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Chipping, failure load and fatigue resistance of anterior veneers manufactured with CAD/CAM technology

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DISSERTATION

CHIPPING, FAILURE LOAD AND FATIGUE RESISTANCE OF ANTERIOR VENEERS MANUFACTURED WITH CAD/CAM TECHNOLOGY

by

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DEDICATION

To my parents Zohair Almarzouki and Aisha Bannan

To my beloved husband, Hossam Jokhadar

My father and mother in law, Faisal and Khadija

and my daughter, Dana

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Boston University, Henry M. Goldman School of Dental Medicine, 2016

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ABSTRACT

Objectives: To evaluate the marginal chipping of anterior veneers made with CAD/CAM by calculating the chipping factor, to evaluate the failure load of different veneering materials and thicknesses under static loading and cyclic loading.

Materials and methods: An ivorine central incisor was prepared to receive a traditional veneer. Using epoxy resin, 120 replication dies were made of the prepared tooth. Four ceramic materials were used; IPS Empress CAD, IPS e.max CAD, VITA ENAMIC and Lava Ultimate. Veneers were milled using a Sirona InLab MCXL at three different thicknesses, 0.4mm, 0.7mm and 1.0mm, *n*=10 for each group. Veneers were inspected under the light microscope to calculate the chipping factor (CF). All veneers were cemented to their tooth replicas using Variolink Veneer resin cement. Five specimens/group were loaded under compression using an Instron universal testing machine at a rate of 0.5 mm/minute until fracture. Another five specimens were subjected to cyclic loading at 30% of the mean fracture load for 30,000 cycles at frequency rate of 1 Hz, and then were loaded under compression to fracture. Modes of failure were recorded after each test.

Results: IPS Empress CAD 0.4mm CF was higher than all other groups, and VITA ENAMIC and Lava Ultimate 1.0mm CF were the lowest. There was a significant difference in the failure load of the IPS Empress CAD and IPS e.max CAD groups under static loading but not in VITA EANMIC and Lava Ultimate groups. Cyclic fatigue had no significant effect on the failure load of different veneering materials and thicknesses.

Conclusions: Chipping factor decreases as the material thickness increases and can be used as an indicator of material machinability. IPS e.max CAD at 1.0mm had the highest static failure load value when compared to other materials. Cyclic fatigue did not affect the failure load values within the groups tested.

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INTRODUCTION

Dental ceramic is an inorganic nonmetallic material composed of oxygen and one or more metallic or semi-metallic elements that is usually processed by firing at high temperature. Dental ceramics consist mainly of glasses, porcelain, glass ceramics or highly crystalline structures. They are strong, temperature resistant, have excellent flexural strength and fracture toughness. However, these materials are brittle and can fracture if flexed or when quickly heated and cooled.[1]

Dental ceramics mainly have three classes: predominantly glassy; particle-filled glasses; and polycrystalline ceramics.[2] They also can be classified according to: 1) their indication (crowns, veneers, posts and cores); 2) fabrication technique (casting, hot pressing and computer aided design/computer aided manufacturing); 3) firing temperature (low fusing, medium fusing and high fusing); 4) translucency (opaque, translucent and transparent); 5) fracture resistance.[1,2] Understanding the different classes of ceramics allows the clinician to choose the best ceramic material for a particular clinical situation.[1]

Mclean and Hughes in 1965 added aluminous porcelain to conventional feldspathic ceramic to strength it but due to its brittleness, it was only suitable in the anterior area. Magne and Belser in 1997 developed a more stable glass-infiltrated alumina. However, the high amount of crystals has led to high opacity which means it can be used only as a core material. Recently, dense sintered high strength ceramics with excellent mechanical characteristics were developed such as zirconia which is considered the most stable of these ceramics.[3]

