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FRACTURE STRENGTH OF ALL-CERAMIC RESTORATIONS AFTER
FATIGUE LOADING

By

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A THESIS

Submitted to the graduate faculty of the University of Alabama at Birmingham,
In partial fulfillment of the requirements for the degree of Master of Science

BIRMINGHAM, ALABAMA

2011

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2011

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BALASUDHA BALADHANDAYUTHAM

MASTER OF SCIENCE IN CLINICAL DENTISTRY

ABSTRACT

Fracture strength of monolithic and bilayered LAVA and e. max lower molar crowns after load cycling was measured and compared. The study included three groups ($n = 8$) from LAVA zirconia and three groups from e. max lithium disilicate to compare influences of different layers, thicknesses and manufacturing techniques. Prefabricated anatomically designed crowns were cemented to dies made from Z 100 composite resin using Rely X Luting Plus resin modified glass ionomer cement. Cemented crowns were stored at 37° C for 24 hours then cyclic loaded to test fatigue properties. The crowns were loaded to 200,000 cycles at 25N at a rate of 40 cycles / minute to simulate oral function. Subsequently, fracture properties for each group were measured using an Instron Universal Testing machine.

Microscopic evaluation of the surface of fatigued samples did not reveal micro-cracks at the end of 50,000 cycles but minor wear facets were observed at the site of contact from the steatite ball antagonist. Crowns from LAVA bilayered groups showed step by step fractures while crowns from all other groups fractured as a single event as observed by the high speed camera. Zirconia bilayered crowns showed the highest loads to fracture while lithium disilicate monolithic crowns showed the lowest, within the limitations of the study. The study also showed that monolithic zirconia crowns of 0.6mm thickness resulted in relatively high magnitude for forces at fracture.

Keywords: zirconia, lithium disilicate, monolithic, bilayered, hand veneered

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DEDICATION

I dedicate my work to my kith and kin for their support and encouragement which has helped me reach this position. I dedicate my work to my committee members for their confidence in giving me this project, their valuable input to help complete the study and encouragement to get through the whole experience.

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1. INTRODUCTION

1.1. Background and significance

Metals and alloys have been used in dentistry as restorative materials based on their strength, longevity, castability and biocompatibility. However, the procedure of casting precious metal alloys for porcelain-fused-to-metal (PFM) restorations is highly technique-sensitive. From an esthetics stand-point, the metallic framework sometimes limits their use in the anterior segments even with the porcelain veneers overlay because PFM systems may appear opaque with monochromatic optical properties and exhibit grayness in the gingival one third. Translucency properties of metallic-ceramic (porcelain-fused-to-metal) restorations results in different absorption and reflection of light compared to dental enamel which show a high degree of translucency(1). Also, the cost of precious metals has increasingly limited their use in dentistry. The quest for a more esthetic restorative material coupled with the cost factor has hastened the introduction of all-ceramic restorations. The ceramic materials that have been tried and used in dentistry include oxides of aluminum, calcium, silicon, and magnesium. This combination renders the ceramic restorations excellent biocompatibility due to chemical inertness(2). Ceramic materials possess high melting points, low thermal and electrical conductivity, in addition to their excellent esthetic quality. The first complete coverage tooth restorations were porcelain jacket crowns for anterior teeth. But early dental ceramics had limited clinical success due to their low tensile strength, fracture toughness (brittle nature), bulk fracture, poor marginal fit and difficulty of repair.

1.2. Advantages of ceramic materials

Ceramic dental materials in dentistry have been continued in part due to a number of advantages(3), their excellent esthetic qualities especially for anterior critically esthetic restorations, their color stability over time, biocompatibility combined with high hardness, wear resistance, and low thermal conductivity.

Evolution of dental ceramics

Ceramics have changed over the past century. *Feldspathic porcelain* crowns were introduced by Land in 1903. Feldspathic porcelain is derived from a mixture of feldspar, potash, quartz, and kaolinite with varying amounts of potassium and sodium(4). Feldspathic porcelain restorations provided excellent esthetics, and biocompatibility along with resistance to compressive forces. However, they exhibited lower tensile strength than metallic restorations and fractured under shear loads(3). In 1958, the first veneering dental porcelain was introduced which led to the widespread use of porcelain-fused-to-metal restorations(2). For reasons mentioned earlier, a number of attempts have been made to replace the porcelain-fused-to-metal restorations with all-ceramic restoration. In 1965 McLean and Hughes introduced the concept of reinforcing dental porcelain with up to 50% aluminum oxide (5). This material produced reflectance and translucency similar to a natural tooth. In 1976 McLean and Sced introduced the use of platinum foil bonded by a tin coating to the inner surface of aluminous dental porcelain to further strengthen the alumina-reinforced ceramic crown(Vita-Twin Foil Jacket®; Vita, Bad Säckingen, Germany)(6).

The first dental glass ceramic was a magnesium silicate glass ceramic introduced by Dicor (Dentsply, USA), in 1984(6). *Glass ceramics* are inorganic materials with both

glassy and crystalline phases. A crystalline phase has a regular arrangement of atoms in a lattice and the amorphous phase lacks the long range arrangement of atoms in a regular manner. Glass ceramics were made by melting the dioxide powder to form glasses, and then using controlled heat treatment to nucleate and precipitate crystals in the glassy matrix(7). This method was called *controlled crystallization*. Dicor restorations were prepared using the *slip casting* technique. Slip casting includes casting the preheated liquid glass ceramic material using lost wax technique. This method of fabrication minimized micro-porosities within the material which was present in the earlier method of *sintering* the ceramic particles. Dicor is no longer available because of its modest survival rate in clinical situations(8). In all the castable glass ceramics the casting process is followed by a crystallization procedure which improves the strength but also results in additional ceramic shrinkage(9). This effect was compensated by the development of hot-press technique introduced in 1983 by the Department of Fixed and Removable Prosthodontics and Dental Materials at the Zurich University(10). In 1985, In-Ceram (Vita) introduced a high strength aluminous core manufactured by *slip casting* technique. The slip-cast alumina is first partially sintered to a refractory die in a furnace, producing a porous framework that is then infiltrated with liquid glass in a second firing process(11). The alumina core consisted of a higher proportion of fine-grained crystalline material, so that a flexural strength three times higher than that of conventional aluminous cores was achieved. The higher crystal content in this material resulted in high opacity. Therefore, they were used as a core material. IPS Empress (Ivoclar), which was introduced in 1991, used hot pressing and dispersion strengthening. It was a leucite reinforced glass ceramic with a flexural strength of 182 MPa. *Leucite* is potassium alumino silicate formed by heating

potassium feldspar to high temperatures by controlled crystallization. It is used as a veneering material for its improved strength and high coefficient of thermal expansion. *Hot pressing* used in fabricating IPS Empress restorations reduced the amount of shrinkage and flaws resulting in higher flexural strength (14). Empress 2 was introduced in 1998, which was a lithium disilicate-reinforced glass – ceramic processed by hot pressing an ingot of the material into a mold. Empress 2 showed fracture strength of 350 MPa. It was an alumino-silicate glass containing lithium oxide in the form of needle-like crystals to about two thirds of the volume of the glass ceramic. The shape and volume of the crystals contribute to about double the flexural strength and fracture toughness of Empress 2 compared to its predecessors(12). The low refractive index of the lithium-disilicate crystals made the material translucent and allowed its use for full-contour restorations. Initial clinical data for anterior restorations were excellent with this material(13). But increased fracture rates in the posterior region due to low fracture toughness, has restricted its use to anterior FPDs. In 2005, an improved pressed ceramic material called IPS e.max Press (Ivoclar-Vivadent) was introduced. The IPS e.max Press material consisted of a lithium disilicate pressed glass ceramic, the same as IPS Empress 2 but with improved mechanical properties produced by a different firing process coupled with different microstructure and concentration of lithium disilicate. Also, the frameworks of IPS e. max Press restorations were veneered with a new type of sintered fluoroapatite porcelain. In comparison with IPS Empress 2, IPS e. max Press exhibited substantially improved physical properties and greater translucency(14).

High strength oxide ceramics exhibit enhanced mechanical properties when compared to other bioceramics. High strength oxide ceramics are solid-sintered monophase

ceramics formed by directly sintering crystals together without any intervening matrix, producing a dense, pore and glass-free, polycrystalline structure. Aluminous-oxide and zirconia are examples of this category of ceramic materials(12).

Zirconia is available in three allotropic forms, that is, same chemical composition but different atomic arrangements(15). The three allotropic forms are temperature dependant. Under equilibrium conditions, the monoclinic form exists in equilibrium between room temperature and 1170°C, tetragonal between 1170°C and 2370°C and the cubic form above 2370°C(16). The zirconia when processed as a metastable material at room temperature in a tetragonal arrangement is the toughest of the three. Zirconia has been meta-stabilized in its tetragonal form at room temperature by adding stabilizing oxides such as magnesia, ceria, yttria, and/or calcium. Zirconia used in dentistry usually contains 3mol% yttria as a stabilizer (3Y-TZP).

1.3. Materials used in the present study

1.3.1. LAVA

The LAVA dental material has been used with CAD/CAM systems to fabricate the zirconia restorations. The LAVA CAD/CAM system was introduced in 2002. In this system, LAVA uses a LASER optic system to digitize information from multiple abutment margin regions in relation to the edentulous ridge. The framework is designed by the LAVA CAD software to be 20% larger than the final, to compensate for final sintering shrinkage. Thus a semi-sintered zirconia block is then selected for milling and each block is bar coded to track appropriate shrinkage magnitude. The computer-controlled precision milling unit is used to mill the restoration according to the specifications re-

ceived from the CAD software. The milled frameworks are then fully sintered to their final dimensions, densities, and strengths(17).

