ABSTRACT

Objectives: Scientific evidence regarding conditioning of different ceramic and hybrid materials and their bonding on titanium abutments is lacking.

Methods: Titanium disks (Tritan) (N=450, n=15) were randomly cemented onto five different ceramic and hybrid materials, namely 1. Zenostar T, 2. Lava Ultimate, 3. IPS e.max CAD, 4. Vita Enamic multicolor and 5. G-ceram using three different cements, Panavia 21, TheraCem and Multilink hybrid abutment. Half of all specimens was thermocycled (5000 cycles, 5-55°C), while the other half was kept dry. Macro shear bond testing was conducted using a universal testing machine. Failure types were classified using a digital microscope. Data was statistically analyzed with three-way ANOVA and Tukey HSD post hoc tests.

Results: Both the ceramic ($P<0.0001$) and cement type ($P<0.0001$) significantly affected the shear bond strength (MPa), while thermocycling did not ($P>0.05$). The incidence of cohesive (50.34%) and adhesive failures (49.66%) were not significantly different.

Discussion*:* As for implant superstructures, when ceramics are bonded to titanium bases, the ceramic and cement type both have an impact on the bond strengths along with the conditioning and bonding protocols for each substrate. An equal affinity of the cements tested to the ceramic, hybrid materials and to titanium can be assumed considering the failure types.

Significance: The combination of Zirconia and TheraCem providing the best shear bond strengths can be recommended for clinical use.

Keywords: Ceramics; Fracture Resistance; Glass-Ceramic; Hybrid; Implant; Lithium Disilicate; Mechanical Loading; Monolithic; Titanium Base Abutments; Zirconia.

INTRODUCTION

Implant dentistry is a widely used treatment modality for the replacement of missing teeth, as it not only offers functional and biological advantages for many patients, when compared with conventional fixed or removable prosthesis,[1] but it also yields excellent long-term results, with reported 10-year success and survival rates above 95%.[2]

The exacting aesthetic demands of both patients and clinicians have led to the need for ideal surgical and prosthetic outcomes in implant dentistry.[3] For optimal aesthetics, the emergence profile of the implant abutment needs to support the surrounding tissue.[4] Implant abutments need to be made from biocompatible materials with adequate mechanical properties to fulfil biological, functional and aesthetic demands.[5] As such, implant abutments are usually made of commercially pure titanium because of its biocompatibility and mechanical properties.[6]

Titanium base, or Ti base, is a term for an abutment which is made from titanium, that acts as a base for the overlying custom abutment or restoration. The use of a Ti base ranges from a single tooth replacement to a full arch prosthesis and provides flexibility for different types of reconstruction materials as well as the freedom for conventional or digital manufacturing processes.[7]

The materials of choice for implant-retained prostheses have evolved from traditional metal-ceramic reconstructions to different ceramic and hybrid materials. As such, zirconium dioxide (zirconia) ceramics have gained remarkable popularity as framework materials in implant dentistry, because of their favourable aesthetics, biocompatibility, and mechanical properties.[7] Computer Aided Design/Computer Aided Milling (CAD/CAM) with the use of industrialized blanks of zirconia has led to improved reliability and cost effectiveness of prosthetic zirconia restorations.[8] In terms of CAD-CAM tooth-coloured custom abutments, zirconia (Lava Plus, 3M, Minnesota, USA) was found to be the most reliable and least sensitive to load level for abutments with titanium inserts when compared to lithium disilicate (IPS e.max CAD, IvoclarVivadent, Schaan, Liechtenstein) or resin-based composite (Lava Ultimate, 3M, Minnesota, USA).[9] Furthermore, mono-layered zirconia (Katana Zirconia ML, Kuraray, Tokyo, Japan) had a significantly higher mean fracture resistance when used as a screw-retained implant restoration in comparison to feldspathic porcelain (Super porcelain AAA, Noritake Dental Supply Co., Miyoshi, Japan) layered zirconia, indirect composite (Estenia C&B, Kuraray, Tokyo, Japan) layered zirconia and a metal (Gold alloy) ceramic restoration.[10] Additionally, zirconia abutments on titanium bases retaining monolithic zirconia crowns showed good in-vitro performance and high fracture resistance.[11]

The type of cement used to adhere the two materials or substrates to one another is a contributing factor for the strength of the bond. For example, the use of a non-temporary resin cement, such as RelyX U200 (3M ESPE), resulted in higher retention of implant-supported crowns on Ti base implant abutments, irrespective of the type of crown material[12]. This emphasises the importance of the cement, notwithstanding the crown material being bonded to the Ti base. MDP-containing resin cements, Panavia SA cement Automix (Kuraray, Tokyo, Japan) and RelyX Unicem 2 Automix (3M, Minnesota, USA) were found to be superior when bonding zirconia copings onto titanium abutments[13]. Thermocycling was also found to affect the bonding behaviour of the self-adhesive composite resins. A systematic review of the literature revealed a significantly higher bonding strength provided by MDP-based cements in comparison to other cement types (self - adhesive cements, 4 – META and Bis – GMA based cements). However, artificial aging reduced the bonding strengths of the MDP cements, implying a need for mechanical treatments to guarantee bonding stability over time.[14]

Protocols have been suggested for titanium bonding,[15] conditioning of zirconia[16] and of glass-based ceramics.[17] However, the increasing variety of available restoration materials, cements, and combination possibilities together with varying manufacturer’s protocols have to be studied in detail. The goal of this study was to assess the effect of bonding titanium bases to different types of ceramics and hybrid materials, using a variety of cements, as well as to evaluate the effect of aging of such samples, to be able to recommend clinical guidelines for daily clinical practice. The null hypothesis tested was that neither material choice, cement choice, aging method nor their combinations would have any significant effect on the shear bond strength of the implant reconstructions.