Metal-ceramic restorations were popular because of their excellent mechanical properties, durability, marginal adaptation and low cost.[4] However, these restorations hardly reproduce natural esthetics especially in situations with limited space for reconstruction.[3] The combination of strength and reasonable esthetics in metal-ceramic restorations made them the gold standard in prosthetic dentistry but the patient need for superior esthetics has driven the development of ceramics for use in dental restorations.[5]

The increased demand for esthetic, more durable material, combined with concerns about metallic restorations has stimulated research for metal-free, tooth colored restorations.[6] All-ceramic restorations are considered the most esthetically pleasing restorations. They produce life-like appearance and allow natural light to pass through them due to the lack of metal substructure.[7] They are becoming more popular because of their biocompatibility, color stability, esthetic properties and wear resistance.[5,6] All-ceramic restorations have been widely used in recent years because of their excellent gingival response, high esthetic quality and marginal accuracies comparable to traditional metal-based restorations.[8] On the other hand, they cause excessive wear to opposing dentition[8], are technique sensitive,[6] and they easily fracture.[6,9] Failure usually begins with microscopic damage from the interaction of previous defects with applied loads. It also can occur due to subcritical crack growth which is usually increased in an aqueous atmosphere.[6]

Porcelain laminate veneers bonded to enamel were first introduced in the early 1980s.[10] Advances in dental materials and techniques in the last few decades, along with more adhesive technologies have led to a huge interest in Minimally Invasive Dentistry.[7,10] Its major advantage is preservation of sound tooth structure and maintenance of the vitality of the restored teeth.[7] The clinical success of porcelain veneers depends on careful case selection, treatment planning, accurate tooth preparation,[10,11] and a strong bond between two materials of similar elastic moduli, enamel and porcelain.[12] The use of porcelain veneers for anterior teeth has increased recently to correct problems such as discolored composite restorations, fractured teeth and incisal wear.[13] The most common failure associated with porcelain veneers are fracture or debonding.[14] Most of the fractures associated with veneers are the result of adhesive failure at the veneer/cement interface leading to fracture or complete debonding of the veneer.[15] During polymerization shrinkage of the resin cement, porcelain veneer does not deform thereby creating residual stress at the interface.[12,14]

Chunling et al. measured the influence of porcelain veneer thickness and enamel thickness on the loads needed to cause initial fracture and catastrophic failure of porcelain veneers. Thirty model discoid porcelain veneer specimens of different thickness were bonded to incisors, artificially aged by thermal cycling, and loaded to failure using an Instron machine. They concluded that increased enamel thickness, increased porcelain thickness and increase of combined thicknesses all raised the failure load needed to cause catastrophic failure.[12]

In 2011, Schmidt et al. evaluated the effect of preparation design and the amount of existing tooth structure on the fracture resistance of ceramic laminate veneers. Thirty-two maxillary central incisors were tested for the effect of preparation design and the amount of tooth structure remaining after preparation. After cementation with veneers, specimens were loaded to failure in a universal testing machine. Preparation design and the existing amount of tooth structure had a significant effect on load to failure for ceramic veneers.[16]

The use of computer aided design/computer aided manufacturing (CAD/CAM) these days continues to grow worldwide, because they offer the delivery of accurate, esthetic restorations rapidly to patients. The materials used must be able to be milled quickly, resist machining damage and finished and polished before placement.[17] CAD/CAM materials have many advantages. They are safe, esthetically pleasing, durable and quickly fabricated, which will benefit the patient and dental lobaratory.[18]

Chair-side milling systems are able to fabricate full-contour restorations from different blocks. This includes feldspathic porcelain and resin composite blocks. These blocks are fabricated continuously in the same manner, which results in a high quality dense material. There is no porosity in these prefabricate blocks whereas several pores can be found in pressed and hand-built restorations. Laboratory-based CAD/CAM systems are used to fabricate multiple-unit restorations with high-strength ceramic materials such as: zirconia, lithium disilicate glass ceramic and alumina. Some of these systems can be used to mill metals, for example titanium, base metal, and even custom implant abutments. [17,18]

