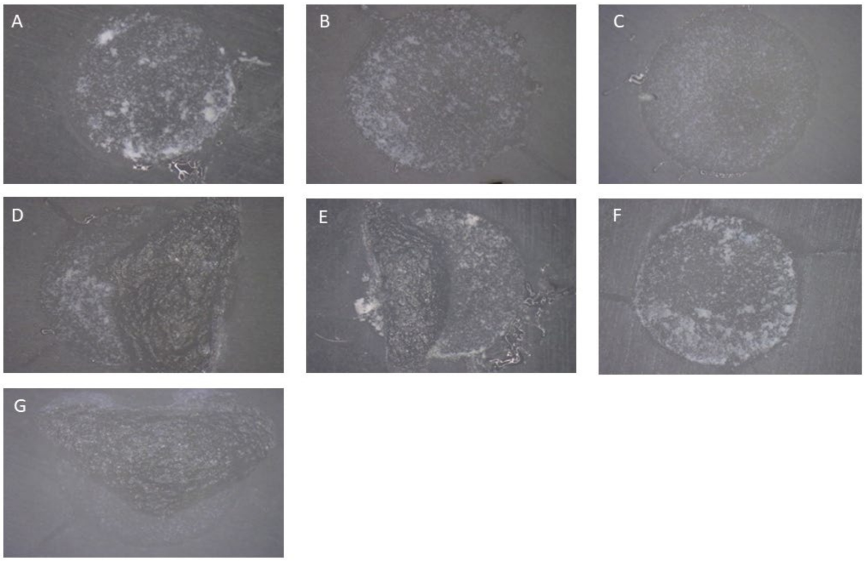

Figure 3. Failure mode illustrating, in the case of no application of silane, (**A**) adhesive failure in group GC; (**B**) adhesive failure in group MX; (**C**) adhesive failure in group PS; (**D**) mixed failure in group RU2; (**E**) mixed failure in group RUN; (**F**) adhesive failure in group RUS; and (**G**) mixed failure in group RUS.

Table 3. Percentage of failure mode analysis for SACs.

Type of SACs	Without Silane			With Silane		
	Cohesive	Adhesive	Mixed	Cohesive	Adhesive	Mixed
GC	0	100	0	0	20	80
MX	0	70	30	0	50	50
PS	0	60	40	0	0	100
RU2	0	0	100	0	20	80
RUN	0	0	100	0	0	100
RUS	0	50	50	0	50	50

In the groups with silane, testing the shear bond strength showed that the failure modes were mostly adhesive or mixed. Specifically, PS and RUN showed a consistent pattern of failure, with all specimens (100%) exhibiting mixed failure mode. Both RU2 and GC exhibited an 80% mixed failure mode. RUS and MX displayed an equitable distribution of failure modes, with an equal split (50%) between adhesive and mixed failures. Figure 4 displays stereomicroscope pictures of the failure mode analysis for SACs with silane.

