

Orthodontic Attachment Adhesion to Ceramic Surfaces

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Abstract: Ceramic materials are constantly evolving, achieving good functionality and aesthetics. Bonding to ceramics may be difficult because of high toxicity procedures and risk of surface damage. The review aims to answer several research questions: Is there a golden standard for bonding to ceramic? Are there adhesives or types of photopolymerization lamps that produce a higher bond strength on certain types of ceramics rather than others? Articles focusing on the bonding process of orthodontic attachments to ceramic surfaces searched in Pubmed, Medline and Embase, published between 1990 and 2018 were revised. Exclusions concerned bonding to non-ceramic surfaces, bonding to ceramic surfaces that are not destined for orthodontics or laser usage. Forty-nine articles that matched the inclusion criteria were researched. The following categories of original research articles were compared and discussed: metallic brackets bonding to ceramic surfaces, ceramic brackets to ceramic surfaces, bonding to new types of ceramics, such as zirconia, lithium disilicate, different photopolymerisation devices used on bonding to ceramics. Some types of adhesive may achieve minimal bond strength (6–8 MPa) even on glazed ceramic. Ceramic surface preparation may be done by sandblasting or hydrofluoric acid (60s application and 9.6%) with generally similar results. Studies rarely show any statistical difference and there are reduced number of samples in most studies. Ceramic brackets show better adhesion to ceramic surfaces and the same bonding protocol is advised. A higher bond strength may lead to ceramic surface. Few studies focus on newer types of ceramics; additional research is necessary. There is no clear evidence that a certain type of photopolymerization device produces higher shear bond strength values.

Keywords: ceramic bond, adhesion, shear bond strength

Introduction

As patient concerns for aesthetics are raising and ceramics is used for frontal and lateral areas in prosthodontics, orthodontists must choose from several modalities of bonding to ceramics. Ceramic materials are versatile and constantly evolving, making it possible to achieve good functionality and aesthetics. This review offers a thorough image of studies focusing on bonding to ceramic surfaces.

For a better understanding of the data provided by the researchers, it is important to understand the differences between several types of ceramics. We can define ceramics by the nature of their composition of glass-to-crystalline ratio. A simple classification based on microstructure categorizes ceramics into four basic categories:

- composition category 1 – glass-based systems (mainly silica),
- composition category 2 – glass-based systems (mainly silica) with fillers, usually crystalline (leucite or lithium disilicate),

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- composition category 3 – crystalline-based systems with glass fillers (mainly alumina)
- composition category 4 – polycrystalline solids (alumina and zirconia).¹

Glass-based systems are made of materials that contain silicon dioxide (silica or quartz), which incorporates various amounts of alumina. Aluminosilicates found in nature are known as feldspars. Synthetic forms of aluminosilicate glasses are also manufactured for dental ceramics.^{1,2}

Glass-based systems with fillers have a very large range of glass–crystalline ratios and crystal types. Thus, the category can be subdivided into three groups, among which the difference is that varying amounts of different types of crystals have either been added or grown in the glassy matrix. The primary crystal types are leucite, lithium disilicate or fluoroapatite. Subcategories include feldspathic porcelain, high leucite containing porcelain, lithium disilicate or IPS Empress II or IPS e.max.^{1,3,4}

Crystalline-based systems with glass fillers are marketed under the name In-Ceram. The system was developed as an alternative to conventional metal ceramics.¹

Polycrystalline solids are solid-sintered, monophase ceramics, that are formed by directly sintering crystals together without any intervening matrix to form a dense, air-free, glass-free, polycrystalline structure. They are either solid-sintered aluminous-oxide or zirconia-oxide frameworks.^{1,2}

All materials can be processed by varied techniques, but a simple classification based on processing is powder/liquid, glass-based systems, machinable or pressable blocks of glass-based systems and CAD/CAM or slurry, die-processed, mostly crystalline (alumina or zirconia) systems.⁵

Important research has been conducted on the adhesive bond between brackets and ceramics. Bracket type and base, adhesive type, ceramic type and prebonding procedures all influence the adhesive bond. Bonding to ceramics is harder to achieve because of hydrofluoric acid toxicity and low pH, that can lead to the damage of the ceramic surface. Procedures such as air particle abrasion and other pre-treatments are needed to be performed prior to the actual definitive placement of the prosthetic restoration into the oral cavity.