Prefabricated reinforced glass ceramic blocks which are available for milling using CAD/CAM have mechanical properties similar or superior to those of tooth enamel. These materials are useful and not considered technique sensitive. Moreover, conventional finishing such as staining and glazing are available. They have also excellent fit and esthetics, are quickly fabricated and exhibit strong durability with adhesive resin cements.[18]

A successful dental restoration is determined by three main factors, which are esthetics, resistance to fracture, and marginal adaptation. Misfit of a restoration could contribute to cement dissolution, plaque accumulation, secondary caries and endodontic inflammation.[19] Ceramic laminate veneers are usually bonded with adhesive resin cements which produce a chemical bond between the veneer and the tooth structure. The adhesive resin cement undergoes thermal cycling, dynamic loading and is subjected to the hydrolytic effect of water in the mouth. Proximity between the margin of the veneer and the tooth structure protects the adhesive resin cement from dissolution which could result in microleakage, discoloration and fracture of the veneers.[20]

It was reported in a previous study that CEREC systems (Sirona Dental Systems Gmbh, Bensheim, Germany) can fabricate restorations with clinically acceptable marginal gaps. Marginal integrity is considered an important factor for the longevity of a restoration. [21] External marginal adaptation of ceramic veneer is the vertical distance between the prepared tooth finish line and the margins of the veneer.[22] With the abrasive machining process (grinding and milling) of CAD/CAM systems, there is a possibility for generation of machining-induced damage that could decrease the integrity of the final restoration.[21] Despite the superior machinability and physical properties of prefabricated ceramic blocks, all available CAD/CAM materials that are machined with diamond grinding burs are subjected to chipping defects, microcracks and surface flaws. These chipping defects can reduce the accuracy of fit of a restoration and may eventually reduce the mechanical strength with time.[21,23]

The machinability of a material can be easily measured qualitatively as the ease with which a material is cut. On the other hand, quantitative measurement is difficult.[24] Tsitrou in 2007 introduced the concept of chipping factor (CF) which is an estimation of the degree of marginal chipping. It is calculated by estimating the ratio of overall marginal chipping over the total marginal circumference of the restoration multiplied by 100 using the equation

$$\mathbf{CF} = \frac{L}{P} * \mathbf{100}$$

Where L is the amount of marginal chipping and P is the marginal circumference of the restoration.[21]

Flanders et al. in 2003 tested the scratch hardness and the amount of edge chipping of five different machinable dental ceramics with respect to the effect of the cutting environment. The authors calculated the degree of chipping by measuring the lengths that chipped out along a scratch that is made on the material. They concluded that environmental effects on chipping were minimal and its more dependent on tool interactions rather than material-specific properties.[25]

Souza et al. evaluated the marginal discrepancy of ceramic crowns manufactured by a CAD/CAM system with different finish lines (tilted chamfer, large chamfer, rounded shoulder). The crowns were fixed on their respective metallic dies using a metallic fixation device and the marginal fit between the crown and the preparation margins was evaluated with 3D optical microscope. It was concluded that the rounded shoulder finish line had marginal discrepancy values significantly lower than the other two finish lines.[26]

Veneer restorations aim to avoid the extensive crown preparations as well as to reinforce the residual tooth structure. However, fracture strength is considered the main concern and the investigation of fracture resistance of ceramic and composite veneers is necessary for the long term stability of these restorations.[27] Lately, minimally invasive veneer preparations have become more popular. These include less tooth reduction and minimal porcelain thickness. Minimally invasive veneers have been reported to be 0.3 mm in thickness, whereas conventional porcelain veneers generally range from 0.3-1.0 mm in thickness. There is limited research on the outcomes of minimally invasive veneers. On the other hand, excellent clinical outcomes and high survival rates for conventional porcelain veneers.[12]