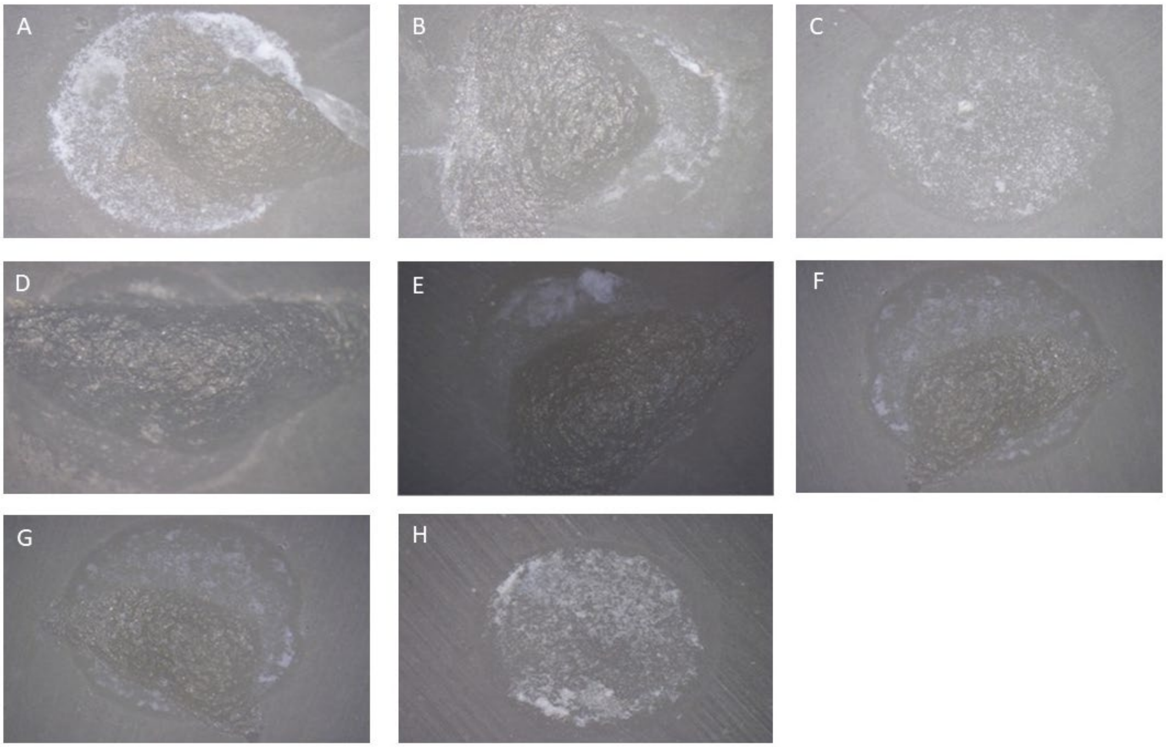

Figure 4. Failure mode illustrating, with respect to the application of silane, (**A**) mixed failure in group GC; (**B**) mixed failure in group MX; (**C**) adhesive failure in group MX; (**D**) mixed failure in group PS; (**E**) mixed failure in group RU2; (**F**) mixed failure in group RUN; (**G**) mixed failure in group RUS; and (**H**) adhesive failure in group RUS.

4. Discussion

Currently, porcelain surface treatment before repairing a restoration can be performed using several methods. The most common method of gaining the best retention is to obtain both mechanical and chemical retention. The most accepted conditioning protocol used for the luting of silica-based ceramics involves HF etching, followed by the application of a silane coupling agent [10–14,18], which promotes adhesion between the resin cement and ceramic material [17,19].

In current study, PS established the highest shear bond strength, which was not significantly different from RUN. Long carbon chain silane (LCSi) monomers are incorporated in PS, which are known for their hydrophobic properties; additionally, PS contains bisphenol A-glycidyl methacrylate (Bis-GMA) monomers, which are considered relatively hydrophilic, but they are significantly less hydrophilic than systems containing acidic groups such as carboxylic or phosphate groups [20,21]. Although PS contains 10-MDP, this longer backbone could increase the hydrophobicity of the cement, exhibiting lower water absorption [21], contributing to enhanced hydrolytic stability, and reducing degradation [17]. Therefore, its bond strength was considered greater than that of other SACs with different phosphate monomers [22]. In accordance with Vanidi et al., we discovered that RUN exhibits a higher bond strength than MX, indicating its superior bonding capabilities that result in a stronger adhesion when attached to porcelain [23]. Sriamporn et al. also reported that PS has a higher bond strength than MX; this finding could imply that PS has a better capacity to adhere to ceramic surfaces than MX [24].

In the silane's prime condition, its silanol functional groups form Si-O-Si covalent bonds with the porcelain surface, while the methacrylate functional groups polymerize with comparatively fewer hydrophilic methacrylate monomers, resulting in a significantly increased shear bond strength. Although PS established the highest shear bond strength in the context of applying silane, without silane, shear bond strength was decreased. PS, including two high-viscosity pastes, may diminish the wettability of cement. Furthermore, the resin's high viscosity and its slow rise after mixing can hinder the long carbon chain silane's ability to move and react with the porcelain surface. Another explanation for the inactivity of long-chain silane is that water generally needs to activate the silane coupling monomer in order for it to hydrolyze, converting alkoxy groups into silanols and reacting with the hydroxyl groups on the porcelain surface. But PS, comprising two high-viscosity pastes requiring mixing before use, may not efficiently absorb atmospheric moisture. Therefore, it is questionable whether silane coupling agents in such pastes undergo hydrolysis effectively during the time frame of clinical application [25]. As a result, the silane agent could not be effectively incorporated into resin cement. On the other hand, the single bottle of silane used in this investigation was prehydrolyzed and already contained a silanol group, whose direct contact with felspathic porcelain enhances its wettability, adaptability, and bond strength. Therefore, separate silanization is more effective and recommended [26].