Micro-etching, air abrasion or air particle abrasion is a technique in which particles of aluminum oxide, generally 50 µm, are projected in order to create abrasion on the surface of enamel or another substrate by high air pressure.⁶ When used for enamel surface preparation, air

abrasion resulted in significantly lower shear bond strength, irrespective of the abrasive particle size, compared to that of using traditional acid etch technique. Air abrasion without acid etching resulted in significantly lower bond strength and it is not advised for clinical use.⁷

The shear bond strength or SBS is most often tested when studying adhesion, as it incorporates forces similar to masticatory ones and is conveniently produced in vitro. Good orthodontic bond strength is considered to be 5–10 MPa and should not exceed 40–50 MPa as such a great force may damage enamel.⁸ This criteria may also be applied to ceramics, as damage to the vestibular surface of a veneer or crown may be considered after debonding.

There are also differences when bonding ceramic brackets instead of metallic brackets. The mean SBS of polycrystalline ceramic brackets was found to be significantly higher than that of stainless steel brackets in several studies when bonding to enamel.^{9–12}

This review tries to answer several important questions the orthodontist needs to take into regard. Is there a golden standard for bonding to ceramic? Are there adhesives that produce a higher bond strength on certain types of ceramics rather than others? Are general rules of bonding that have proven correct for enamel surfaces also applicable to ceramics? Are there other factors that are seldom overlooked when choosing adhesive type and ceramic surface conditioning?

Materials and Methods

Databases Pubmed, Medline, Embase have been investigated by two independent researchers in February 2018, search terms: ceramics bond orthodontics, ceramics adhesion orthodontics. Exclusions have been made by reading titles and abstracts. The inclusion criteria were as follows: (1) articles focusing on the bonding process of orthodontic attachments to ceramic surfaces published between 1990 and 2018 were revised; (2) original researches; (3) experimental, in vitro studies. Exclusions criteria were as follows: (1) studies about bonding to non-ceramic surfaces; (2) bonding to ceramic surfaces that are not destined for orthodontics or laser usage for bracket base preparation or for ceramic surfaces (it involves technology that is not currently used by a majority of orthodontists). In February 2021, an update has been performed prior to publication of the article, following the same inclusion/exclusion criteria, which led to 12 more articles included in the review.

Researchers finally listed articles that focused on bonding metallic or ceramic brackets to ceramic surfaces by using regular means, available in most dental offices.

Results

Upon initial investigation, 98 articles were found. After carefully applying the exclusion criteria, 49 articles have been studied further. Upon update, 12 articles were added, which contain information published up to 2020. In order to evaluate the articles, we decided to divide them into three categories, based on the assessment technique: (a) studies assessing the bonding between metallic brackets and feldspathic ceramic materials; (b) studies assessing the bonding between esthetic brackets and feldspathic ceramic materials; (c) studies assessing the different types of brackets and different types of ceramic materials. Upon updating, 12 articles were added, mainly on the topic of bonding to non-feldspathic ceramics. They are all resumed in [Tables 1–3](#).

Discussion

The aim of this study was to evaluate the literature regarding the bonding between different orthodontic brackets and ceramic materials. We selected 61 articles in this study. Exclusions have been made by reading titles and abstracts. Only experimental *in vitro* studies have been included, as clinical studies are difficult to reproduce and there are some uncontrollable factors, such as different use of appliances, doctor's capabilities.

A meta-analysis published in 2010 by Finnema and his team shows that many times, research articles do not take into consideration all factors that influence adhesion, such as storage of samples in water, photopolymerization time and crosshead speed.¹³ Reliability of studies increases when efforts are made to achieve similarity with the oral environment, for example, through thermocycling of the tested samples, as this influences bond strength.^{14–22} Throughout the articles included in this review, minimal bonding strengths were 6–8 MPa.²³

Many studies rely on mean shear bond strength when comparing different primers or different ceramic surface preparation techniques, as few of them obtain statistically significant results. There are few studies comparing certain types of adhesives, for example, Panavia or Concise, or primers, making it difficult to establish a reliable conclusion of the literature on a certain adhesive.

For an optimal evaluation process, all the studies included were divided according to the type of bracket and/or type of ceramic used in the research.