LAVA DVS dental system is a new technique introduced by LAVA in 2010 to eliminate the variables involved in hand veneering technique. In this system, the core is milled from zirconia blanks. The veneer is also milled but from feldspathic porcelain blocks. Fusion porcelain is applied to the milled core along the inner surface of the milled veneer and parts fused together by sintering. This reduces porosity between the layers and a better adaptation. This system minimizes the technique sensitivity related to hand veneering and provides a more reliable restoration for more predictable outcomes(18). Controlled milling of veneering porcelain are said to result in, a more homogenous and higher density restoration (8).

1.3.2. IPS e.max CAD

The e. max CAD dental material was developed for CAD/CAM applications in 2006. In this system, the partially sintered blocks called blue blocks contain metastable lithium disilicate crystals. The blue block is then exposed to a second sintering process to achieve the final microstructure. The blue block contained approximately 40 vol% lithium metasilicate crystals and a crystal size range of 0.2 to 1.0 μm with and a flexural strength of 130 to 150 MPa . Studies showed that milling of the blue blocks to desired shapes was possible. They were then crystallized at 850°C in vacuum. The thermal treatment converted lithium metasilicate to lithium disilicate that demonstrated a characteristic tooth color. The resulting ceramic restoration listed a grain size of approximately 1.5 μm and a crystal volume of 70% lithium disilicate incorporated in a glass matrix. This CAD/CAM processed glass ceramic showed a flexural strength of 360MPa (19).

1.3.3. CAD/CAM systems

Three functional components of CAD/CAM systems (38):

The first component is capture (or scanning), of the tooth preparation, adjacent teeth and occluding teeth .

The second component is the Computer Aided Designing to design the restoration for fit on the preparation which is performed according to conventional dental requirements.

The third component is Computer Aided Milling or CAM to fabricate the restoration. Pictures of scanner systems are shown in (Fig. 1).



Fig 1A: LAVA scan optical 3D scanner



Fig 1B: LAVA frame zirconia framework



Fig 1C: LAVA computer aided milling machine



Fig 1D: LAVA sintering furnace

Figure 1: Pictures of LAVA CAD-CAM System

Advantages of CAD/CAM:

CAD/CAM systems have a number of advantages. These are as follows-

- (1) Processing and the microstructure of ceramic is under the control of the manufacturer. The manufacturer can generally provide a superior material by controlling the physical and optical properties(20)
- (2) Commercially formed blocks of material provide a higher- and more uniform-quality material (36)
- (3) Restoration-shaping processes can be standardized (36)
- (4) Production time and cost is reduced (36)

1.4. Failure of all-ceramic restorations and factors influencing them

A number of factors have been associated with failure of all-ceramic restorations. The main properties that influence the biomechanical survival of these restorations in the oral environment relate to the fracture toughness of the material and its resistance or response to fatigue from masticatory function.

1.4.1. Fracture strength

Fracture strength is an important mechanical property that has been shown to influence the clinical success of dental restorations. Dental ceramics are brittle materials with a high elastic modulus. In brittle materials, fracture often begins from a single location, such as a flaw or a defect that has developed from mechanical, chemical or thermal processing where defects act as a localized stress concentrator(21). Applied stress can cause cracks to originate from the flaws and propagate, leading to catastrophic failure(22).

1.4.2. Fracture toughness

Fracture toughness has been described as the capability of a material to withstand a load in the presence of a pre-existing flaw, or simply, the resistance of a material to crack propagation. It represents an indication of the strain-energy-absorbing ability of brittle materials(23).

1.4.3. Fatigue

Fatigue can be described as the process of strength degradation of ceramics in aqueous environments involving the steady growth of cracks from pre-existing flaws(24).

1.5. In vitro studies

Studies of individual anatomic and physiologic characteristics, have shown that bite force varies depending on the specific region in the oral cavity. The greatest bite force was found in the first molar region. The mean values for the maximal force level have varied from 216 to 847N(25). To sum up the results of several studies, posterior fixed partial dentures (FPDs) should be strong enough to withstand a mean load of 500 N. Also, it is recognized that cyclic fatigue loading and stress corrosion fatigue caused by the oral environment should also be considered while testing all-ceramic restorations in vitro. Catastrophic failure, that is, fracture through the core results from a final loading cycle that exceeds the mechanical capacity of the remaining sound portion of the ceramic material(38). Tinschert et al studied fracture resistance using the universal testing machine to load lithium disilicate and zirconia posterior 3-unit fixed partial dentures to failure. They reported that zirconia FPDs have three times more fracture resistance compared to lithium disilicate. This study also showed that the fracture resistance was higher for

veneered monolithic structures(26). In another study Sundh et al, found that cyclic loading did not affect the fracture resistance of hot isostatically pressed zirconia but heat-treatment and veneering reduced its fracture resistance(27). A study by Drummond et al, comparing leucite strengthened feldspathic pressable porcelains to a low fusing feldspathic porcelain and an experimental lithium disilicate ceramic showed that the lithium disilicate ceramic showed higher values for flexural strength and fracture strengths when compared to the feldspathic porcelain groups and leucite reinforced feldspathic porcelain which was stronger than the low fusing feldspathic porcelain. The study also showed a 15–60% decrease in the flexural strength and fracture toughness for all of the groups during cyclic loading in air or water(28). Another study by Tsalouchou et al on CAD/CAM zirconia copings with pressed zirconia veneer and sintered zirconia veneer demonstrated a fracture of veneer materials before the rupture of core material after fatigue loading. The copings were made of Y-TZP with 5 mol% of yttria stabilizer and the veneer materials were made of a zirconia infiltrated glassy matrix. This study illustrates the strength of pure zirconia as opposed to zirconia with a glass component(29). A study done by Chai et al compared the probability of failure between the specimens from four different commercially available zirconia ceramics using a three-point flexural bend test. The DC-Zircon, a post-sintered Y-TZP showed higher values than LAVA and Cercon and the two pre-sintered machined Y-TZPs. The low-zirconia(35%) containing In-Ceram Zirconia had the highest probability of failure(30). A study conducted by Silva et al compared lithium disilicate glass ceramic crowns (e. max CAD) with Y-TZP crowns and metal ceramic crowns by analyzing failure after fatiguing, and showed that e. max CAD provided more resistance to failure. The same paper also reported in vivo data on clinical survival

of zirconia FPDs (Lava Crowns and Bridges, 3M ESPE) veneered with leucite-reinforced veneering ceramic (Lava Ceram Overlay Porcelain, 3M ESPE) compared with e. max Press. The LAVA zirconia FPDs showed increased survival rates compared to e. max Press lithium disilicate. It should be noted here, that e. max Press has a higher flexural strength of 400 MPa compared to e. max CAD with a flexural strength of 360MPa(31).

1.6. In vivo studies

A prospective study on randomized groups compared the long-term performance of titanium (n = 22) and high-gold (n = 25) three and four-unit porcelain-fused-to-metal (PFM) restorations. The 5-year survival rate was 84% for titanium and 98% for high-gold alloy. There was no reported failure in the high-gold group. Titanium restorations exhibited an increased risk of metal–ceramic failure(32). In a prospective clinical study by Sailer et al the success rate of 3- to 5-unit zirconia frameworks for posterior fixed partial dentures (n = 57) were studied after 5 years. The success rate of the zirconia frameworks was 97.8%. Veneering chipping was observed in 15.2% of the restorations(33). Tinschert et al in a prospective study, evaluated the clinical performance of anterior and posterior fixed partial dentures (n = 65) with frameworks made using DC-Zirkon after a mean observation time of 3 years. No absolute failures were observed for a mean observation period of 38 months. The veneering material fractured in the posterior region of FPDs, resulting in a relative failure rate of 6%(34). Valenti et al in a retrospective study, evaluated the clinical performance and long-term survival of a lithium disilicate all-ceramic restorations IPS Empress 2 (n = 261) in anterior and posterior FPDs over a 10-year period. The overall survival rate was 95.5%(35). Another prospective clinical study on IPS Empress 2

by Marquardt et al evaluated the survival rates of 27 single crowns on molars and premolars, and 31 three-unit FPDs in the anterior and premolar regions after an observation period of up to 5 years. A survival rate of 100% for crowns and 70% for FPDs was observed. In a retrospective analysis of a leucite-reinforced glass-ceramic Empress crowns (n = 125), 93 anterior and 32 posterior crowns were included in the study by Fradeani et al. A total failure rate over the entire observation period of 11 years was 4.8%. A failure rate of 1.1% was observed in the anterior segment, while 15.6% was observed in the posterior segment(36).

These studies provide information about which material and design that have been used in a given clinical situation. These studies show that glass ceramics have been used for anterior and zirconia ceramics are used for posterior restorations till date.

1.7. Primary study that supported the design of the present study

In 2010, A.Herrmann et al studied the Initial Strength of CAD CAM Veneered All-ceramic Posterior Restorations comparing between Lava DVS crowns, crowns made of Lava core over-layered with IPS e.max ZirPress veneer, monolithic IPS e.max crowns at 1.2mm thickness and monolithic IPS e.max crowns at 1.5 mm thickness. Results showed that LAVA DVS had the highest fracture strength followed by e. max crowns at 1.5mm thickness. e. max crowns at 1.2mm thickness showed the lowest fracture strength. This led to the need for follow-up investigations.

1.8. Rationale for the present study

The fracture strength of currently available commercial materials at different thickness parameters, at different layers, and manufacturing techniques have been li-

mitted, in the peer reviewed literature. There remains a question about which material is more appropriate for posterior restorations to exceed the survival rates of metal based crowns. A quest continues about the best direction for a material that can be used both in the anterior and posterior segments of the dental arch without compromising strength and/or esthetics. A search continues for a material which can sustain high stresses at minimum thickness to reduce tooth reduction and obtain minimal inter-occlusal clearance. This experience has resulted in the design of the present study comparing the fracture strength of two commercially available materials using different thickness parameters and different layering techniques with some fabricated using a new computer aided method.