MATERIALS AND METHOD

2.1 Specimen preparation

Four hundred and fifty titanium discs, each with a diameter of 20mm and 1.5mm depth (Tritan; Dentaurum GmbH) and rectangular blocks of five different ceramic and hybrid materials: Zenostar T (Wieland Dental + Technik IvoclarVivadent, Schaan, Liechtenstein) zirconia material, Lava Ultimate (3M ESPE, MN, USA) nano-ceramic hybrid material, IPS e.max CAD (IvoclarVivadent, Schaan, Liechtenstein) lithium disilicate ceramic, Vita Enamic (VITA Zahnfabrik, Bad Säckingen, Germany) hybrid polymer ceramic, G-ceram (Atlas-Enta, İzmir-Turkey) feldspathic porcelain (N=450, n=15) were obtained. The ceramic and hybrid materials were cut into smaller blocks with an electrical precision diamond wire saw (Well; Walter Ebner) at 250 rpm, with a wire diameter of 0.17 and 30µm roughness under constant water cooling, while the titanium discs were obtained from the manufacturer. A rotating disc with a #2400 grit silicon carbide paper (Struers, Willich) was used to polish and remove any overhangs following the cutting stage to provide a flat block of material for accurate seating onto the titanium disc.

2.2 Conditioning

Conditioning of titanium discs consisted of air abrasion for 20s at 2.5 bar pressure at a distance of 1cm using 30-micron CoJet Sand (3M ESPE), followed by ultrasonic cleaning in distilled water for 5min and then air drying with oil-free air. Following this, Monobond Plus primer (Ivoclar Vivadent) was applied and allowed to react for 1 minute and then air dried. One of three cements Panavia 21 (Kuraray Noritake Dental, Tokyo, Japan,), TheraCem (Bisco, Anaheim, CA, USA), Multilink hybrid abutment (Ivoclar Vivadent) was then applied to the titanium disc.

The conditioning protocol varied for the type of ceramic with consideration of individual material properties. Lava Ultimate (3M ESPE), IPS e.max CAD (IvoclarVivadent), Vita Enamic (Vita), G-ceram (Atlas-Enta) were all treated as a form of glass ceramic. Following construction of the ceramic block (cutting and then smoothing on a rotating disc), it was cleaned in an ultrasonic bath containing distilled water for 5minutes. The blocks were etched with hydrofluoric acid, the duration and concentration depended on the composition of the glass ceramic (5% HF for 20s for lithium disilicate reinforced ceramic; 5% HF for 1 min for leucite reinforced ceramic and 9.6% HF for feldspathic ceramic). The HF acid was washed and rinsed and neutralising agent (CaC03 and NaHCO3 power mixed with distilled water) applied for 1 minute. The blocks were then cleaned again in an ultrasonic water bath containing distilled water for 5 minutes. Following this, one coat of Monobond Plus primer (Ivoclar Vivadent) was applied on the etched ceramic for one minute and then dried with oil-free air.

2.3 Cementation protocol

The ceramic block was then placed onto the titanium disc containing the cement and pressure was applied to ensure full seating and whilst excess cement was removed. Lastly, the block was photo-polymerised from all directions using a light with an output of at least 400mW/cm2 for 60 seconds.

Zirconia (Zenostar T), due to the lack of a silica phase, is not susceptible to etching and silica application18 and therefore required an alternative conditioning protocol. The zirconia blocks were placed in an ultrasonic bath containing distilled water for 5 minutes. This was followed by air abrasion with CoJet Sand (3M ESPE) at a blasting pressure of 2.5 bar for approx. 20 s for an area of 1 cm at a distance of 1 cm in a circling motion to evenly roughen the surface. Subsequently, the steps that followed were identical for the other ceramic blocks, namely, ultrasonic cleaning, primer application, drying, placement onto the titanium discs and photopolymerization.

Three types of cements were used to bond the titanium discs to the different ceramic blocks: a methacrylate-based self-adhesive cement (Multilink hybrid abutment), an MDP-based cement (Panavia 21) and TheraCem (self - adhesive MDP based resin cement). The selection of Multilink hybrid abutment was due to the fact that it is a cement reserved for extra-oral use only, for bonding titanium bases to ceramic structures in hybrid abutments or crowns. An MDP- based cement (Panavia 21 – the original MDP - based cement) was chosen as this tended to provide higher bonding strengths compared to other cements.13,19 TheraCem is also a self-etching, self-adhesive, dual-cured resin luting cement marketed as being able to bond to most substrates, including zirconia.

Thirty specimens were made for each ceramic and cement combination making a total of four hundred and fifty specimens. Once the ceramic blocks were cemented onto the discs, the exact size of the ceramic blocks was determined to three decimal places so that the area of each block of specimen could be calculated. The area was used in the calculation of the shear bond forces required in megapascals (MPa) to debond the ceramic block from the titanium disc.

2.4 Chewing simulation

Half of the specimens of each group were stored in a temperature-controlled oven at 37°C for 24 hours prior to testing to ensure complete polymerisation of the cements as well as a consistent time frame for testing of the specimens.

The other half of the specimens were aged by thermocycling for 5000 cycles between 5-55°C. Subsequently, the bonded specimens were subjected to macro shear bond testing in a Universal Testing Machine (1 mm/min). This type of testing method was used in order to accurately measure the bond strength between the adherent and the substrates by ensuring the bonding interface was the most stressed region.