Feldspathic Ceramic Surface and Metallic Brackets

The first studies performed on feldspathic ceramic established that deglazed surfaces are better at achieving minimal adhesion for orthodontic forces. They used either sandpaper, acidulated phosphate fluoride, a coarse diamond bur or a Busch silent wheel to remove glazing.^{24,25} There are two studies, however, that contradict this finding, with similar results on glazed or deglazed ceramics.^{26,27}

Silane use is generally considered to increase bond strength. In a study published in 1996, Zachrisson established that silane greatly increases tensile bond strength,²⁸ results that coincided with Cochrane's. The latter also advised that the use of silane increased the occurrence of porcelain fracture at debonding.²⁹ Another study supporting this is led by Chung in 1999, concluding that silane use means significantly higher shear bond strength, but it may also cause damage of the ceramic surface upon debonding.³⁰ Bishara and collaborators find that the most reliable bonding procedure to ceramic surfaces is by using hydrofluoric acid and a silane before bonding, but this also produces the greatest damage to the porcelain surface.³¹ When comparing hydrofluoric acid concentrations of 4% or 9.6%, Traklyali finds no statistically significant difference.³² In a study performed in 2019, higher concentrations of hydrofluoric acid seem to increase SBS.²⁰ Larmour et al³³ by comparing phosphoric acid to hydrofluoric show that HF produces better results, confirmed also by other research teams.^{16,34–36} Contradicting this, Ajlouni and collaborators³⁷ find two similar bonding sequences with similar results: HF, followed by silane and composite and phosphoric acid, followed by self-etching primer-adhesive and composite.

In 2003, a study conducted by Schmage contradicts this by obtaining the highest SBS through sandblasting and silane use or hydrofluoric acid without silane. Diamond roughening and sandblasting showed the highest surface roughness, but they can damage the ceramic surface. The results of this study are reliable, as thermocycling was done in 5000 cycles.³⁸ A study published in 1999 by Bourke and his team reach a similar conclusion, that hydrofluoric acid or deglazing is unnecessary to achieve bond strength when using Right On bonding

Table 1 Metallic Brackets Bonded to Feldspathic Ceramic Surfaces in Publishing Order

No. and Year of Publication	Adhesive Type	Additional Testing	Results
1993 ²⁴	Glazed/deglazed, different composites		Inadequate SBS obtained, better when deglazed
1995 ²⁵	Deglazed with sandpaper/deglazed with diamond bur/ glazed, Acidulated phosphate fluoride on glazed/deglazed		APF – not enough SBS, mechanical retention needed, improved by silane
1996 ²⁸	Sandblasting/silane/HF9.6%/4% APF gels, either Concise or 4-Meta resin	Thermocycling	Silane sgn increases SBS, HF > APF gel, 4-Meta resin, similar to Concise
1997 ²⁹	Sandblasting/sandblasting+silane/HF/HF+silane/ diamond bur +silane		Highest SBS when silane was used, but risk of fracture
1998 ³⁵	Diamond bur/HF 8%/microetching Al particles, followed by silane+RightOn/silane+Concise/High-Q-Bond without silane	SEM	Silane+RightOn or silane+Concise>High-Q-Bond without silane HF>diamond bur, microetching
1999 ¹⁴	Deglazing/HF/phosphoric acid/silane, Right On composite for all	Thermocycling	HF produced damage, thermocycling sgn reduced SBS, HF or deglazing unnecessary to achieve bond strength
1999 ³⁰	Concise composite/Concise+ silane/Geristore/ Geristore +silane/Fuji Ortho LC/Fuji+silane, HF 9.6% for all		Silane groups sgn higher SBS, no sgn difference between groups, ceramic damage in silanized groups and Geristore
2002 ³⁹	Control/diamond bur/HF 10%/sandblasted + Scotchprime silane+ Concise		All groups – adequate SBS
2003 ³⁸	Diamond bur/sandblasting/HF 5%/silica coating, self-curing composite for all, with or without silane	Thermocycling	Highest SBS sandblasting +silane/HF without silane
2003 ²³	Fuji LC/American Ortho Spectrum/Transbond/TP orthodontics Python/Herculite, silane for all, phosphoric acid		Herculite and TP orthodontics lower than 6–8 range
2005 ³⁷	37% phosphoric acid +sealant+ adhesive (1)/HF+silane +composite (2)/phosphoric acid+self-etching (3) primer-adhesive+composite		Group 2 and 3 high, similar SBS, group 1 lowest
2005 ³³	Phosphoric acid + Transbond/HF +Transbond/Fuji Ortho LC +Transbond/Fuji Ortho LC +Phosphoric acid, silane for all		Fuji had sgn lower SBS, phosphoric and HF not sgn different
2005 ³¹	37% phosphoric acid + Transbond/microetchingHF +silane+ Transbond/acid etch primer+ Transbond/35% phosphoric acid+cyanoacrylate adhesive		Cyanoacrylate lowest SBS<conventional bonding<acid-etch primer=HF group
2006 ²⁶	Deglazed porcelain + Transbond XT/Glazed with Transbond XT/deglazed +Fuji Ortho LC/Fuji Ortho LC	Thermocycling	No sgn difference between groups
2009 ³²	HF 9.6%/HF 5%, Pulpdent Silane/Reliance silane, Unite adhesive for all		Reliance sgn higher SBS than Pulpdent, concentration of etching gels no sgn difference
2011 ⁷⁵	10% HF 20s/60s, silane, Transbond XT, 4 different light sources halogen, led, argon laser or plasma arc		No difference between light sources, 20s etching, sgn lower SBS
2011 ⁴⁴	HF+Embrace First Coat/HF +silane/sandblasting +silane, Transbond XT for all, SSBS or cyclic shear bond strength		SBS sgn higher than CSBS, sandblasting better than HF groups, sandblasting+Embrace best results

(Continued)

Table 1 (Continued).