1.9. Null hypotheses

Hypothesis 1: There is no difference in the mean fracture strength between monolithic LAVA and e. max crowns

Hypothesis 2: There is no difference in the mean fracture strength between bilayered LAVA and e. max crowns

Hypothesis 3: There is no difference in mean fracture strength between hand layered LAVA crowns and those from digital veneering system

2. MATERIALS AND METHODS

The materials used in this study are listed in table 1; and schematic diagrams in (Fig. 2) following the table explain the design specific to each group. Crowns in the LAVA DVS group had a zirconia core of 0.6mm thickness and a veneer layer of 0.6mm thickness, fabricated using the Digital Veneering System. The zirconia core for LAVA hand veneered crowns were fabricated using CAD/CAM technology and veneered by hand with the same thickness parameters as the LAVA DVS crowns. LAVA monolithic crowns were fabricated only with zirconia core and no veneering, at a thickness of 0.6mm. Lithium disilicate e. max monolithic crowns were fabricated using CAD/CAM technology at two different thicknesses of 1.2mm and 1.5mm. Crowns in the bilayered group were also CAD/CAM fabricated with a lithium disilicate core and then hand veneered.

Table 1: Description of Materials

Groups	Materials	Dimensions
1	LAVA DVS	1.2 mm. occlusal thickness (0.6mm. zirconia core and 0.6mm. DVS)
2	LAVA Hand veneered	1.2mm. occlusal thickness (0.6mm. zirconia core and 0.6mm. feldspathic porcelain hand layered)
3	LAVA Monolithic	0.6mm polished zirconia core (no feldspathic veneer)
4	IPS e. max CAD LT	Monolithic lithium disilicate 1.2mm. thickness
5	IPS e. max CAD LT	Monolithic lithium disilicate 1.5mm. thickness
6	IPS e. max CAD	Bilayered lithium disilicate core with feldspathic veneer (1.5mm. thickness)

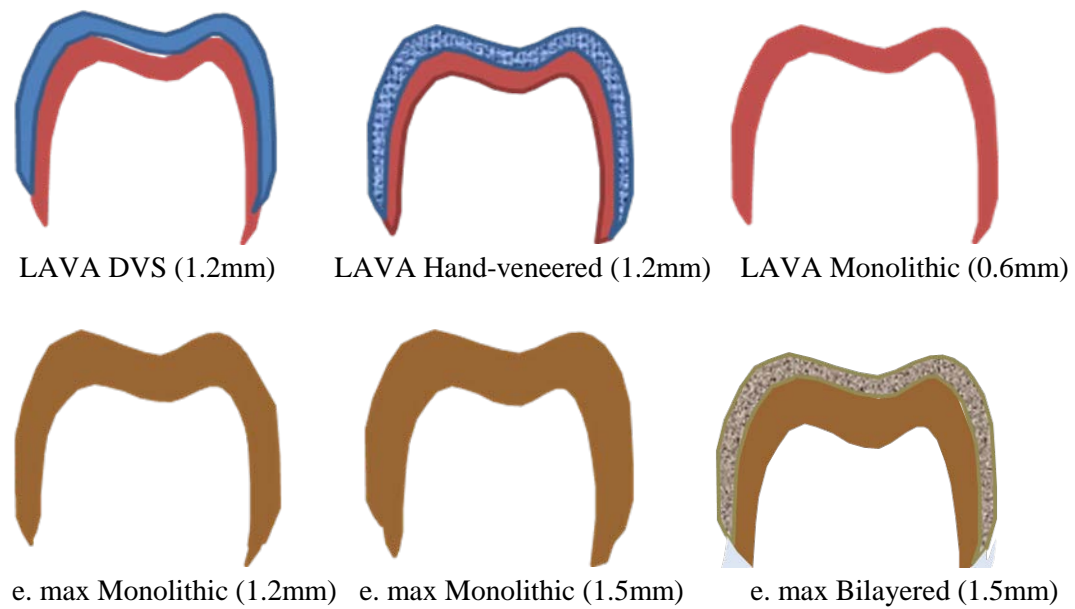


Figure 2: Schematics of six crowns and material systems used.

2.1. Preparation and fabrication of dies:

A full crown preparation was made on an ivorine lower left first mandibular molar from a typodont model (Kilgore model 201) as master preparation. This preparation was scanned using LAVA COS scanner and the scans sent to 3M ESPE. Resin dies were milled using Z 100 composite resin following manufacturer's instructions. These dies were replicated to meet the requirements of the study design as shown in (Fig. 3).

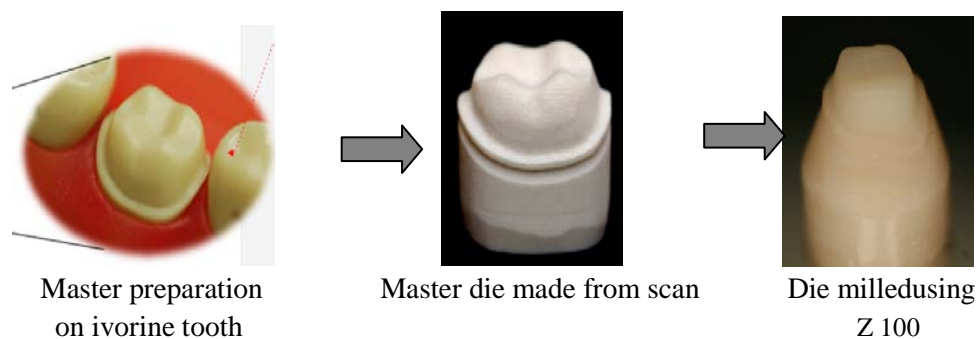


Figure 3: Pictures on fabrication of dies

2.2. Fabrication of LAVA crowns

A prepared typodont tooth (mandibular first molar) with a circumferential chamfer preparation was scanned with the LVA COS Intraoral scanner and the scans sent to 3M ESPE where the LAVA DVS crown was designed with the full contour Lava Design 5.0 Software. The anatomically designed LAVA zirconia copings and LAVA DVS veneers were milled on the Lava CNC 500 Milling Machine. The veneer and the coping were fused by sintering and the crowns finished. Veneering was done by experienced technicians for the CAD/CAM milled cores, which were sintered and finished for the hand veneered group. Monolithic crowns were fabricated in the same manner without the veneer.

2.3. Fabrication of e. max crowns

Crowns were fabricated for the bilayered e.max CAD material by scanning the original typodont tooth and using the scanned images to construct the crowns using CAD/CAM technology. The cut back and layered e.max was fabricated by hand veneering on CAD/CAM fabricated cores.

2.4. Sample preparation

Replicate individual dies were received along with individual crowns from the manufacturer as shown in (Fig. 4). The crowns were cemented to the dies with RelyX Luting Plus (3M ESPE, St Paul, MN), a resin modified glass ionomer which was compressed with 2kg weight to standardize the cementation process. Specimens were then stored in water in an incubator maintained at oral temperature (37°C) for 24 hours before cyclic loading .



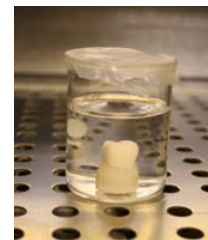
Anatomically formed crowns
from LAVA and e. max



Crowns cemented with Rely X
Luting Plus



Cemented crowns compressed using 2Kg. weight

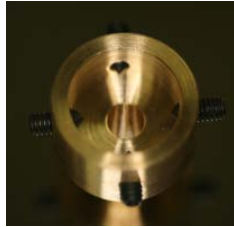


Cemented crowns stored incubator

Figure 4: Crown cementation

2.5. Fatigue test

The specimens were placed into brass fixtures for mounting on the lower stage of a cyclic fatigue machine (Fig. 5). Steatite balls of 6mm diameter were fixed to the lower end of the testing machine styli as the antagonist for fatigue loading. De-ionized water was used as the media. The specimens were loaded for 200,000 cycles using a load of 25 N at a rate of 40 cycles per minute. Loading was interrupted at 50,000 cycles and examined for veneer chipping, cracks or bulk fracture by staining the crown surface with 10% methylene blue. After digital images were made using Keyence digital microscope at 40x and 100x magnification cyclic loading was resumed until the completion of 200,000 cycles.



Brass fixture



Specimens placed into
brass fixtures



6mm steatite ball
antagonist



Brass fixtures mounted
onto the fatigue machine



Articulating paper used to centrally
position the antagonist



Keyence image after
50,000 cycles (40x)



Fatiguing (200,000 cyc. 25N load)

Figure 5: Pictures on fatigue testing

2.6. Fracture test

The fracture test was based on the maximum force leading to final (significant load drop) fracture. Since all crowns were the same size and shape and were loaded in an axial direction on the same contact points, the term strength is used to describe the frac-

ture properties. After completion of the fatigue testing, the crowns were placed into the Instron Universal Testing Device and a compressive load applied to failure at a crosshead speed of 1 mm/min. using a 3 mm diameter stainless steel ball (Fig. 6). The crowns were centrally positioned under the ball indenter of the Universal Testing Machine using articulating paper. The initial failure, namely, veneer chipping, and final failure, viz., core fracture, was recorded. Initial fracture was determined by the sequence of a maximum load followed by a direct vertical drop in the load-deformation relationship (Fig. 10-15). Data on load to fracture were obtained from the software connected to the Instron.