2.5 Statistical Analysis

Failure types were classified using images taken from analysis of the debonded discs under a digital microscope (Keyence, Tokyo, Japan). The failure modes for each specimen were graded as 0, 1, 2 or 3 to dictate the type of failure of the bond, according to the following parameters:

Score 0 - adhesive failure - no cement left on the titanium specimen

Score 1 - <1/3 of cement left

Score 2 - >1/3 of cement left

Score 3 - complete cohesive failure - all surface is covered with cement

The above research methodology is summarized in Figure 1. The results were then analyzed using 3-way ANOVA and Tukey’s statistical methods to arrive at appropriate conclusions in an effort to determine a complete adhesion protocol for titanium base abutments to the different ceramic and hybrid materials tested.

RESULTS

No pre-failures were observed during thermocycling or testing. Both the ceramic ($P<0.0001$) and cement type ($P<0.0001$) significantly affected the shear bond strength (MPa), whereas the condition (thermocycled or dry) did not significantly impact the shear bond strength ($P>0.05$) (Table 5). The interaction terms ceramic x cement ($P<0.001$), ceramic x condition ($P<0.001$), cement x condition ($P= 0.0001$), ceramic x cement x condition ($P=0.0159$) all reached statistical significance ($P<0.05$). Regardless of the conditioning (aging process i.e. dry or thermocycled), the combination of Zirconia and TheraCem presented significantly higher results compared to all other ceramic and cement combinations ($P<0.05$). Assessment of the failure modes showed little difference between adhesive failures (score of 0 and 1 combined) in 49.66% and cohesive failures (score 2 and 3 combined) in 50.34% of the specimens. Examples of how the failure scoring was applied are provided in Figure 2.

DISCUSSION

The purpose of this study was to test the collaborative effects of the bonding protocols available for the different types of ceramics and hybrid materials using multiple types of cements when bonding to titanium. As both the ceramic and cement significantly affected the shear bond strengths, part of the null hypothesis was rejected. However, thermocycling and type of failures were found to be not significant.

In relation to the ceramic and hybrid materials tested, five different material types were purposely selected to test their bonding ability to titanium. Firstly, Zirconia (Zenostar T) was chosen as this is one of the most commonly used materials in modern implant reconstructions. Secondly, a lithium disilicate ceramic (e.max) was selected due to its frequent use in single unit implant crowns especially in the anterior regions of the dentition to achieve optimal aesthetics. Thirdly, it was important to select hybrid ceramics (Vita Enamic and Lava Ultimate) containing different amounts of ceramic and composite resin particles for comparison to Zirconia and lithium disilicate. Vita Enamic is a hybrid ceramic that is made up of a ceramic network (86% by weight) containing a methacrylate polymer network (14% by weight). Lava Ultimate is a resin nano-ceramic containing silica and zirconia nanoclusters with an 80% by weight filler content. Lastly, the choice of G-ceram was due to the leucite content for esthetic applications.

Zirconia presented the highest mean MPa value of 38.72 with a standard deviation (SD) of 11.21, followed by G-ceram with 24.83 (SD 11.94) and e.max with 24.40 but with a higher SD of 17.09. Furthermore, the e.max group had a total of 85 compared to 90 specimens, which was due to 5 of the specimens being lost during the construction phase. Vita Enamic had a mean MPa value of 20.81 (SD 12.15) and lastly Lava a mean MPa of 11.50 (SD 10.38). The standard deviations for the other four ceramics were between 10.38-12.15 compared to a much higher e.max SD of 17.09. The findings of this study revealed the best performance by zirconia compared to lithium disilicate and other hybrid materials and is in agreement with previous studies.[9-11]

Regarding the cement, TheraCem had the highest mean MPa value of 32.08 (SD 14.63), followed by Multilink hybrid abutment with 22.56 (SD 13.29) and lastly Panavia 21 with a mean MPa value of 17.39 (SD 14.63). TheraCem is a self-etching, self-adhesive, dual-cured resin cement that contains 10-Methacryloyloxydecyl Dihydrogen Phosphate (MDP)10-30%. Panavia 21, which also contains MDP, however, performed the worst, with the methacrylate based Multilink hybrid abutment being in between these two cements. The fact that an MDP cement outperformed a methacrylate-based cement is in keeping with other studies, however, the effects of thermocycling were unremarkable.[13,14] As the used cement contained MDP monomer, the use of zirconia primer with the MDP in its composition was dispensable.

In relation to the condition, the dry specimens had a mean MPa value of 24.40 (SD 15.43) compared to thermocycled specimens which had a very similar mean MPa of 23.69 (SD 15.43). Figure 8 shows the changes in shear bond strength as a percentage in MPa due to thermocycling for all the specimen combinations. However, thermocycling did not have an impact on the shear bond strengths for this study design, which is in contrast to some previous studies.[13,14] This could be explained due to the fact that the glass transition temperature was not reached.

All the specimens showed little difference in cohesive failures in 50.34% (combination of complete cohesive failure and >1/3 of cement left groups) and adhesive failures in 49.66% (combination of adhesive failure group and <1/3 of cement left). It can be deduced from this that the bonding capacity of the cements is similar to both substrates in the ceramics and the titanium.[18,19]

Assessing the sum of squares, it showed that the ceramic had the biggest impact on the MPa values (34523.761), followed by the cement (16933.99) and the lowest impact was the conditioning method (94.815).

The three-way ANOVA followed by Tukey HSD post hoc test take into account the differences between the groups in both sample size and variance. In addition, this test restricts the total type I error (α) across all pairwise tests to 5%. The specimens with the highest least square mean values, all in the letter A group (i.e. not significantly different from one another) included Zirconia + TheraCem, e.max + TheraCem, Zirconia + Multilink, Vita Enamic + TheraCem, and Zirconia + Panavia. It can be concluded that the highest bonding strengths were achieved with Zirconia as the ceramic, independent of the cement as the A group included Zirconia and all three of the tested cements.[18,19] In addition, it also shows that the most successful cement was TheraCem, as it was able to provide the highest bonding strengths with the most different types of ceramics (notably Zirconia, e.max, Vita Enamic). Furthermore, the combination of the 'best' ceramic (Zirconia) and the 'best' cement (TheraCem), also provided the overall highest least squared mean value. Flat specimen surfaces were used for testing the research question although the taper and height of the Ti base would contribute to retention. As clinically relevant parameters. Clinical studies should report on the failures and verify the results of this in vitro study.