No. and Year of Publication	Adhesive Type	Additional Testing	Results
2012 ⁴¹	HF 10% 20s/60s, half with silane in each group, Transbond XT/Fuji Ortho LC		Transbond XT higher SBS than Fuji, longer etching, silane increases SBS
2012 ⁴³	10-MDP adhesive = Panavia 2/TransbondXT/Fuji Ortho LC	Thermocycling	Panavia highest mean SBS
2015 ³²	10% HF. Transbond XT or Fuji Ortho LC, stored for 24 h or 6 months in distilled water at 37 degrees C		Transbond XT SBS higher; storage time also influences SBS
2015 ¹¹	10%HF, Transbond XT for all, different light sources: Radii Plus Led, XL 2500 halogen	± thermocycling	Thermocycling and light sources influence bond strength
2015 ¹³	37% phosphoric acid + silane/37% phosphoric not rinsed +silane/10% HF/10% HF+silane, Transbond for all		HF and silane best SBS, but risk of ceramic fracture
2016 ¹⁶	± 10% HF, Clearfil Ceramic Primer CCP/ RelyXCeramic Primer RCP, then Transbond XT	± thermocycling	HF higher SBS, thermocycling reduced SBS, CCP silane best amongst tested spec
2019 ²⁰	HF: 1–1%;2–2.5%;3–5%;4–7.5%;5–10% (storage 24 h); 6–1%;7–2.5%;8–5%;9–7.5%; 10–10% (thermal cycling) for 60s each + silane	± thermocycling	The different HF acid concentrations 5.0%, 7.5% and 10% influenced the SBS. Thermocycling decreased SBS significantly.
2019 ⁷⁹	10% HF 60 s + 2 layers of silane, VALO Ortho Cordless 3200 mW/cm2 for 3 s/Optilight Max 1200 mW/cm2 40s	± thermocycling	No significant difference was observed between SBS means in the different light activation devices used. The samples subjected to thermocycling - lower SBS values.

system.¹⁴ In a study published by Sant'Anna, adequate SBS is achieved through either sandblasting, 10% hydrofluoric acid or diamond bur roughening or no preparation at all when using Scotchbond silane and Concise.³⁹

In conclusion, some adhesive types may achieve minimal bond strength even on glazed ceramic. Sandblasting may be a viable option for ceramic surface preparation, but it may be more difficult to use than HF. Statistical difference is rarely obtained, as there are few samples in each group for most studies. When using hydrofluoric acid, 60s application and 9.6% solution are advised.

Different Bonding Materials

Many studies compare different adhesives. Composites have generally shown better SBS values than glass ionomers and newer types of silane are reliable options.

The Transbond XT bonding system, a golden standard for bonding to enamel surfaces is also tested on ceramic, showing more reliable results than glass-ionomer Fuji.^{26,40} In a study led by Pannes,²³ by comparing Fuji, American Ortho Spectrum, Transbond, TP Orthodontics Python and Herculite bonding agents, only the TP system and

Herculite did not achieve the adequate bonding strength. Surface preparation was done with phosphoric acid and silane for all groups. Costa concludes that Transbond XT exhibits higher shear bond strengths than Fuji and longer etching and silane use increases shear bond strength.⁴¹ By using 10% hydrofluoric acid and either Transbond XT or Fuji Ortho LC, stored for 24 h or 6 months in distilled water at 37 degrees C, Costa and his team of researchers found that the composite shows higher strength and storage time influences adhesion.⁴²

Two studies contradict Transbond superiority. Sundareswaran found the best shear bond strength for Panavia, when comparing it to Transbond XT and Fuji Ortho LC.⁴³ Lifshitz finds no significant difference between deglazed or glazed ceramic surface followed by either Transbond XT system or Fuji Ortho LC.²⁶

Abdelnaby and his team research several aspects, starting with different primers: Embrace First-Coat primer and a regular silane have comparable shear bond strength. No significant difference was found when using either hydrofluoric acid and Embrace First-Coat or sandblasting and silane.⁴⁴ Clearfil Ceramic Primer shows better results than