All ceramic restorations are subjected clinically to masticatory forces under dry and wet conditions, therefore, these conditions must be considered during in vitro testing. Cyclic loading fatigue significantly reduces the fracture load of all ceramic crown systems. Limited information is available regarding the effect of cyclic fatigue loading on the fracture load of composite and all ceramic CAD/CAM restorations.[28,29]

Johnson et al. investigated the effect of restoration thickness and material type on the fracture strength of posterior occlusal veneers. Sixty maxillary occlusal veneers were milled with CAD/CAM fabricated from Paradigm MZ100 and Lava Ultimate at minimal occlusal thicknesses of 0.3, 0.6 and 1.0 mm. Occlusal veneers were adhesively bonded and subjected to vertical load to fracture using a universal testing machine. Restoration thickness in this study had no statistical difference on the fracture strength. However, material type affected the fracture strength and those fabricated with Lava Ultimate fractured at higher loads than Paradigm MZ100 veneers.[30]

A similar study by Egbert et al. compared the fracture strength and failure modes of ultrathin occlusal veneers (0.3 mm). Sixty maxillary occlusal veneers were milled with CAD/CAM from a composite material (Paradigm MZ100), a resin nanoceramic (Lava Ultimate) and a hybrid ceramic (Vita Enamic) at 0.3 mm thickness. Veneers were cemented and vertically loaded to determine the fracture strength. Occlusal veneers made from Lava Ultimate had the highest fracture strength, whereas, Paradigm MZ100 and Vita Enamic veneers were not significantly different.[31]

Magne et al. evaluated the fatigue resistance of ceramic and composite posterior occlusal veneers. Thirty extracted molars received a traditional preparation simulating advanced occlusal erosion. Veneers were milled at 1.2 mm thickness with CAD/CAM fabricated from leucite-reinforced and lithium disilicate ceramics (IPS Empress CAD and IPS e.max CAD, respectively) and a composite resin (Paradigm MZ100). Restorations were all bonded with preheated luting material and subjected to cyclic loading starting with 200 N for 5000 cycles followed by stages of 400, 600, 800, 1000, 1200 and 1400 N at a maximum of 30,000 cycles each. IPS Empress CAD failed at 900 N without reaching all 185,000 cycles. However, IPS e.max CAD and Paradigm MZ100 survival rates were 30% and 100% respectively.[32]

Alghazzawi et al. studied the effect of material and preparation design on the failure load of anterior veneers and its mode of fracture. A typodont lateral incisor received an incisal overlapped preparation (IOP) and a three-quarter preparation (TQP) and they were used to fabricate the composite resin abutments. Ten veneers for each preparation design were fabricated from yttria-stabilized zirconia covered with porcelain (VITA VM9), lithium disilicate glass ceramics (IPS e.max CAD) and feldspathic porcelain (Super porcelain EX-3). Zirconia and glass ceramic veneers were milled with CAD/CAM. Veneers were cemented to the abutments at an angle of 135 degrees and loaded under a universal testing machine until failure. The preparation design did not affect the failure load of veneer materials. However, zirconia veneers had a higher load before fracture than the other materials used.[14]

A study by Lin et al. evaluated the marginal discrepancy and fracture resistance of two veneering materials (ProCad, Ivoclar Vivadent, Amherst NY) milled by CAD/CAM and conventional sintered feldspathic porcelain using two preparation designs (full and traditional). Forty-eight specimens cemented on composite resin dies were used in the study. The fracture resistance of the veneers was measured with a universal testing machine. It was found that there was no correlation between the thickness and the marginal discrepancy of veneers. Traditional veneer preparation with conventional sintered feldspathic porcelain and full preparation design with ceramic material such as ProCad were the most favorable combinations in terms of marginal discrepancy and fracture resistance.[10]

OBJECTIVES

The objectives of this study were:

1) To evaluate and compare the marginal chipping of anterior veneers made with different ceramic materials using computer aided design/computer aided manufacturing (CAD/CAM) by calculating the chipping factor (CF).
2) To evaluate and compare the failure load of different veneering materials and thicknesses under static loading
3) To evaluate the effect of cyclic loading on the failure load of different veneering materials and thicknesses.
4) To evaluate failure modes (cohesive, adhesive or catastrophic failure) among different veneering materials and thicknesses.