Instron Universal
Testing Machine



Centrally positioned indenter



Compressive load applied

Figure 6: Positioning the stylus and applying laod to fracture

2.7. Statistical analysis

One-way Analysis Of Variance was used to compare means of fracture magnitudes among the six groups and Tukey-Kramer's test was used for pair-wise comparisons among the group means with significance set at $p = 0.05$. Levene's test was used to evaluate the homogeneity of variance among the groups before conducting the ANOVA test. Contrasts were used to test pre-planned comparisons based on linear combinations of group means. Comparisons were constructed by combining the means of specific groups

for each specific comparison for contrast. Because these contrasts were specified prior to examining the data, p-values less than 0.05 were considered significant for each comparison.

3. RESULTS

3.1. Fatigue testing

No cracks were observed on the surface of samples from any of the groups when examined using Keyence Digital Microscope after staining the surface with 10% methylene blue at the end of 50,000 cycles. But wear facets from the antagonist contact were present in occlusal surface of crowns from all the groups (Fig. 7).



Staining with 10% methylene blue (100x)

Figure 7: Microscope images at the end of 50,000 cycles showing wear facets

3.2. Fracture testing

After the samples were loaded to final failure, the broken pieces were examined under the Keyence Digital Microscope. The maximum failure loads are shown in Figure 9. In some crowns from LAVA DVS and LAVA hand veneered groups, fracture occurred in steps, that is, chipping by fragments and then fracturing completely under the applied

load. All other groups showed catastrophic failure without initial chipping including crowns from the bilayered lithium disilicate group.

3.3. Observations on the structural dimension of crowns

The fractured crowns were examined for dimensions using the Keyence Digital microscope. Some of the crowns had separated from the die and the cement while some of them had not. Thickness of the crowns was measured avoiding the cement layer. The core and the veneer layers were equal thickness for LAVA DVS and hand veneered crowns (Fig. 8). Measurements at multiple sites of the fractured sections of e. max bi-layered crowns showed a veneer layer that was thinner than the core. The thicknesses correlated with the manufacturer's specification at the central pit for crowns from all groups. Also, the thicknesses of the crowns increased from the central pit to the cusps for all groups, but the thicknesses were not the same in all areas of crowns.

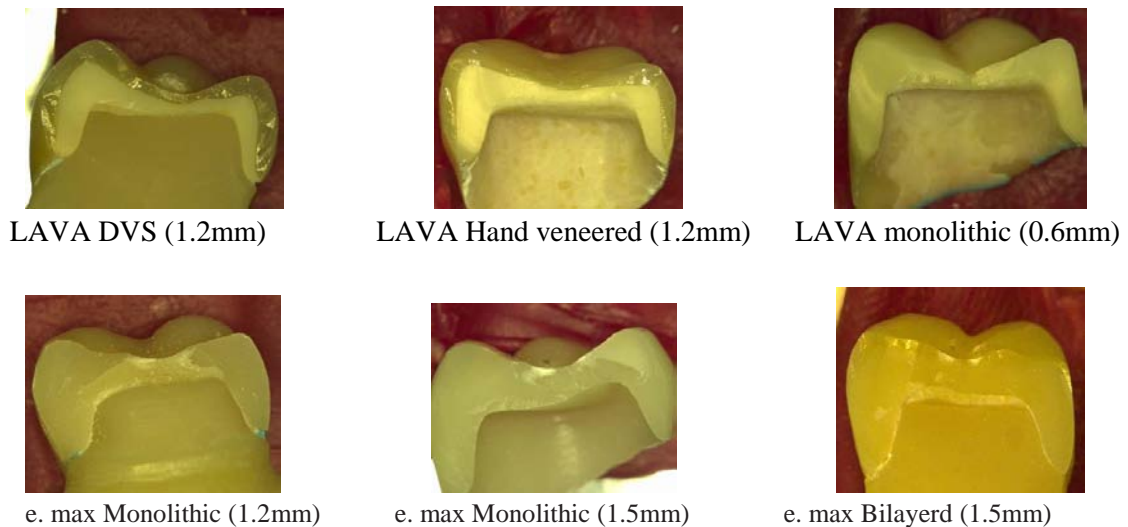


Figure 8: Images of fractured sections of crowns (20x magnification)

3.4. Fracture strength evaluation by group

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	10133187.29	2026637.46	13.80	<.0001
Error	39	5727429.80	146857.17		
Corrected Total	44	15860617.09			

Table 2: Means were compared among the materials using one-way ANOVA

3.5. Tukey- Kramer's test

Tukey-Kramer's test was used to conduct pair-wise comparisons among the means of groups, as shown in Table 3.

Least Squares Means for effect Group Pr > t for H0: LSMean(i)=LSMean(j) Dependent Variable: FailureLoad						
i/j	1	2	3	4	5	6
1		1.0000	<.0001	0.0643	0.0005	0.0003
2	1.0000		<.0001	0.0454	0.0003	0.0002
3	<.0001	<.0001		0.0953	0.7315	0.9067
4	0.0643	0.0454	0.0953		0.7119	0.5522
5	0.0005	0.0003	0.7315	0.7119		0.9995
6	0.0003	0.0002	0.9067	0.5522	0.9995	

Table 3: Tukey-Kramer's test on pairwise comparisons

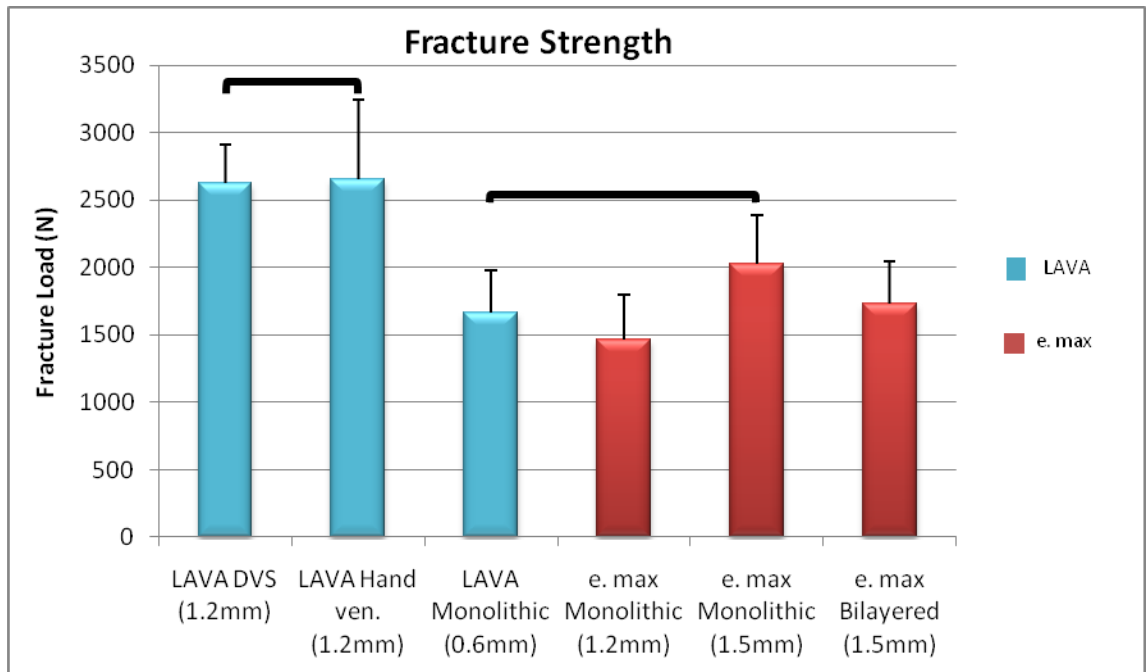


Figure 9: Graph representing statistically similar groups

3.6. *Graphs representing the load to failure of individual samples from each group:*

LAVA DVS (1.2mm)