Table 2 Esthetic Brackets Bonded to Feldspathic Ceramic Surfaces in Publishing Order

No. and Year of Publication	Bracket Type	Adhesive Type	Additional Testing	Results
2001 ⁴⁸	Ceramic	Sandblasting 50 um/silane/sandblasting+silane/HF 9.6%/sandblasting + 4-Meta adhesive, no-mix bonding composite		HF+ silane sgn higher SBS, similar to sandblasting+silane
2003 ⁴⁶	Ceramic	HF/microetching + Ideal I (without silane)/Right On (with silane)		HF sgn higher SBS, both adhesives satisfactory results
2003 ¹⁷	Composite	Self-cure non mixed resin Unite with either etching/silane/etch+silane	Thermocycling half of specs	Highest SBS etch + silane, no thermocycling
2004 ⁴⁹	Polycarbonate	Phosphoric acid+primer+bonding agent/HF+primer +bonding agent/tribochemical silica coating+silane/APA 30 um+silane+bonding agent, composite for all	Thermocycling	Silica coating + silanizationsgn higher SBS than phosphoric acid, APA=HF groups
2006 ⁷⁷	Ceramic	HF 9.6% 2 min + silane (1)/APA+HF 9.6%+silane (2)/APA +silane (3), Light Bond adhesive for all	Thermocycling	Group 1=2, lower SBS in Group 3
2006 ⁷⁸	Ceramic	HF 9.6% 2 min+silane+adhesive, curing soft start LED or halogen light		Sgn higher SBS for LED lamp
2007 ⁷⁶	Ceramic	APA 25 um+HF 9.6%+silane+ halogen curing unit for 10s or 20s/LED 3.5 or 10s in standard or fast mode		No sgn differences between SBS, ARI scores, porcelain damage and bracket base fracture.
2012 ⁵²	Ceramic	Control/diamond bur +orthophosphoric 37%/HF 10%/HF 10%+silane, Transbond XT for all		HF+silane best SBS, but risk of damage
2012 ⁵⁰	Metallic and ceramic	HF 9% + silane for all, 2 composites, 4 light curing units, 3 led, 1 halogen		SBS sufficient in all groups, mean SBS higher for ceramic brackets

RelyXCeramic Primer.¹⁶ TheOrmco primer-Concise porcelain bonding system was significantly stronger than the Scotchprime-Transbond.⁴⁵ In a study published in 2018, researchers compared All Bond Universal, Adhese Universal, Clearfil Universal Bond, and Single Bond Universal efficiency on etched lithium disilicate glass ceramics after or without silane application, concluding that the non-silanized groups had a reduced bonding effectiveness and additional silane pretreatment helped improve the long-term durability.¹⁹

Similar shear bond strength values were observed, when testing different bonding materials, on carefully prepared ceramics or enamel.

Feldspathic Ceramic Surface and Ceramic or Composite Brackets

In general, ceramic brackets show better adhesion to ceramic surfaces, than metallic ones, as shown by.⁵ Hydrofluoric acid also seems a viable solution for bonding, as shown by Harari

and his team.⁴⁶ Hydrofluoric acid followed by silane shows better results,⁴⁷ similar to sandblasting and silane, than sandblasting or HF alone.⁴⁸ Similar results, higher SBS than phosphoric acid alone, may be achieved through silica coating and silanization.⁴⁹ Indifferent of type of composite or photopolymerization lamp, the results are consistently within accepted orthodontic range when using HF and silane, but higher for ceramic brackets than metallic ones.^{50,51}

Ramos and collaborators found that HF followed by silane reach the best SBS, compared to diamond bur use, orthophosphoric acid 37% or HF without silane. However, in the case of HF followed by silane treatment of the ceramic, there is a higher risk of damage of the ceramic surface during the debonding stage.⁵²

Non-Feldspathic Ceramics

When talking about newer types of ceramics, there is rarely more than one study researching a certain type of ceramic.