The factors that influence the shear bond strength among these SACs are as follows: High water sorption might lead to the occurrence of expansion stress [21,27]. However, it has also been reported that although expansion might lead to gap closure, it is rather unlikely that marginal integrity can be restored [28]. Water sorption is influenced by various factors, such as the composition of cements; for example, RUN and RU2 have monomers that are considered relatively less hydrophilic than carboxylic or phosphate groups [20,21], and they tend to exhibit lower water absorption [21], contributing to enhanced hydrolytic stability and reducing degradation [28]. In contrast, MX contains GPDM, and it has two polymerizable methacrylate groups, one phosphate acidic functional group, and a short spacer hydrocarbon chain with comparatively hydrophilic properties [29], while GC has urethane dimethacrylate (UDMA), phosphoric acid ester, and 4-META, all containing a phosphate group. The behavior of water absorption in polymers with UDMA is influenced by the material's hydrophilicity and flexibility, which can lead to chain slipping and plasticization of the polymer structure [30]. The hydrophilic nature of UDMA polymers is attributed to their urethane groups, which contain amide linkages capable of forming strong hydrogen bonds with water and acidic substances. This characteristic enhances the material's ability to absorb liquids, aligning with research that indicates UDMA-based materials have a higher tendency for water absorption [31]. This is in agreement with previous studies demonstrating that polymers with a high concentration of hydrophilic moieties will tend to absorb more water [32,33]. For this reason, GC and MX showed lower shear bond strength when compared to RUN and RU2.

The other influencing factor is pH neutralization behavior, which is the ability of a material to absorb water, and it is more influenced by the quantity of unreacted acidic groups remaining after the material sets than by the initial amount of acidic groups present. This is because the ion-leachable fillers in the material may neutralize some acidic groups during the setting process. In the present study, RUN and RU2 exhibited significantly higher shear bond strengths compared to GC and MX, respectively. These findings are consistent with prior research examining the pH neutralization characteristics of GC, MX, and RUN [34]. One study reported that after 48 h, RUN achieved a neutral pH of 7.0, whereas GC and MX only reached pH levels of 3.6 and 2.4, respectively [34]. It can be concluded that the rapid pH neutralization observed in RUN is associated with reduced water absorption compared to GC and MX, respectively.

The findings indicated that GC exhibits a significantly higher shear bond strength compared to MX and RUS. Moreover, the reason is the composition of cement such as GPDM and UDMA, which induces high water sorption [29,31]. However, MX exhibits higher water absorption compared to GC due to its pH-neutralization characteristics [35]. After a duration of 48 h, the pH levels of MX were observed to be lower than those of GC, indicating that MX demonstrates slower pH-neutralization behavior in comparison to GC [34]. Eventually, the acid component of MX becomes insufficient for triggering chemical bonding, and consequently, high bond strength may not be produced [22].

Quantities of filler constitute another reason for water sorption. Therefore, the increasing sorption values among the materials studied, i.e., PS < MX < GC < RUN < RU2 < RUS, go along with their decreasing mean filler content: PS (62%), MX (66%), GC (65–70%), and RUN, RU2, and RUS (72%) [30,36].