CONCLUSIONS

Based on the findings of the present in vitro study, the following conclusions were drawn:

1. The combination of Zirconia and TheraCem provided the highest bond strength results when bonded to titanium compared to all other ceramic- cement combinations tested in this study.
2. Thermocycling did not have an impact on the shear bond strengths of the ceramics and hybrid materials when bonded to titanium.

3. Assessment of the type of failures revealed no difference between the incidence of cohesive and adhesive failures, implying an equal affinity of the cements to the ceramic and hybrid materials and to titanium.

DISCLOSURE

The authors declare that they have no conflict of interest.

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Legends for table and figures:

Tables:

Table 1. Material type, brands, manufacturer and chemical compositions of materials used in the study.

Table 2. Descriptive statistics - Mean and SD of MPA for each group.

Table 1. Descriptive statistics in MPA by ceramic, cement and conditioning method.

Table 2. Failure mode score distribution.

Table 3. Summary of 3-way ANOVA for MPA by Cement, Ceramic and conditioning method.

Table 4. Tukey multiple comparison test for specimens.

Figures:

Fig. 1a) Flow chart showing a summary of the research methodology.

Fig. 2a-d) Failure mode determination by assigning a score of a) 0, b) 1, c) 2 or d) 3 to the images taken of each titanium disc following shear bond testing of the specimens.

Fig. 3) Graph to show the Shear bond strength (MPa) of all the specimens tested.

Fig. 4) Graph to show the Shear bond strength (MPa) of all the specimens tested with colour codes to differentiate the cements tested.

Fig. 5) Graph to show the Shear bond strength (MPa) of all the specimens tested with colour codes to differentiate the different ceramics tested.

Fig. 6) Graph to show the Shear bond strength (MPa) of all the specimens tested with colour codes to differentiate the dry and thermocycled specimens tested.

Fig. 7) Graph to show the Shear bond strength (MPa) of all the specimens tested with differentiations for the ceramic, cement and condition of the specimens tested.

Fig. 8) Effect of thermocycling on specimens expressed as a % change in MPa.

Figures:

Fig. 1) Flow chart showing a summary of the research methodology.

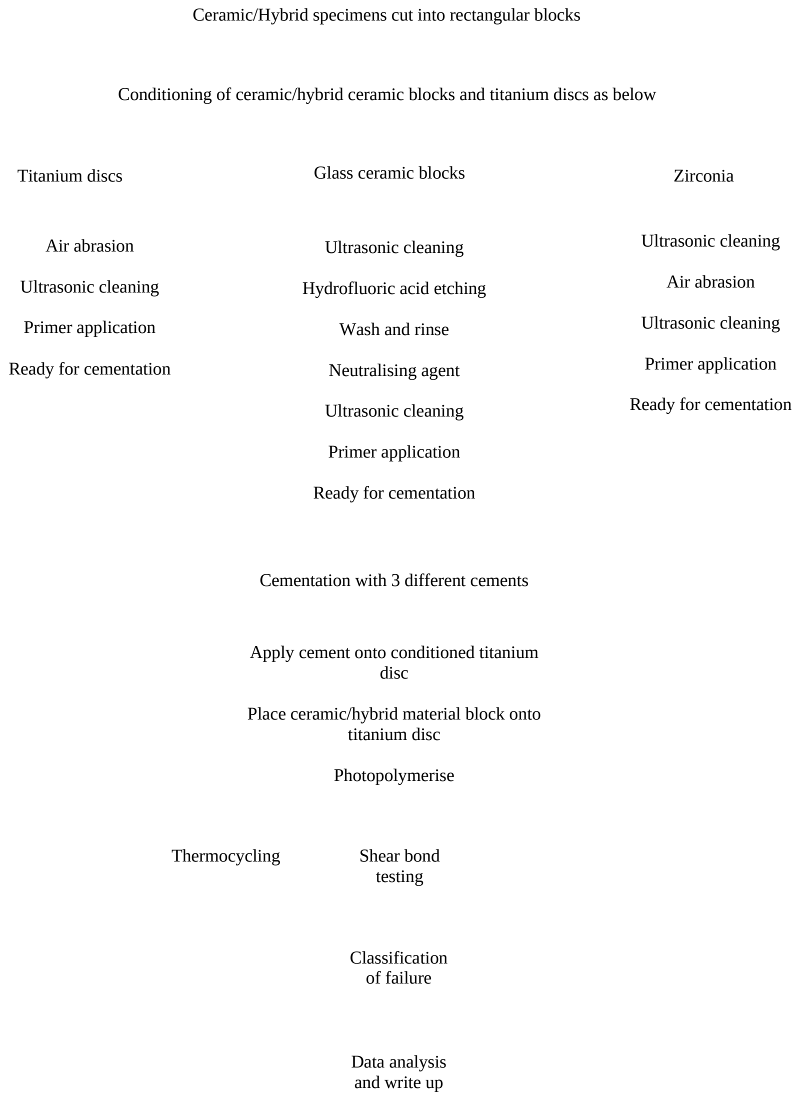
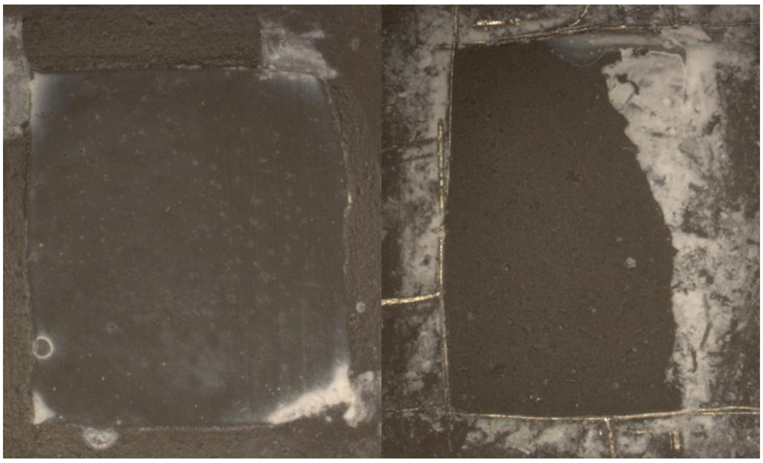