Table 3 Ceramic or Metallic Brackets Bonded to Different New Ceramic Surfaces in Publishing Order

No and Year of Publication	Ceramic Type	Bracket Type	Adhesive Type	Additional Testing	Results
1994 ^[47]	Feldspathic	Ceramic	Silane/ no silane		Sgn difference when silane was used
1999 ^[40]	Amalgam/ precious alloy/ ceramic	Ceramic Transcend / Fascination silanized brackets	APA/ HF 9.6% +Fuji Ortho LC/ Photac Bond (GIC) Control groups used Transbond or Concise		Both GIC satisfactory SBS, silanized brackets lower SBS, only Fuji on metal alloy, composites obtained higher SBS than GIC s
2005 ^[70]	Finesse Empress 2 all ceramic/ feldspathic Vita Omega	Metallic	Phosphoric acid + silane+ Unite Bond		SBS for Finesse sgn higher, no sgn difference in ARI scores
2006 ^[59]	Feldspathic and lithium disilicate	Metallic	Silane on glazed/ APA 25um/APA 50 um/ HF 9.6%/ 40um diamond bur/ 60um diamond bur	Thermocycling	Lowest SBS HFA sgn difference, highest SBS diamond burs, lithium disilicate higher SBS for all groups
2006 ^[73]	Low fusing and high fusing ceramics	Metallic	Resin removal with multifluted carbide bur with and without polishing discs		No sgn difference between the 2 types of ceramics on debonding force, no difference between clean-up methods
2007 ^[72]	In-Ceram, IPS Impress, ceramo-metal	Metallic			Ceramo-metal and In-Ceram comparable results, IPS_Impress lower SBS sgn
2007 ^[58]	Feldspathic, leucite based, lithia disilicate	Metallic	Sandblasting/sandblasting+HF/ sandblasting+silane /sandblasting +HF+silane /tribochemical silica coating+silane	Thermocycling	Lowest SBS sandblasting only, feldspathic and lithia disilicate highest SBS with silica coating, leucite based HF without silane, similar to silica coating.
2010 ^[68]	IPS Empress 2/ In-Ceram alumina	Metallic and ceramic	HF 9.6%/phosphoric acid/ sandblasting for all		Acid etching sgn increased SBS, ceramic brackets sgn different fracture pattern at the adhesive-bracket interface
2010 ^[74]	Aluminous and fluorapatite ceramic (Vitadur Alpha/IPS Emax)	Ceramic and metallic	Different bracket bases: beads-Inspire Ice, large round pits Crystalline IVs, irregular base Clarity, optimesh stainless brackets for control		Highest SBS Inspire Ice sgn different than the others, all were satisfactory
2011 ^[72]	Feldspathic, fluoro-apatite, leucite reinforced	Metallic	Air particle abrasion 25 um/ silica coating 30 um	Thermocycling	Lowest SBS air particle abrasion feldspathic and fluoro-apatite, highest SBS silica coating leucite reinforced ceramic, silica coating better overall
2014 ^[67]	Monolithic zirconium oxide ceramic	Metallic	Glazed/polished +air abrasion 30 um/air abrasion 50 um + Monobond Plus+ Transbond XT Primer+Transbond XT		Air abrasion improved SBS

(Continued)

Table 3 (Continued).

2014 ^[65]	Yttria stabilized tetragonal polycrystalline zirconia	Metallic	RelyX adhesive cement and RelyXUnicemselfadhesive	24h or 6 months at 37 degrees C	Self-adhesive cement RelyXUnicem not able to sustain bond
2016 ^[66]	Feldspathic/ zirconia	Metallic	Sandblasting all groups + 4% HF, Porcelain Conditioner silane Primer/Reliance Assure/ Reliance Assure Plus/Z Prime Plus		Tensile bond strength similar for all groups, silanization after sandblasting, similar to other protocols
2016 ^[56]	CAD/CAM lithium disilicate	Metallic	HFA+Silane/ HFA, deglazed/ glazed		HF + silane – acceptable SBS values indifferent of adhesive, but slightly higher on roughened surface
2016 ^[69]	Silica IPS Classic glazed	Metallic	9.6% HF, 9.6% HF+silane/ sandblasting+silane/ tribochemical silica (CoJet) +silane, all TransbondXT		HF alone not sufficient SBS, CoJet + silane and sandblasting+silane higher than the other groups
2017 ^[18]	Y-TZP	Metallic	Abrasion with alumina/ tribochemical silica coating + ESPE-Sil/Alloy Primer/Clearfil/ Scotchbond	+/-thermocycling	Thermocycling influences results, better results when mechanically treated
2018 ^[55]	Feldspathic and lithium disilicate	Metallic	Sandblasting, 9.6% HF, Transbond XT/ Assure Plus	thermocycling	Assure Plus better results, minimized damage on lithium disilicate
2018 ^[19]	Lithium disilicate	Ceramic	HF + All Bond Universal/Adhese Universal/ Clearfil Universal Bond/ Single Bond Universal +/- silane	Thermocycling, SEM	Thermocycling influences results. SBS of the silane groups were higher and their microleakage percentages lower than those of the non-pretreated groups
2019 ^[51]	IPS e-max CAD	Ceramic	HF 60 s/3 min/HF+S/MDP adhesive followed by resin cement	SEM, fractographic analysis	Monocrystalline brackets with HF or HF+S showed highest values, Polycrystalline with MDP only – lowest values.
2019 ^[57]	IPS E-max and zirconia	Metallic	E-max HF + MDP primer 1 coat; Zirconia MDP 1/2/3 coats	Thermocycling	E.max and zirconia with 3 MDP primer applications highest SBS
2019 ^[64]	Lithium silicate infused with zirconia (CELTRA® DUO, Zirconia and Lithium disilicate	Metallic	+/- HF		SBS of the lithium silicate infused with zirconia - significantly lower than HF lithium disilicate group. HF may increase SBS in Celtra DUO.
2020 ^[53]	IPS E-max, CAD/ CAM, IPS d.Sign Ceramic fused to metal	Metallic	Transbond, Light Bond or Blugloo +/- HF		Significant differences in SBS related to ceramic, surface treatment, and resin cement. HF etching increased SBS.