HYPOTHESES

1) There is no significant difference in the marginal chipping of anterior veneers made with different ceramic materials using the computer aided design/ computer aided manufacturing (CAD/CAM) by calculating the chipping factor (CF).
2) There is no significant difference in the failure load of different veneering materials and thicknesses under static loading.
3) There is no significant difference in the failure load of different veneering materials and thicknesses under cyclic loading.
4) Cyclic fatigue has no significant effect on the failure load of different veneering materials and thicknesses.

MATERIALS AND METHODS

An ivorine typodont right central incisor (Model #D95SDP-200; Kilgore International, Inc., Coldwater, MI) was selected to receive a traditional veneer preparation. The tooth was prepared with a diamond rotary cutting instrument from a veneer preparation set (Brasseler USA® Dental, Savannah, GA). The typodont tooth was sprayed with IPS lab side contrast spray (Ivoclar Vivadent, Liechtenstein) and scanned using an inEos Blue scanning camera (Sirona, Bensheim Germany). Ceramic veneers were designed using Sirona InLab 3D software SW4 4.2.5 then milled into three different thicknesses (0.4 mm, 0.7 mm and 1.0 mm) using a Sirona InLab MCXL milling machine. Four different ceramic materials were used in this study. Table 1 summarizes types and compositions of materials used. Milled veneers were inspected under the optical light microscope (IVS FSF Metallurgical Microscope, Zeiss, Germany) to determine the marginal chipping by taking a series of images of the perimeter of the veneer. Eight samples per group were inspected under the light microscope. The prepared ivorine incisor was used as the master die to fabricate 120 prepared tooth replicas using a highly filled epoxy adhesive resin. All veneers were cemented to their tooth replicas using Variolink veneer resin cement (Ivoclar Vivadent, Liechtenstein). Ten specimens per group were made. Five specimens from each group were loaded under compression using an Instron universal testing machine at a rate of 0.5 mm/minute until fracture. The mean fracture load was calculated. The other five specimens were subjected to cyclic loading at 30% of the mean fracture load for 30,000 cycles at frequency rate of 1 Hz, and then were loaded under compression to fracture.

Test Groups:

I. IPS e.max CAD 0.4 mm thickness

II. IPS e.max CAD 0.7 mm thickness

III. IPS e.max CAD 1.0 mm thickness

IV. IPS Empress CAD 0.4 mm thickness

V. IPS Empress CAD 0.7 mm thickness

VI. IPS Empress CAD 1.0 mm thickness

VII. VITA ENAMIC 0.4 mm thickness

VIII. VITA ENAMIC 0.7 mm thickness

IX. VITA ENAMIC 1.0 mm thickness

X. Lava Ultimate 0.4 mm thickness

XI. Lava Ultimate 0.7 mm thickness

XII. Lava Ultimate 1.0 mm thickness

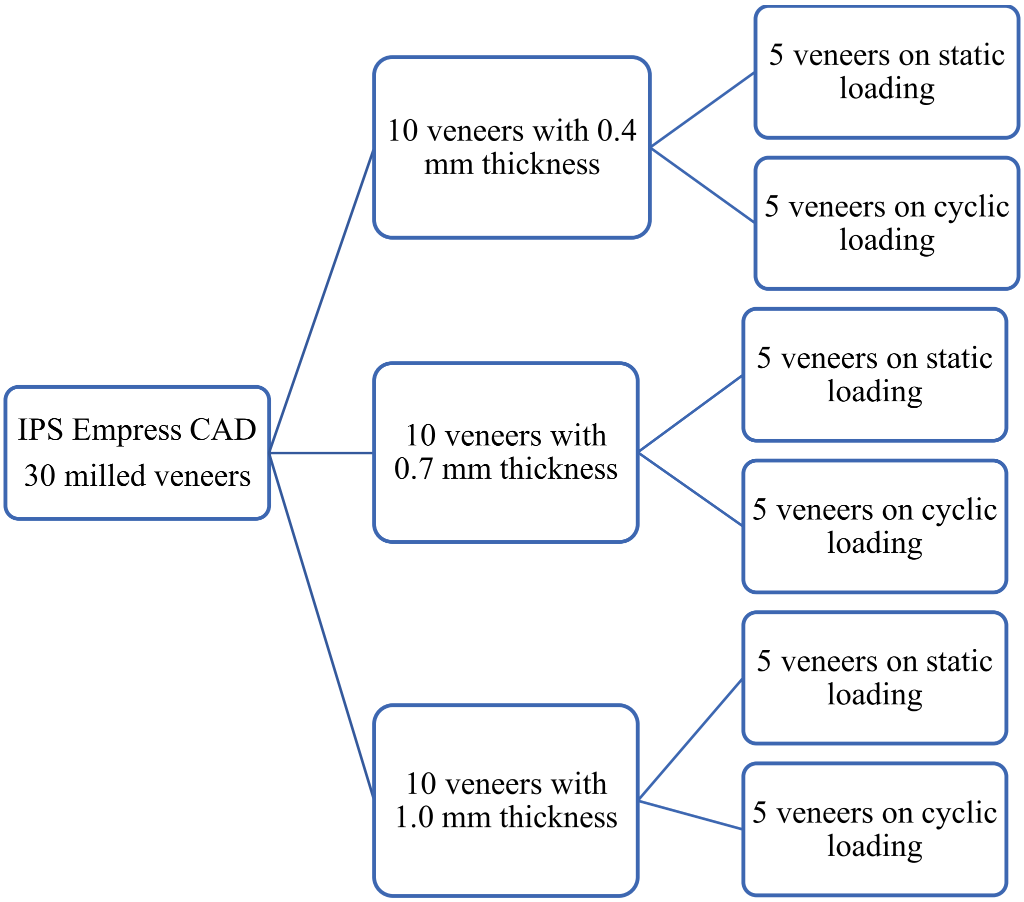
Table 1: Materials used in this study

Material	**Composition wt%**
IPS Empress CAD (Ivoclar Vivadent, Liechtenstein)	Luecite-reinforced glass ceramic SiO_2:60.0-65.0%, Al_2O_3:16.0-20.0%, K_2O:10.0-14.0%, Na_2O: 3.5-6.5%, other oxides 0.5-7.0%, pigments 0.2-1.0%
IPS e. max CAD (Ivoclar Vivadent, Liechtenstein).	Lithium disilicate glass-ceramic SiO_2 57.0-80.0%, Li_2O 11.0-19.0%, K_2O 0.0-13.0%, P_2O_5 0.0-11.0%, ZrO_2 0.0-8.0 %, ZnO 0.0-8.0%, Al_2O_3 0.0-5.0%, MgO 0.0-5.0%, Coloring oxides 0.0-0.8%
VITA ENAMIC (Vita Zahnfabrik, Germany)	Interpenetrated phase ceramic SiO_2 58.0-63.0%, Al_2O_3 20.0-23.0%, Na_2O 6.0-11.0%, K_2O 4.0-6.0%, B_2O_3 0.5-2.0%, CaO<1, TiO_2<1
Lava Ultimate (3M ESPE, USA)	Resin composite Nano ceramic silica and zirconia particles 80.0% embedded in a highly cross-linked polymer matrix