The technique for blending paste-based resin cement can vary, including manual mixing on a paper pad (hand-mixed) or using an auto-mixing device (machine-mixed and auto-mixed syringe). Manual or hand mixing may lead to a variety of air void sizes and quantities within the resin. Typically, luting cements are composed of at least two separate pastes. Research indicates that the process of mixing these pastes can inadvertently introduce air bubbles and voids into the mixture. Such inclusions can compromise the cement's integrity, resulting in diminished mechanical properties such as lower strength. Porosity and voids within the polymer matrix can increase the movement of liquids into and out of the material, leading to higher rates of absorption and dissolution [31,37]. Suliman et al. stated that machine-mixed or auto-mixed syringe cements perform better than hand-mixed cements [37], in contrast with Zorzin et al., who observed that capsule products, specifically GC capsules and RUN maxicap, exhibited significantly higher water solubility and sorption values ($p < 0.05$) compared to their counterparts mixed by hand or through auto-mix syringe. This difference is attributed to increased porosity within these capsule products [35]. Therefore, in this study, the results indicate that both the auto-mixed and machine-mixed cements, exemplified by RUN, and the auto-mixed syringe cements, such as PS, exhibit high shear bond strength within the group utilizing silane coupling agents. This finding suggests that the mixing method is a significant factor influencing the physical properties of SACs.

RUS exhibited the lowest shear bond strength among the SACs tested in this study, a significant variance attributed to its unique monomer composition, which differs from that found in RUN and RU2. RUS, which incorporates 2-hydroxyethyl methacrylate (HEMA), triethylene glycol dimethacrylate (TEGDMA), and UDMA [38], displays greater water sorption than other SACs [39]. This leads to poor shear bond ability, resulting in RUS having lower shear bond strength than RUN and RU2.

The application of silane was found to enhance the shear bond strengths of GC, PS, and RUN compared to conditions where silane was not applied, and this was due to silane coupling agents, which are widely recognized as effective promoters of adhesion for silica-based or silica-coated direct and indirect dental restorations [13,14,40]. The silane coupling agent enhance the etched ceramic surface by improving its wettability, which in turn allows for more effective infiltration of the resin cement into the etched surface irregularities [16]. Additionally, they establish a covalent bond that connects the ceramic's inorganic phase with the resin cement's organic phase via siloxane bonds. To achieve robust and long-lasting adhesion between the substrate and resin material, surface pre-treatment methods such as acid etching for porcelain is employed prior to the application of silane [17]. A previous study showed that the additional step of bis-silane application along with the use of universal adhesives with or without silane in their composition significantly increased the repair bond strength of feldspathic porcelain. Our results in the group of GC, PS, and RUN are in agreement with those reported [41,42].

The analysis of failure modes, both with and without silane application, revealed distinct outcomes for various SACs when applying silane to porcelain; shear bond strength testing revealed the primarily adhesive and mixed failure mechanisms. In the context of the current study, it was observed that, in the group without silane application, RU2 and RUN demonstrated high shear bond strength. Similarly, in the group with silane application, PS and RUN also exhibited high shear bond strength, with 100% mixed failure occurring within the porcelain in both groups. High shear bond strength was frequently associated with mixed failure modes within ceramics, in accordance with Sriamporn et al. [24]. This could be due to the improved chemical bond of the SACs. Mixed failures within porcelain are often due to the fact that feldspathic porcelain is weaker than the bonding strength achieved between SACs and the porcelain surface [43].

A limitation of this study is that it only used one type of porcelain, not representing all types of porcelain. Additionally, this study only assessed the bond strength after 24 h, which may not accurately reflect its long-term performance. In real-life conditions, the bond may degrade over time due to factors like temperature changes and mechanical stress. Further studies may require using different types of porcelain, and long-term bonding durability should be performed by thermocycling, providing a better understanding of the material's long-term performance.

5. Conclusions

The aim of this study was to evaluate the shear bond strengths of SACs when applied to a porcelain surface. In the absence of silane, it was observed that RU2 established the highest shear bond strength, with a significant difference compared to GC, PS, RUS, MX, and RUN. In context of applying silane, it was observed that PS and RUN established the highest significant shear bond strength, which was significantly different from GC, MX, RU2, and RUS. Therefore, the null hypothesis that there is no difference in the shear bond strength of different SACs when applied to a porcelain surface with or without a silane agent is rejected.

(1) The application of a silane agent prior to using the SACs was found to enhance the SBS in G-Cem One, Panavia SA Luting Multi, and RelyX Unicem;
(2) Fixing broken porcelain with G-Cem One, Panavia SA Luting Multi, and RelyX Unicem is simple and straightforward. Simply etch the porcelain with HF to create micromechanical retention, and apply the silane agent before the SACs to achieve chemical retention for optimal bond strength.

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