(Continued)

Table 3 (Continued).

2019 ^[60]	Lithium disilicate and zirconia	Metallic and ceramic	HF / Phosphoric acid and silane		HF use on zirconia and lithium-disilicate, does not cause a significant increase in SBS, compared to etching with PhA and silane application. HF can weaken the surface structure.
2019 ^[21]	Zirconia	Ceramic	MDP ceramic primer + orthodontic primer / universal adhesive / MDP ceramic primer + universal adhesive.	Thermocycling	For ceramic brackets to zirconia, ceramic primer used with an orthodontic primer, rather than using a universal adhesive, is recommended.
2020 ^[22]	Lithium disilicate E-max and lithium silicate infused with zirconia (CELTRA® DUO)	Ceramic	aluminium oxide air abrasion + 3 different brackets		Mean SBS of the E-max groups were significantly less than CELTRA® DUO. Only the Symetri bracket was effective for both substrates.

On etchable ceramics, hydrofluoric acid increases shear bond strength.⁵³

On lithium disilicate ceramics, IPS ceramic etching gel™ and Monobond plus achieved better results than the one step system, containing etching and primer.^{54,55} Feldspathic and lithium disilicate were bonded with either Transbond primer or Assure Plus after sandblasting and etching with 9.6% HF. Bracket bond to lithium disilicate by Assure Plus was significantly stronger than that to feldspathic porcelain. Cohesive porcelain fracture had the lowest frequency in the lithium disilicate/Assure Plus group. When working on CAD/CAM lithium disilicate, hydrofluoric acid followed by silane shows acceptable SBS values indifferent of adhesive, but slightly higher on roughened surface⁵⁶ or MDP adhesive.⁵⁷ On feldspathic, leucite based and lithium disilicate samples, testing showed lowest SBS when sandblasting only, feldspathic and lithium disilicate highest SBS with silica coating, leucite based ceramics showed highest SBS values for HF without silane, similar to silica coating.⁵⁸ Contradicting these findings, only one study shows that on both feldspathic and lithium disilicate ceramics, lowest SBS was achieved with HF, at a statistically significant difference and highest SBS was achieved when using diamond burs. Lithium disilicate showed higher SBS for all groups.⁵⁹ Another study compared HF use to phosphoric acid and silane on both dilithium silicate and zirconia, showing no significant advantage of HF use. However,

SBS in zirconia groups was lower than in lithium disilicate for both procedures.⁶⁰

On Vita Enamic CAD/CAM ceramics, CoJet coating gives better results than HF acid which are also higher than diamond bur roughening and phosphoric acid use.⁶¹

When testing different surface preparations on feldspathic, leucite, leucite free, fluorapatite ceramics, researchers found no difference between ceramic types in terms of SBS, just that leucite and leucite-free ceramics differed most with respect to their surface roughness. Conditioning with conventional 5% HF or sandblasting resulted in significantly higher bond strengths, than with 9.6% HF.⁶²

When comparing Empress 2, Finesse, Ceramco II, Barceló et al⁶³ found that deglazing helps adhesion for all types.