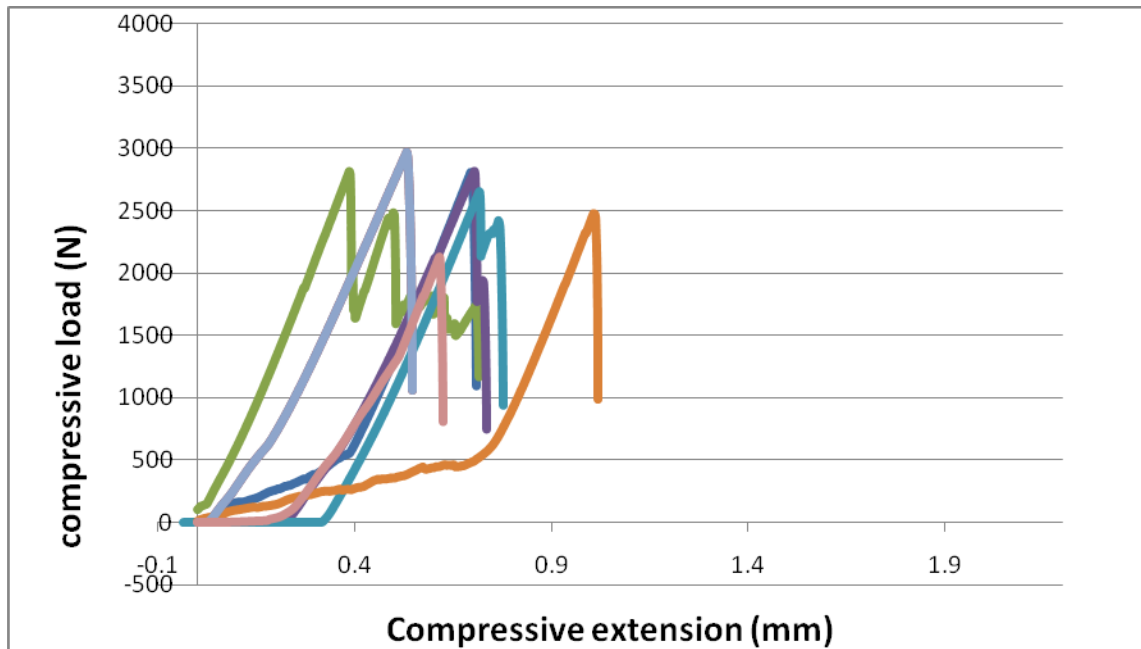


Figure 10: Graph representing failure load of LAVA DVS crowns

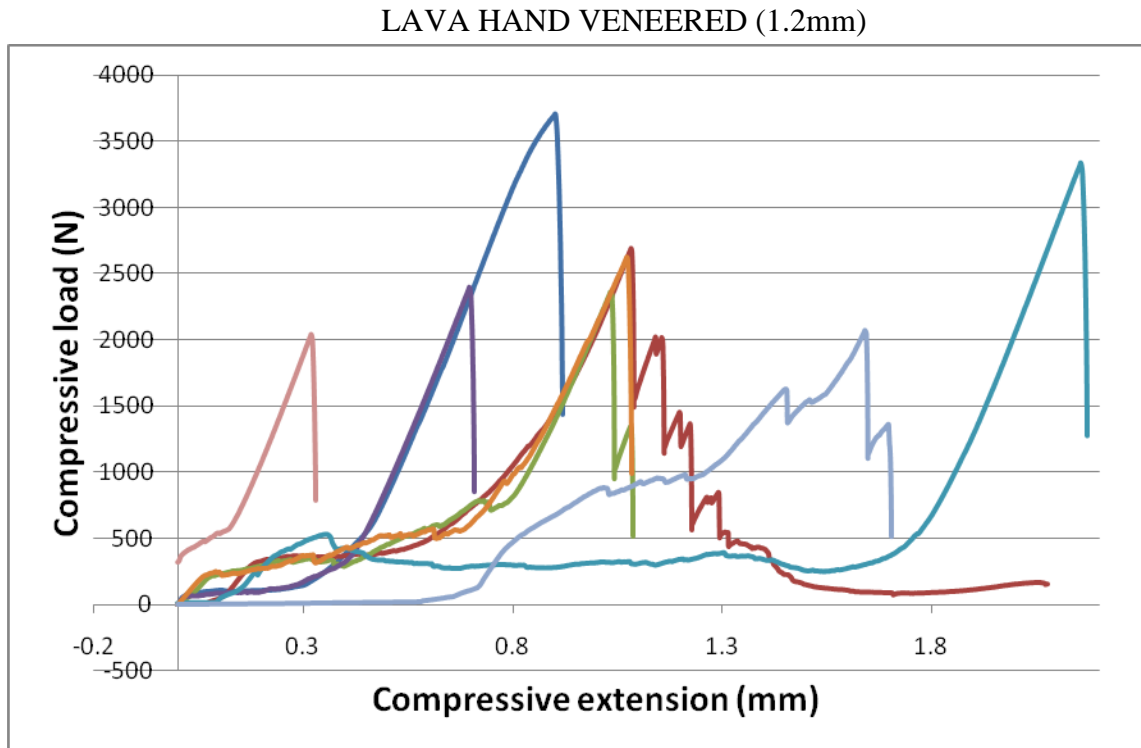


Figure 11: Graph representing failure load of LAVA Hand veneered crowns

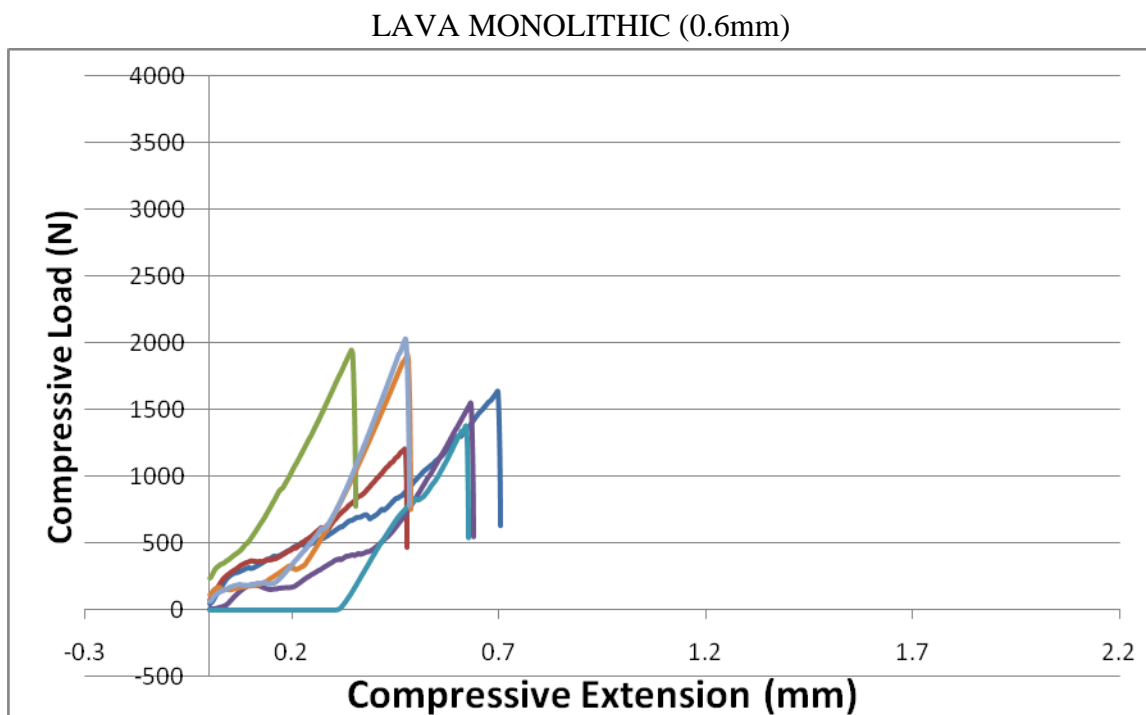


Figure 12: Graph representing failure load of LAVA Monolithic crowns

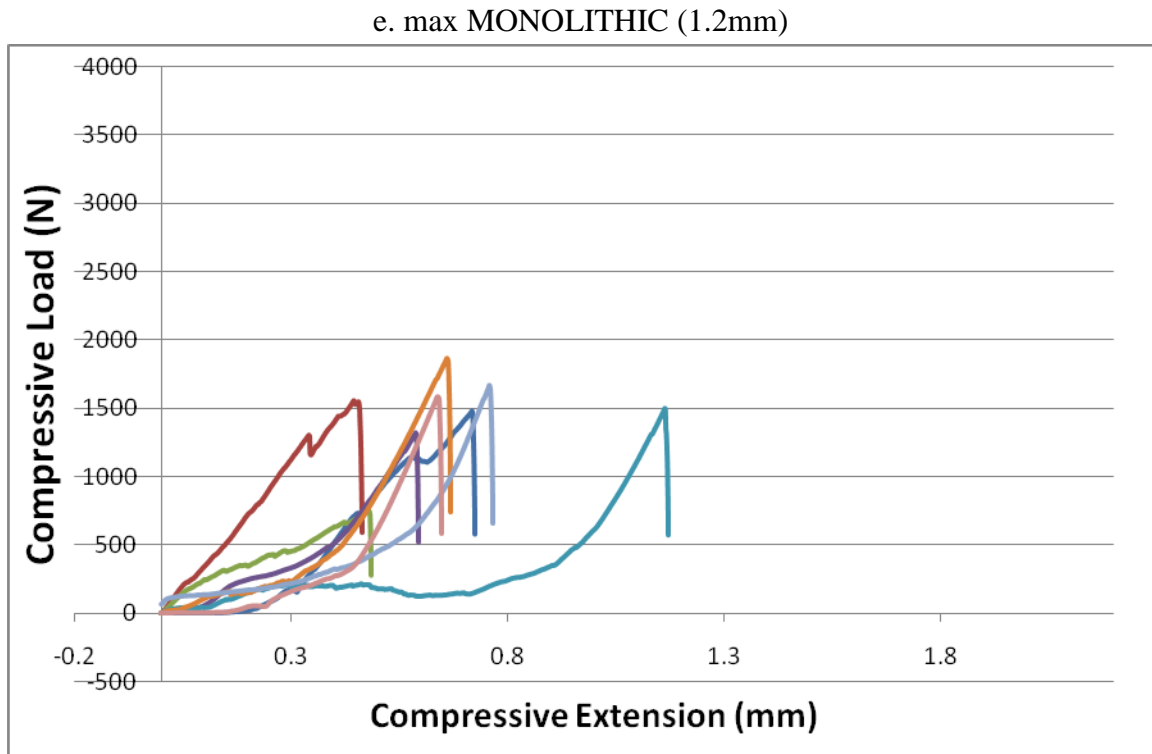


Figure 13: Graph representing failure load of e. max Monolithic (1.2mm) crowns

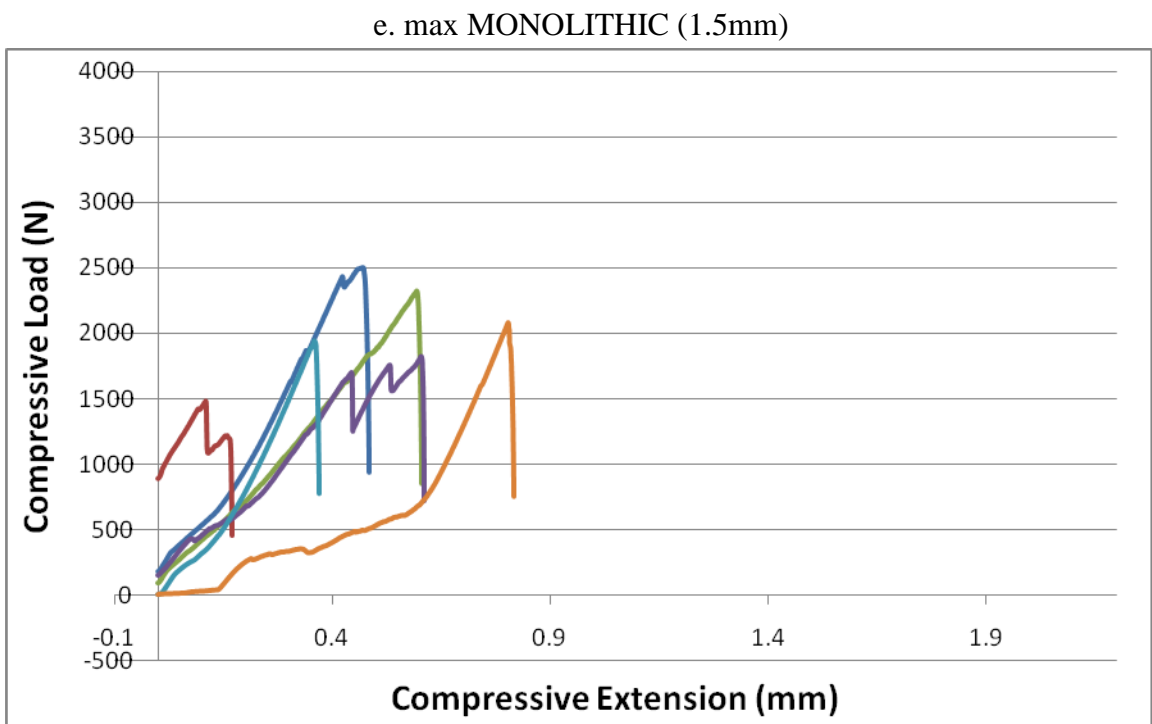


Figure 14: Graph representing failure load of e. max Monolithic (1.5) crowns

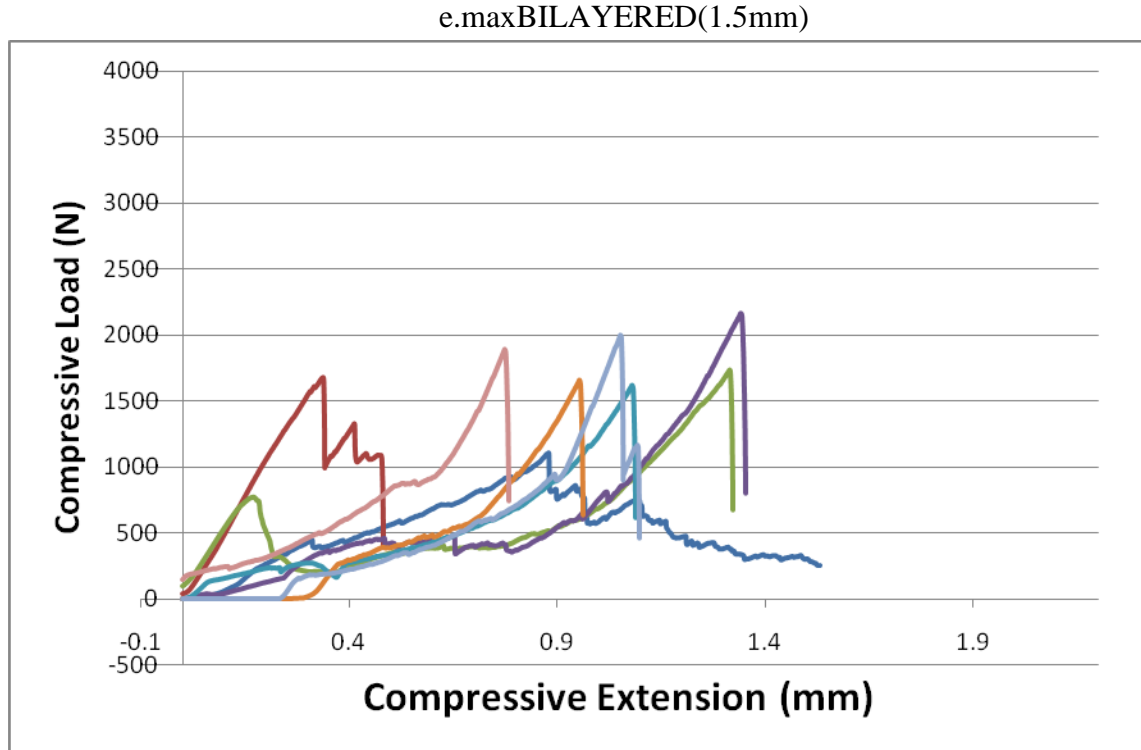


Figure 15: Graph representing failure load of e. max Bilayered crowns

The graphs above show the maximum load to failure for each sample in the respective groups (Fig. 10 – 15). The vertical axis shows the compressive load in Newtons plotted with a minimum value of -500 N and a maximum value of 4000N for all the groups. The horizontal axis shows the compressive extension in millimeters plotted with a minimum value of -0.1mm and a maximum value of 2.2mm. Compressive extension is actually the distance travelled by the indenter into the sample before the sample fractured. Some of the samples from all the groups fractured in stages, while most of them shattered all at ones. The straight lines travelling upwards with only one peak shows samples that fractured as a single event. The lines showing a number of peaks were expected to be step by step failures. Interestingly, that was not the case in all the groups. Except LAVA DVS and LAVA hand veneered groups, samples from all other groups failed as a single event

whether the corresponding lines in the graph showed one peak or a number of peaks in steps. This was inferred by relating the video footage for each sample. The step by step fracture pattern in samples other than LAVA DVS and LAVA hand veneered groups has been found to be the settling of the indenter into sample before it could apply load to the specimen. This helps us to conclude that the results of the present study is in line with the previous studies showing veneer chipping with zirconia crowns and not with lithium disilicate crowns. These results can be related to the difference in the physical properties between the core and the veneer material with zirconia and lithium Disilicate groups.

4. DISCUSSION