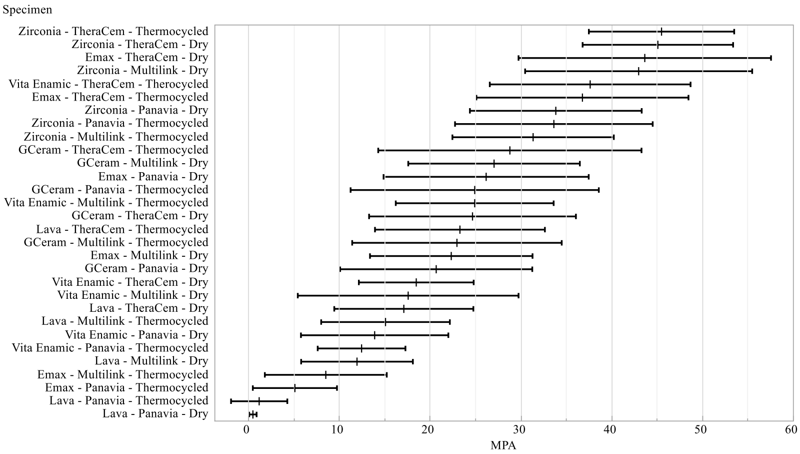
Fig. 2a-d) Failure mode determination by assigning a score of a) 0, b) 1, c) 2 or d) 3 to the images taken of each titanium disc following shear bond testing of the specimens.

Score 0: Score 2



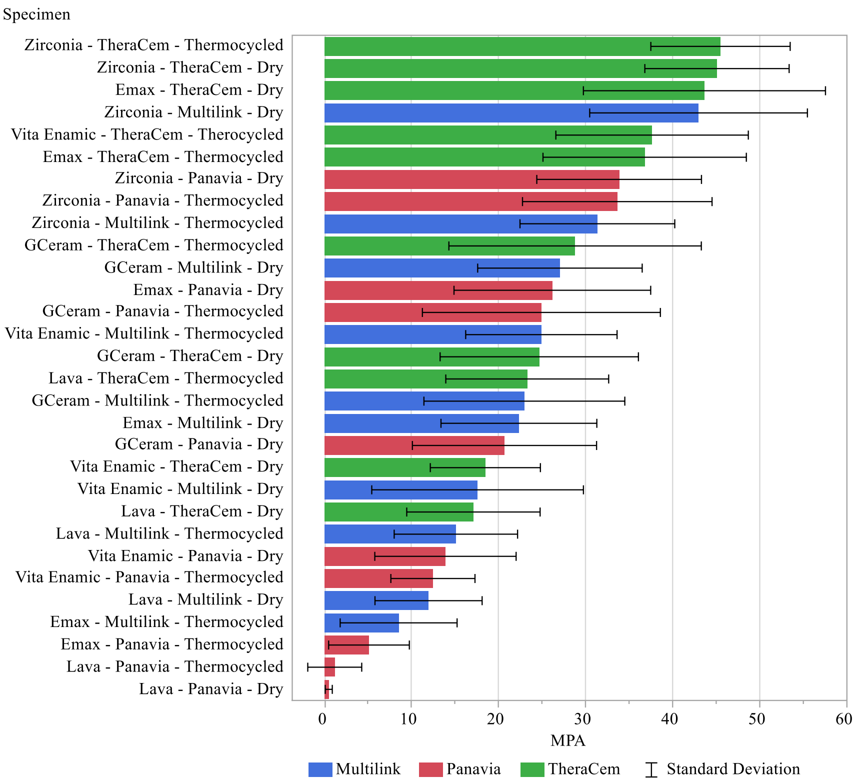
Score 2: Score 3:

Fig. 3) Graph to show the Shear bond strength (MPa) of all the specimens tested.



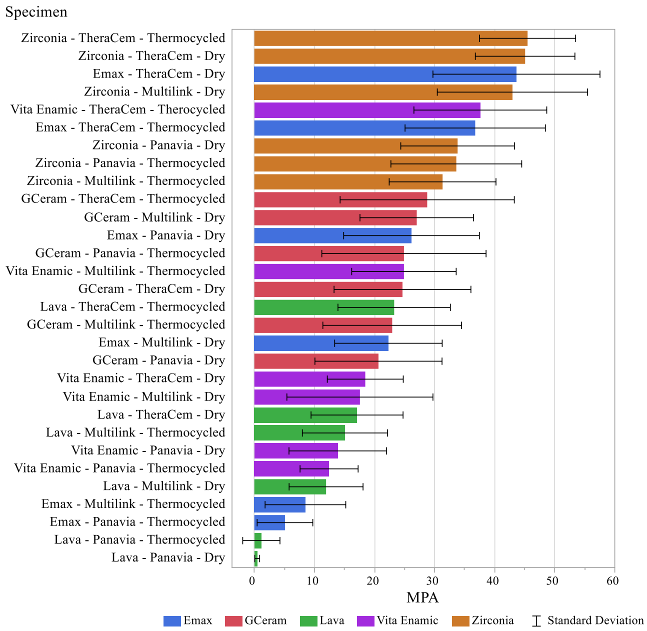
Note: Each error bar is constructed using 1 standard deviation from the mean.