On non-etchable, zirconia-based ceramics, different types of surface preparation methods have been investigated. Mechanical preparation of the surfaces through particle abrasion or polishing with silicon carbide paper achieved better results than untreated surfaces on Yttria stabilized tetragonal polycrystalline zirconia ceramic surfaces.¹⁸ Three coats of MDP primer showed better results than one coat on zirconia ceramics.⁵⁷ When compared to universal adhesive or orthodontic adhesive, MDP showed better results²¹ On lithium silicate infused with zirconia, Celtra DUO, SBS was significantly lower than the hydrofluoric acid pre-treated lithium disilicate group. Acid etching may, however, improve adhesion to

this new type on ceramics.⁶⁴ When using aluminium oxide air abrasion, mean SBS of an E-max CAD group were significantly less than the CELTRA[®] DUO group, showing efficacy of this method on the new ceramic material.²² On Yttria stabilized tetragonal polycrystalline zirconia, RelyX self-adhesive cement was not able to sustain the bond, no matter if new generation primers such as MDP and tribochemical silica were used.⁶⁵ When comparing sandblasted feldspathic to zirconia ceramics and different primers, such as Assure, Assure plus, Porcelain Conditioner or Z prime, the researchers found similar tensile bond strengths on all surfaces.⁶⁶ Air abrasion improved SBS on monolithic zirconium oxide ceramic when using Monobond and Transbond.⁶⁷

Abu Alhaija and collaborators tested IPS Empress II and In-Ceram alumina. They sandblasted and acid treated surfaces with either HF 9.6% or phosphoric acid, bonded metallic and ceramic brackets and reached the following conclusions: acid etching significantly increased SBS, the fracture pattern at the adhesive–bracket interface is significantly different for ceramic brackets, compared to metallic brackets and no significant difference was found between the two ceramic types.⁶⁸ Some tests on IPS silica ceramics revealed that hydrofluoric acid alone does not achieve satisfactory SBS and the combination of CoJet and silane or sandblasting and silane give higher values than the other groups.⁶⁹ By comparing IPS Empress II and Finesse all ceramic to feldspathic ceramic, the first two achieved significantly higher SBS when phosphoric acid and Unite were used.⁷⁰

When testing either feldspathic, fluoro-apatite, leucite reinforced ceramics, researchers found the lowest SBS on air particle abraded feldspathic and fluoro-apatite and highest SBS on silica coated leucite reinforced ceramic, silica coating showed better overall results.⁷¹

Ceramo-metal and In-Ceram showed comparable results, IPS Impress had significantly lower SBS values.⁷²

On low fusing and high fusing ceramics, no statistically significant difference was found between the two types of ceramics on debonding force and no difference between clean-up methods.⁷³

On aluminous and fluorapatite ceramic, Vitadur Alpha and IPS Emax, researchers tested different bracket base designs, either beads, large round pits, irregular base and one group of stainless steel brackets mesh base. Beads in Inspire Ice brackets showed the highest SBS, significantly

different than the other groups. The SBS of all base designs could withstand normal orthodontic force.⁷⁴

Photopolymerization Light Sources

Gonçalves compared different etching times, 20s or 60s when 10% HF was used, together with 4 different light sources: halogen, led, argon laser or plasma arc. Researchers found no difference between light sources and statistically significant lower shear bond strength for 20s etching.⁷⁵ When comparing halogen curing unit for 10s or 20s to a LED unit for 3.5 or 10s in standard or fast mode, Elekdag-Turk and collaborators found no statistically significant differences between SBS, ARI scores, porcelain damage and ceramic bracket base fracture.⁷⁶

In opposition to this, De Abreu Neto shows that thermocycling and type of photopolymerization lamp influences shear bond strength.¹⁵ Türk kahraman also finds significantly higher SBS for LED lamp than halogen when bonding ceramic brackets to porcelain surfaces in thermocycled samples,⁷⁷ which is also supported by another study.⁷⁸ When comparing VALO Ortho Cordless appliance with irradiance 3200 mW/cm² for 3 s and Optilight Max appliance with irradiance 1200 mW/cm² for 40 s, researchers found no significant difference in SBS.⁷⁹

Conclusion

Some types of adhesive may achieve minimal bond strength (6–8 MPa) even on glazed ceramic. Ceramic surface preparation may be done by sandblasting or HF acid with generally similar results. When using hydrofluoric acid, 60s application and 9.6% solution are advised. Studies rarely show any statistical difference and there are reduced number of samples in most studies. Ceramic brackets show better adhesion to ceramic surfaces, than metallic ones and the same bonding protocol may be used. A higher bond strength may lead to ceramic surface damage of the prosthetic restoration.

Concerning non feldspathic, newer types of ceramics, there is rarely more than one study researching a certain type of ceramic. Therefore, additional research is necessary. General rules seem to apply to these categories also.

There is no clear evidence that a certain type of photopolymerization device produces higher SBS values.

Abbreviations

HF, hydrofluoric acid; APA, air particle abrasion; SEM, scanning electron-microscopy; SBS, shear bond strength;

CSBS, cyclic shear bond strength; Sgn, statistically significant; TS, tribochemical silica coating.

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