Prior studies have shown that the ability of all-ceramic restorations to withstand occlusal forces can be compromised by the presence of two types of inherent flaws within the restoration : (i) internal defects like internal voids, porosities, or microstructural features from fabrication; and (ii) surface cracks and structural irregularities which are defects on the surface that result from machining and grinding. Fracture can begin from microscopic damage resulting and the interaction of preexisting defects with applied loads. Failure can also occur because of impact forces or subcritical crack growth, which can be enhanced in an aqueous environment(37).

The microstructural properties of the material used to fabricate dental restorations plays a very important part in determining the forces that restorations can withstand(38). A study comparing the initial strength of CAD/CAM veneered zirconia and lithium disilicate posterior restorations showed statistically different values when the restorations were fabricated from different materials(39). This is supported by the results of the present study which showed much higher strength properties for LAVA bilayered crowns

compared to e. max bilayered crowns although the thickness for e. max was greater than the LAVA crowns.

A study on fracture mode of zirconia disks layered with porcelain using a hot pressing and sintering technique revealed delamination for some of the samples. Delamination did not occur at the interface, but rather the crack propagated within the material of lower fracture toughness and elastic modulus, the porcelain(40). A similar pattern of fracture was observed in the present study for some of the samples in the hand veneered LAVA group. This was indicative of the bond strength of veneer to core when sintered together and the low fracture toughness and elastic modulus of the hand veneered porcelain (Fig. 16).

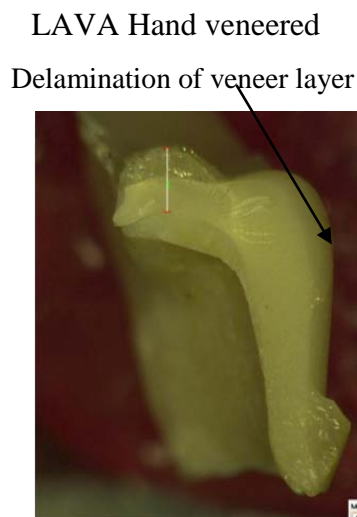


Figure 16: Delamination of LAVA Hand veneered crowns

Most of the crowns from the e. max, and the veneered LAVA groups showed surface damage at the indenter site with cone cracks beneath the surface damage (Fig. 17). This was characteristic of glassy structures, as observed in previous studies(41).

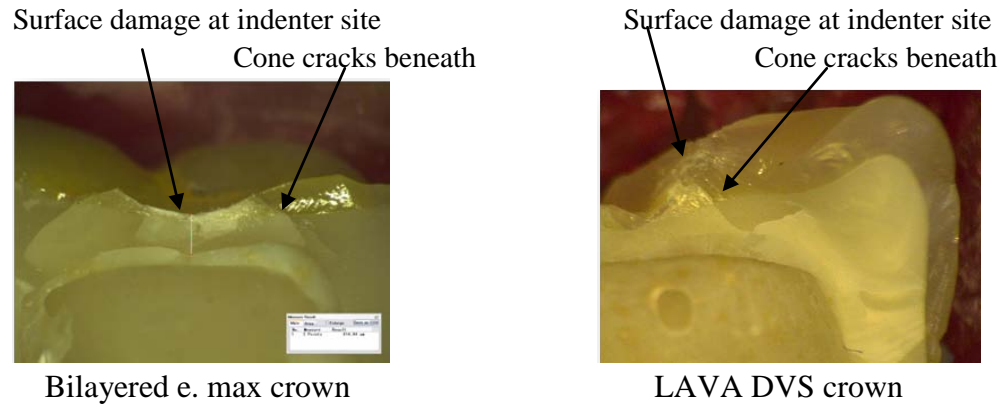


Figure 17: Surface damage on e. max Bilayered and LAVA Bilayered crowns

A threshold for damage and bulk fracture was detected in the range of 1100 to 1200 N for CAD/CAM processed lithium disilicate restorations. The CAD/CAM processed restorations revealed a high density with a minimum of structural flaws. This has been shown to result in an increased Weibull modulus and reliability for CAD/CAM-fabricated materials(42). The two types of inherent flaws can be minimized when using CAD/CAM technique. The results from the present study support the findings from the previous study.