Fig. 4) Graph to show the Shear bond strength (MPa) of all the specimens tested with colour codes to differentiate the cements tested.



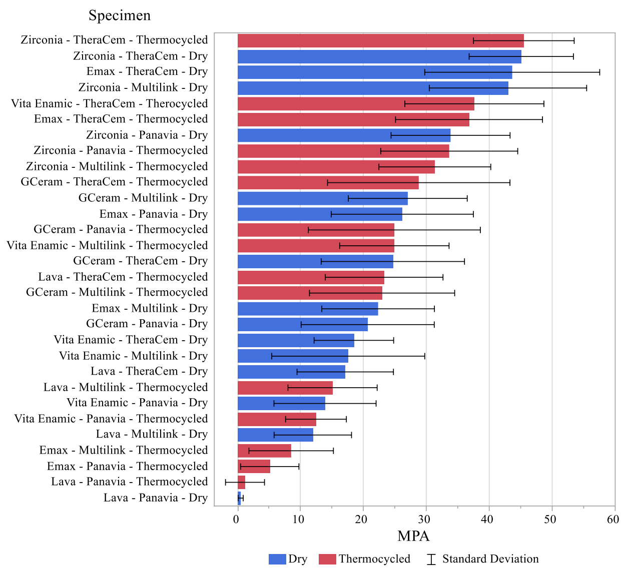
Note: Each error bar is constructed using 1 standard deviation from the mean.

Fig. 5) Graph to show the Shear bond strength (MPa) of all the specimens tested with colour codes to differentiate the different ceramics tested.



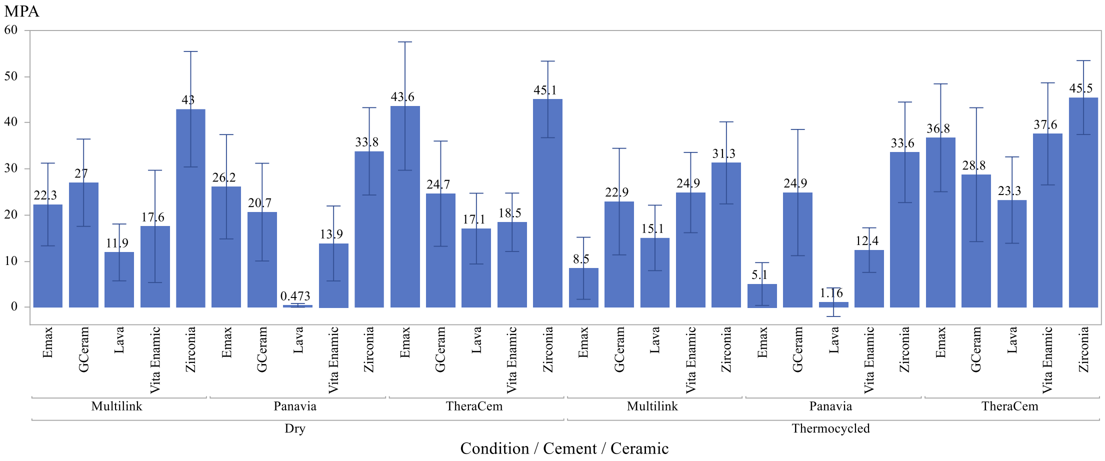
Each error bar is constructed using 1 standard deviation from the mean.

Fig. 6) Graph to show the Shear bond strength (MPa) of all the specimens tested with colour codes to differentiate the dry and thermocycled specimens tested.



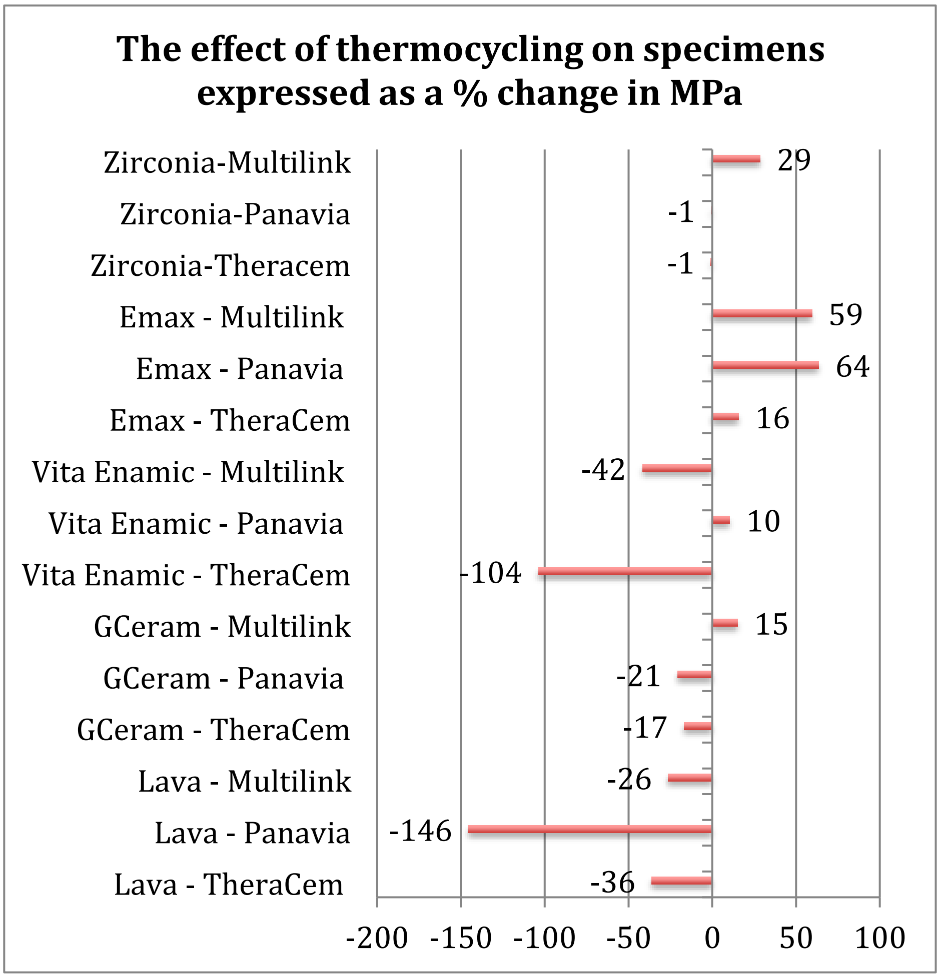
Each error bar is constructed using 1 standard deviation from the mean.

Fig. 7) Graph to show the Shear bond strength (MPa) of all the specimens tested with differentiations for the ceramic, cement and condition of the specimens tested.



Each error bar is constructed using 1 standard deviation from the mean.

Fig. 8) Effect of thermocycling on specimens expressed as a % change in MPa.



Tables

Table 1. Material type, brands, manufacturer and chemical compositions of materials used in the study.

Material type	*Brand*	*Manufacturer*	*Chemical composition*
Tetragonal zirconium oxide (3Y-TZP)	Zenostar T	Wieland Dental (IvoclarVivadent, Schaan, Liechtenstein)	Zirconium dioxide (ZrO_2 + HfO_2 + Y_2O_3) > 99.0 %, yttriumoxide (Y_2O_3) > 4.5 – ≤ 6.0 % hafniumoxide (HfO_2) ≤ 5.0 %, aluminiumoxide (Al_2O_3) + otheroxides ≤ 1.0 %
Resin nano ceramic	Lava Ultimate	3M ESPE (Maplewood, Minnesota, USA)	Silica nanomers 20nm, Zirconia nanomers 4-11nm, Silica-zirconia nanoclusters average particle size of 0.6-10 micrometers, Fillers 80% by weight

Lithium disilicate glass-ceramic	IPS e.max CAD	Ivoclar Vivadent	SiO_2 (57-80%), Li_2O (11-19%), K_2O (0-13%), P_2O_5 (0-11%), ZrO (0-8%), ZrO_2 (0-8%), Al_2O_3(0-5%) and MgO (0-5%) colouring oxides (0-8%)
Hybrid ceramic	Vita Enamic	Vita (Bad Säckingen, Germany)	86% ceramic network by weight containing: SiO_2 (58-63%), Al_2O_3 (20-23%), Na_2O (6-11%), K_2O (4-6%), B_2O_3 (0.5-2%), CaO<1%, TiO_2<1% 14% polymer network by weight containing methacrylate polymer
Leucite-Reinforced Feldspar	G-ceram	Atlas/Gulsa-Enta (Izmir, Turkey)	Leucite reinforced feldpathic ceramic
Tritan – cPTi grade 1	Titanium discs	Dentaurum GmbH & Co.KG, Ispringen, Germany	Ti^3 99.5%, others 0.5%
Universal primer	MonobondPlus	Ivoclar Vivadent	Silane methacrylate, phosphoric acid methacrylate, sulphide methacrylate
Self-curing luting composite	Multilink hybrid abutment	Ivoclar Vivadent	Monomer matrix: Dimethacrylate and HEMA Inorganic fillers: Barium glass, ytterbium trifluoride, spheroid < mixed oxide and titanium oxide. Average particle size is 0.9μm (range 0.15-3.0μm). Inorganic fillers content is approximately 36%.
Adhesive resin cement	Panavia 21	Kuraray (Chiyoda, Tokyo, Japan)	Catalyst paste: 10-Methacryloyloxydecyl dihydrogen phosphate, hydrophbic aromatic dimethacrylate, hydrophobic aliphatic dimethacrylate, silanated silica filler, colloidal silica, catalysts Universal paste: Hydrophobic acromaticdimethacrylate, hydrophobic aliphatic dimethacrylate, hydrophilic aliphatic dimethacrylate, silanated barium glass filler, catalysts, accelerators, pigments
Self - adhesive resin cement	TheraCem	Bisco (Anaheim, California, USA)	Base: Ytterbium w/ BariumGlass 30-50%, Portland Cement 10-30%, YtterbiumFluoride 1-5%, BrombenzenesulfinicAcid, SodiumDihydrate 1-5%, BisGMA 1-5% Catalyst: 10-Methacryloyloxydecyl DihydrogenPhosphate 10-30%, 2-Hydroxyethyl Methacrylate 1-5%, Tert-butylPeroxybenzoate 1-5%
Ceramic Etching Gel	IPS Ceramic Neutralising powder	Ivoclar Vivadent	Sodium carbonate (25-50%)
Blast coating agent for silicatisation	Cojet Sand	3M ESPE	Aluminium oxide (>97%), amorphous silica (<5%), Titanium dioxide (<0.6%)

			30μm grain size
Ceramic etchant	IPS Ceramic etching gel	Ivoclar Vivadent	Hydrofluoric acid 4.5%

Table 2. Descriptive statistics - Mean and SD of MPA for each group.