Natural teeth, resin dies and metal dies have been used for the purpose of testing fracture load of ceramic restorations(43, 44). Natural teeth show multiple variations due to their age, structure and mineral content(46). This type of specimen introduces variables in elastic modulus and flexural strength of the substratum, which may influence the overall properties including bonding strength at cementation site. The elastic modulus of the supporting die influences the fracture load of all-ceramic crowns. Metallic teeth have very high strength and hardness compared to natural teeth substrates. Clinically, ceramic restorations are uniformly supported on a relatively elastic foundation(45), that is, the

dentin. In this study therefore, Z100 dies were selected for the substratum because of properties comparable to dentin(45). Efforts were made to create clinically relevant standardized uniform specimens when preparing the dies, as well as in fabricating the crowns.

Rely X Luting Plus resin modified glass ionomer was used to cement the crowns to the dies primarily because the manufacturers of both the groups advocate using a resin modified glass ionomer cement. For example, prior studies comparing the retention of zirconia crowns using a composite resin cement with a bonding agent and Rely X Luting cement did not show a statistical difference between the two cementing systems(46, 47). Lithium disilicate crowns also showed relatively high values on fracture strength when conventional cementation with resin modified glass ionomer was employed(48).

Studies have shown that an anatomically designed core provides support to the overlying veneer layer throughout the entire crown. This concept was utilized in all the groups. Clinical studies on zirconia fixed partial dentures with anatomic framework design showed promising survival rates in three and five-year mean follow-up studies(34, 49).

In the present study, LAVA DVS and LAVA hand veneered crowns recorded similar loads to fracture, but the standard deviation was higher for the hand veneered group. The variability in fracture magnitudes, of the LAVA hand veneered group results in an opinion that LAVA DVS restorations could result in a more reliable outcome when compared to LAVA hand veneered restorations.

The step by step fracture (sequential) mode exhibited by both LAVA DVS and LAVA hand-veneered crowns observed with the help of high speed video camera

provided insights into the fracture pattern which could be related to the difference in the physical properties of high strength zirconia core compared to the overlying feldspathic glass ceramic veneer. This difference was not pronounced for the e. max lithium disilicate bilayered group.

Comparisons to Clinical Findings

The clinical performance of all-ceramic crown is known to be associated with a complex combination of factors including the material selected, structural thicknesses, damage introduced during shaping and placement procedures, adhesive/luting system, the tooth substrate (natural dentin or foundation restoration), and the response in cyclic loading (fatigue) to complex loading of occlusal function(50).

Although the zirconia substructure is fracture-resistant, a high percentage of failures of the ceramo-zirconia restoration have been found related to ceramic chipping and delaminating(51). Chipping of the veneering ceramic constitutes clinical failure and has been reported to occur at a rate of 13% during a 3-year observation(52). One randomized controlled clinical trial involving 3- to 5-unit zirconia-supported fixed partial dentures showed that chip-off fractures occurred in 25% of the zirconia-supported prostheses in comparison to 19.4% of the metal-ceramic restorations. The findings of this 3-year follow-up have shown that the zirconia-supported prostheses also presented unacceptable numbers of major fractures of the veneering ceramic relative to the minor chips observed in the metal-ceramic system(53). A two year follow-up study of e. max CAD restorations showed no clinically identified cases of crown fracture or surface chipping(54). The present study supports these findings related to the failure patterns observed on the frac-

tured crowns of LAVA hand veneered group and the absence of these patterns in the e. max bilayered group (Fig. 18).

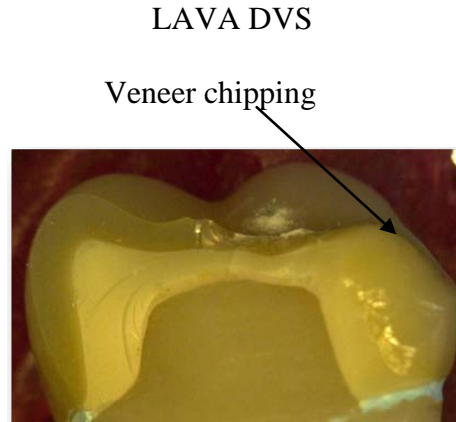


Figure 18: Veneer chipping of LAVA DVS crowns

5. CONCLUSIONS

The primary conclusions from this study were as follows:

(1) Mild wear facets were observed in most of the crowns during and after fatigue loading to 50,000 cycles did not show any visible cracks when viewed at 100x magnification using a Keyence Digital Microscope, indicating the removal of glaze on the occlusal surface at the site of loading.

(2) Cone cracks, radial cracks and chipping were observed in all samples except the monolithic zirconia. Observations on the mode of crown failure using the Keyence high speed camera (4000 frames per second), showed slow crack growth from indenter site to the periphery of the crowns. This was also observed for some monolithic e. max crowns. Some crowns showed cracks originating from gingival margin from the LAVA hand layered group.

(3) LAVA bilayered crowns showed significantly higher fracture strength compared to other groups with a p-value less than 0.05. The e. max monolithic crowns

(1.2mm) showed the lower fracture strength with a p value less than 0.05. The bilayered LAVA crowns showed significantly higher fracture strength compared to bilayered e. max crowns at a p-value of 0.0001. There was no statistically significant difference in fracture strength between monolithic zirconia (0.6mm) and monolithic lithium disilicate crowns (1.2mm, 1.5mm) ($p = 0.8565$). The fracture strength of bilayered LAVA crowns was significantly greater than fracture strength of monolithic LAVA crowns at a p-value of 0.0001 by contrast. The fracture strength of LAVA DVS crowns was not significantly different from that of hand layered LAVA crowns ($p = 0.1660$) by contrast.

(4) Crowns made with LAVA DVS system showed consistent loads to failure compared to LAVA hand veneered. This is inferred from the small standard deviation of LAVA DVS crowns compared to the large standard deviation of LAVA hand veneered crowns. Hence LAVA DVS crowns are more reliable for use in clinical situations with more predictable outcome.

(5) LAVA monolithic groups showed fracture strength close to 1650 N in the present study. In vitro studies showing a fracture strength of 1000 N was found to equate with a clinically relevant occlusal load of 500 N. This puts the results obtained from the monolithic LAVA crowns (1650N) well within the normal range of occlusal forces, that is, 100 – 800 N. This then, shows that LAVA monolithic crowns at a thickness of 0.6mm. can be used for those clinical conditions with limited occlusal clearance.

(6) Fracture strength of e. max monolithic crowns of 1.2mm thickness was much less (< 1500 N) compared to those from the crowns of 1.5mm thickness. this leads us to conclude that the manufacturer's specification of 1.5mm occlusal thickness should be adhered to very strictly.

Considerations of the hypotheses were as follows:

The 1st and the 2nd hypotheses looked at comparisons in fracture strength between LAVA and e. max monolithic and bilayered crowns. The 3rd hypothesis looked at comparisons in fracture strength of LAVA DVS and LAVA hand veneered crowns.

The 1st hypothesis was not rejected because there was no statistically significant difference in fracture strength of LAVA and e. max monolithic crowns at a p-value = 0.8565

The 2nd hypothesis was rejected because LAVA bilayered crowns showed statistically significant high fracture strength compared to that of e. max bilayered crowns at a p-value < 0.0001

The 3rd hypothesis was not rejected because there was no statistically significant difference in fracture strength of LAVA DVS and LAVA hand veneered groups at a p-value = 0.1660.

6. STRENGTHS OF THE STUDY

The prior literature shows that damage caused by occlusal adjustments in the clinical situation is one of the reasons cited to introduce flaws that could weaken the structure and hasten crown failures. This was avoided in the present in vitro study. Consistent experimental procedure was possible in the in vitro study and all groups were tested under the same conditions. Observation of the fractured samples show modes of clinical failure that correlated with results from prior studies. Preclinical fatigue loading tests provide information on fracture strengths of the materials tested, and paves the direction to designing the pertinent clinical study. Testing of commercial materials prepared according to manufacturer's specifications provides an opportunity to evaluate

“ideal” condition. This gives a measure of the clinical performance of commercially available materials.

7. CONSIDERATIONS FOR FUTURE STUDIES

The following possibilities are recommended for future studies: examine the crown surface using the digital microscope after every 50,000 cycles and at the end of fatigue cycling before transferring the specimens for fracture testing; test at higher loads and numbers of cycles to evaluate extreme stress conditions; include (3D) motion fatigue cycle to fracture to better represent masticatory function; add SEM analysis of the fatigued samples to provide information on inherent flaws that could relate to the fracture patterns; use replicates of crowns as antagonists for fatigue and fracture tests; and provide uniform four points contacts on the cusps by fabricating the crowns with identical cusps which was not possible with the design of crowns in the present study.

8. LIST OF REFERENCES

1. Raptis NV, Michalakis KX, Hirayama H. Optical behavior of current ceramic systems. *The International journal of periodontics & restorative dentistry*. 2006;26(1):31.
2. Chu S, Irfan Ahmad BDS. A Historical PERSPECTIVE OF SYNTHETIC CERAMIC AND TRADITIONAL FELDSPATHIC PORCELAIN. *Pract Proced Aesthet Dent*. 2005;17(9):593-8.
3. Zarone F, Russo S, Sorrentino R. From porcelain-fused-to-metal to zirconia: Clinical and experimental considerations. *Dental Materials*. 2011;27(1):83-96.
4. Magne P, Belser U. Esthetic improvements and in vitro testing of In-Ceram Alumina and Spinell ceramic. *The International journal of prosthodontics*. 1997;10(5):459.
5. McLean JW, Hughes TH. The reinforcement of dental porcelain with ceramic oxides. *British dental journal*. 1965;119(6):251.
6. Studer S, Lehner C, Brodbeck U, Schärer P. Six-year results of leucite-reinforced glass ceramic crowns. *Acta Med Dent Helv*. 1998;3:218-25.
7. Höland W, Rheinberger V, Schweiger M. Control of nucleation in glass ceramics. *Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences*. 2003;361(1804):575.