Group	MPA Mean	SD
Lava - TheraCem - Dry	17.09	7.66
Lava - Panavia - Dry	0.47	0.41
Lava - Multilink - Dry	11.94	6.15
Lava - TheraCem - Thermocycled	23.28	9.36
Lava - Panavia - Thermocycled	1.16	3.10
Lava - Multilink - Thermocycled	15.08	7.09
GCeram - TheraCem - Dry	24.66	11.39
GCeram - Panavia - Dry	20.66	10.58
GCeram - Multilink - Dry	27.03	9.45
GCeram - TheraCem - Thermocycled	28.77	14.50
GCeram - Panavia - Thermocycled	24.90	13.67
GCeram - Multilink - Thermocycled	22.95	11.54
Vita Enamic - TheraCem - Dry	18.46	6.32
Vita Enamic - Panavia - Dry	13.88	8.12
Vita Enamic - Multilink - Dry	17.57	12.16
Vita Enamic - TheraCem - Therocycled	37.62	11.06
Vita Enamic - Panavia - Thermocycled	12.44	4.83
Vita Enamic - Multilink - Thermocycled	24.90	8.70
Emax - TheraCem - Dry	43.63	13.90
Emax - Panavia - Dry	26.16	11.30
Emax - Multilink - Dry	22.32	8.95
Emax - TheraCem - Thermocycled	36.77	11.68
Emax - Panavia - Thermocycled	5.10	4.64
Emax - Multilink - Thermocycled	8.50	6.72
Zirconia - TheraCem - Dry	45.07	8.29
Zirconia - Panavia - Dry	33.83	9.46
Zirconia - Multilink - Dry	42.96	12.51
Zirconia - TheraCem - Thermocycled	45.48	8.00
Zirconia - Panavia - Thermocycled	33.62	10.89
Zirconia - Multilink - Thermocycled	31.33	8.89

Table 5. Descriptive statistics in MPA by ceramic, cement and conditioning method.

	MPA		
Ceramic	Mean	Std Dev	N
Emax	24.40	17.09	85
GCeram	24.83	11.94	90
Lava	11.50	10.38	90
Vita Enamic	20.81	12.15	90
Zirconia	38.72	11.21	90

Cement	Mean	Std Dev	N
Multilink	22.56	13.29	147
Panavia	17.39	14.63	148
TheraCem	32.08	14.63	150

Condition	Mean	Std Dev	N
Dry	24.40	15.43	223
Thermocycled	23.69	15.45	222

Table 6. Failure mode score distribution.

Failure mode score	N	%
Adhesive failure	62	13.93%
>1/3 of cement left	193	43.37%
<1/3 of cement left	159	35.73%
Complete cohesive failure	31	6.97%

Failure mode	N	%
Cohesive failure	224	50.34%
Adhesive failure	221	49.66%

Table 7. Summary of 3-way ANOVA for MPA by Cement, Ceramic and conditioning method.

Source	Sum of Squares	*df*	Mean Square	F	*P*
Ceramic	34523.761	4	8630.94	93.277	<.0001
Cement	16933.99	2	8466.995	91.505	<.0001
Ceramic x Cement	6463.847	8	807.981	8.732	<.0001
Condition	94.815	1	94.815	1.025	>0.05
Ceramic x Condition	6223.464	4	1555.866	16.815	<.0001
Cement x Condition	1705.173	2	852.587	9.214	0.0001
Ceramic x Cement x Condition	1767.048	8	220.881	2.387	0.0159
Error	38400.11	415	92.53		
Total	105678.51	444			

Table 8. Tukey multiple comparison test for specimens.

Specimen													Least Sq Mean
Zirconia, TheraCem, Thermocycled	A												45.479
Zirconia, TheraCem, Dry	A												45.074
Emax, TheraCem, Dry	A	B											43.633
Zirconia, Multilink, Dry	A	B											42.958
Vita Enamic, TheraCem, Thermocycled	A	B	C										37.619
Emax, TheraCem, Thermocycled	A	B	C										36.766
Zirconia, Panavia, Dry	A	B	C	D									33.833
Zirconia, Panavia, Thermocycled	A	B	C	D									33.619
Zirconia, Multilink, Thermocycled		B	C	D	E								31.335
GCeram, TheraCem, Thermocycled			C	D	E	F							28.775
GCeram, Multilink, Dry			C	D	E	F	G						27.033
Emax, Panavia, Dry			C	D	E	F	G						26.161
GCeram, Panavia, Thermocycled			C	D	E	F	G	H					24.903
Vita Enamic, Multilink, Thermocycled			C	D	E	F	G	H					24.901
GCeram, TheraCem, Dry			C	D	E	F	G	H					24.659
Lava, TheraCem, Thermocycled				D	E	F	G	H					23.275
GCeram, Multilink, Thermocycled				D	E	F	G	H					22.946
Emax, Multilink, Dry				D	E	F	G	H	I				22.318
GCeram, Panavia, Dry				D	E	F	G	H	I				20.662
Vita Enamic, TheraCem, Dry					E	F	G	H	I	J			18.465
Vita Enamic, Multilink, Dry						F	G	H	I	J			17.573
Lava, TheraCem, Dry						F	G	H	I	J			17.094
Lava, Multilink, Thermocycled							G	H	I	J			15.079
Vita Enamic, Panavia, Dry							G	H	I	J	K		13.881
Vita Enamic, Panavia, Thermocycled								H	I	J	K	L	12.441
Lava, Multilink, Dry								H	I	J	K	L	11.939
Emax, Multilink, Thermocycled									I	J	K	L	8.501
Emax, Panavia, Thermocycled										J	K	L	5.098
Lava, Panavia, Thermocycled											K	L	1.163
Lava, Panavia, Dry												L	0.473

α=0.050 Q=3.77563

Note: Levels not connected by same letter are significantly different.