8. Malament KA, Socransky SS. Survival of Dicor glass-ceramic dental restorations over 14 years: Part I. Survival of Dicor complete coverage restorations and effect of internal surface acid etching, tooth position, gender, and age. *The Journal of prosthetic dentistry*. 1999;81(1):23-32.
9. Schaerer P, Sato T, Wohlwend A. A comparison of the marginal fit of three cast ceramic crown systems. *The Journal of prosthetic dentistry*. 1988;59(5):534.
10. Lehner CR, Schärer P. All-ceramic crowns. *Current opinion in dentistry*. 1992;2:45.
11. Sulaiman F, Chai J, Jameson LM, Wozniak WT. A comparison of the marginal fit of In-Ceram, IPS Empress, and Procera crowns. *The International journal of prosthodontics*. 1997;10(5):478.
12. Albakry M, Guazzato M, Swain MV. Fracture toughness and hardness evaluation of three pressable all-ceramic dental materials. *Journal of dentistry*. 2003;31(3):181-8.
13. Marquardt P, Strub JR. Survival rates of IPS empress 2 all-ceramic crowns and fixed partial dentures: results of a 5-year prospective clinical study. *Quintessence international* (Berlin, Germany: 1985). 2006;37(4):253.
14. Stappert CFJ, Att W, Gerds T, Strub JR. Fracture resistance of different partial-coverage ceramic molar restorations: An in vitro investigation. *The Journal of the American Dental Association*. 2006;137(4):514.
15. Kisi EH, Howard CJ. Crystal structures of zirconia phases and their inter-relation. *Key Engineering Materials*. 1998;153:1-36.
16. Denry I, Kelly JR. State of the art of zirconia for dental applications. *Dental materials*. 2008;24(3):299-307.
17. Liu PR. A panorama of dental CAD/CAM restorative systems. *Compendium*. 2005;26(7):507-13.
18. Schechner G. Efficient CAD CAM Veneering Process within the LAVA System. 2009.
19. Guess PC, Schultheis S, Bonfante EA, Coelho PG, Ferencz JL, Silva NRFA. All-Ceramic Systems: Laboratory and Clinical Performance. *Dental Clinics of North America*. 2011.
20. Kelly JR, Nishimura I, Campbell SD. Ceramics in dentistry: historical roots and current perspectives. *The Journal of prosthetic dentistry*. 1996;75(1):18-32.
21. Scherrer SS, Robert Kelly J, Quinn GD, Xu K. Fracture toughness (K_{Ic}) of a dental porcelain determined by fractographic analysis. *Dental Materials*. 1999;15(5):342-8.
22. Sadighpour L, Geramipناه F, Raeesi B. In Vitro Mechanical Tests for Modern Dental Ceramics. *Journal of Dentistry of Tehran University of Medical Sciences*. 2006;3(3).
23. Freiman SW. Fracture mechanics applied to brittle materials: ASTM International; 1979.
24. Morena R, Beaudreau GM, Lockwood PE, Evans AL, Fairhurst CW. Fatigue of dental ceramics in a simulated oral environment. *Journal of Dental Research*. 1986;65(7):993.
25. Waltimo A, Könönen M. A novel bite force recorder and maximal isometric bite force values for healthy young adults. *European Journal of Oral Sciences*. 1993;101(3):171-5.
26. Tinschert J, Natt G, Mautsch W, Augthun M, Spiekermann H. Fracture resistance of lithium disilicate-, alumina-, and zirconia-based three-unit fixed partial dentures: A laboratory study. *The International journal of prosthodontics*. 14(3):231.
27. Sundh A, Molin M, Sjögren G. Fracture resistance of yttrium oxide partially-stabilized zirconia all-ceramic bridges after veneering and mechanical fatigue testing. *Dental materials: official publication of the Academy of Dental Materials*. 2005;21(5):476.
28. Drummond JL, King TJ, Bapna MS, Koperski RD. Mechanical property evaluation of pressable restorative ceramics. *Dental materials: official publication of the Academy of Dental Materials*. 2000;16(3):226.

29. Tsalouchou E, Cattell MJ, Knowles JC, Pittayachawan P, McDonald A. Fatigue and fracture properties of yttria partially stabilized zirconia crown systems. *Dental Materials*. 2008;24(3):308-18.
30. John Chai BDS, Mj DL, Kok-heng Chong BDS. Probability of Failure of Machined Zirconia Dental Ceramic Core Materials. 2009.
31. Silva NRFA, Thompson VP, Valverde GB, Coelho PG, Powers JM, Farah JW, et al. Comparative reliability analyses of zirconium oxide and lithium disilicate restorations in vitro and in vivo. *The Journal of the American Dental Association*. 2011;142(suppl_2):4S.
32. Walter M, Reppel PD, Böning K, Freesmeyer WB. Six year follow up of titanium and high gold porcelain fused to metal fixed partial dentures. *Journal of oral rehabilitation*. 1999;26(2):91-6.
33. Sailer I, Fehér A, Filser F, Gauckler LJ, Lüthy H, Hämmerle CH. Five-year clinical results of zirconia frameworks for posterior fixed partial dentures. *The International journal of prosthodontics*. 20(4):383.
34. Tinschert J, Schulze KA, Natt G, Latzke P, Heussen N, Spiekermann H. Clinical behavior of zirconia-based fixed partial dentures made of DC-Zirkon: 3-year results. *The International journal of prosthodontics*. 2008;21(3):217.
35. Valenti M, Valenti A. Retrospective survival analysis of 261 lithium disilicate crowns in a private general practice. *Quintessence international* (Berlin, Germany: 1985). 2009;40(7):573.
36. Fradeani M, Redemagni M. An 11-year clinical evaluation of leucite-reinforced glass-ceramic crowns: a retrospective study. *Quintessence international*. 2002;33(7):503-10.
37. Zahran M, El Mowafy O, Tam L, Watson PA, Finer Y. Fracture Strength and Fatigue Resistance of All Ceramic Molar Crowns Manufactured with CAD/CAM Technology. *Journal of Prosthodontics*. 2008;17(5):370-7.
38. Quinn JB, Sundar V, Lloyd IK. Influence of microstructure and chemistry on the fracture toughness of dental ceramics* 1. *Dental Materials*. 2003;19(7):603-11.
39. Herrmann A. Initial strength of CAD CAM veneered all-ceramic posterior restorations. 2010.
40. Guazzato M, Proos K, Quach L, Vincent Swain M. Strength, reliability and mode of fracture of bilayered porcelain/zirconia (Y-TZP) dental ceramics. *Biomaterials*. 2004;25(20):5045-52.
41. Lawn BR, Deng Y, Thompson VP. Use of contact testing in the characterization and design of all-ceramic crownlike layer structures: A review* 1. *The Journal of prosthetic dentistry*. 2001;86(5):495-510.
42. Wolf D, Bindl A, Schmidlin PR, Lüthy H, Mörmann WH. Strength of CAD/CAM-generated esthetic ceramic molar implant crowns. *The International journal of oral & maxillofacial implants*. 2008;23(4):609.
43. Beschnidt SM, Strub JR. Evaluation of the marginal accuracy of different all ceramic crown systems after simulation in the artificial mouth. *Journal of oral rehabilitation*. 1999;26(7):582-93.
44. Holmes JR, Sulik WD, Holland GA, Bayne SC. Marginal fit of castable ceramic crowns. *The Journal of Prosthetic Dentistry*. 1992;67(5):594-9.
45. Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. *The Journal of prosthetic dentistry*. 1999;81(6):652-61.
46. Palacios RP, Johnson GH, Phillips KM, Raigrodski AJ. Retention of zirconium oxide ceramic crowns with three types of cement. *The Journal of prosthetic dentistry*. 2006;96(2):104-14.

47. Ernst CP, Cohnen U, Stender E, Willershausen B. In vitro retentive strength of zirconium oxide ceramic crowns using different luting agents. *The Journal of prosthetic dentistry*. 2005;93(6):551-8.
48. Hill TJ. Cementation Effect on the Fracture Load of Two CAD/CAM materials. 2009.
49. Molin MK, Karlsson SL. Five-year clinical prospective evaluation of zirconia-based Denzir 3-unit FPDs. *The International journal of prosthodontics*. 2008;21(3):223.
50. Thompson VP, Rekow DE. Dental ceramics and the molar crown testing ground. *Journal of Applied Oral Science*. 2004;12(SPE):26-36.
51. Pjetursson BE, Sailer I, Zwahlen M, Hämmerle CHF. A systematic review of the survival and complication rates of all ceramic and metal–ceramic reconstructions after an observation period of at least 3 years. Part I: single crowns. *Clinical oral implants research*. 2007;18:73-85.
52. Fischer J, Stawarczyk B, Tomic M, Strub JR, HÄMmerle CHF. Effect of thermal misfit between different veneering ceramics and zirconia frameworks on in vitro fracture load of single crowns. *Dental materials journal*. 2007;26(6):766-72.
53. Sailer I, Gottnerb J, Kanelb S, Hammerle CH. Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: a 3-year follow-up. *Int J Prosthodont*. 2009;22(6):553-60.
54. Fasbinder DJ, Dennison JB, Heys D, Neiva G. A clinical evaluation of chairside lithium disilicate CAD/CAM crowns. *The Journal of the American Dental Association*. 2010;141(suppl 2):10S.