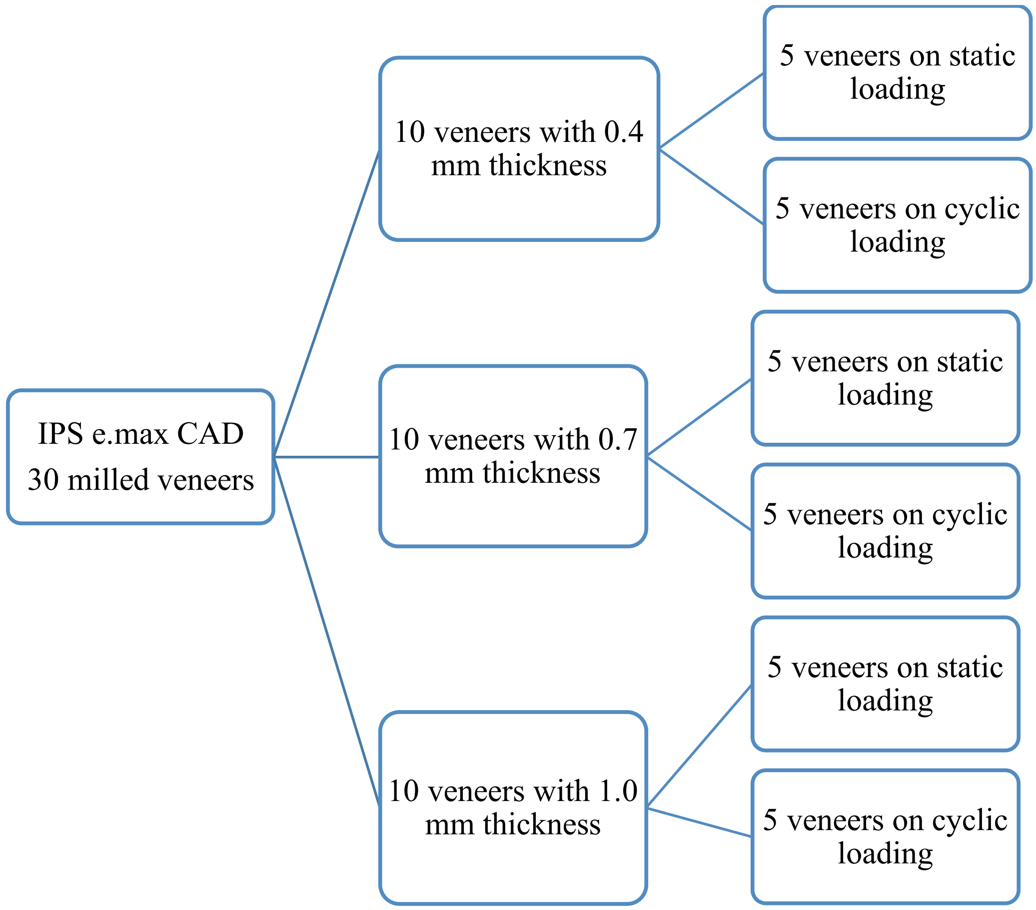
Variolink Veneer (Ivoclar Vivadent, Liechtenstein)	Light curing resin cement Urethane dimethacrylate, inorganic fillers, Ytterbium trifluoride, initiators, stabilizers, pigments ExciTE F DSC A dual cure, fluoride releasing adhesive **Adhesive** — **Wt%** Phosphonic acid acrylate, dimethacrylates, Hydroxyethyl methacrylate — 72.0% Highly dispersed silicone dioxide — 0.5% Ethanol — 24.5% Catalysts, stabilizers, fluoride — 3.0% **Applicator** coated with initiators Monobond Plus Ethanol 50-100%, Trimethoxysilylpropyl methacrylate ≤ 2.5% Methacrylated phosphoric acid ester ≤ 2.5%
3M epoxy resin DP100 FR	Epoxy adhesive Polyurethane, acrylic, cyanoacrylate and others

Table 2: Physical properties of materials used in the study

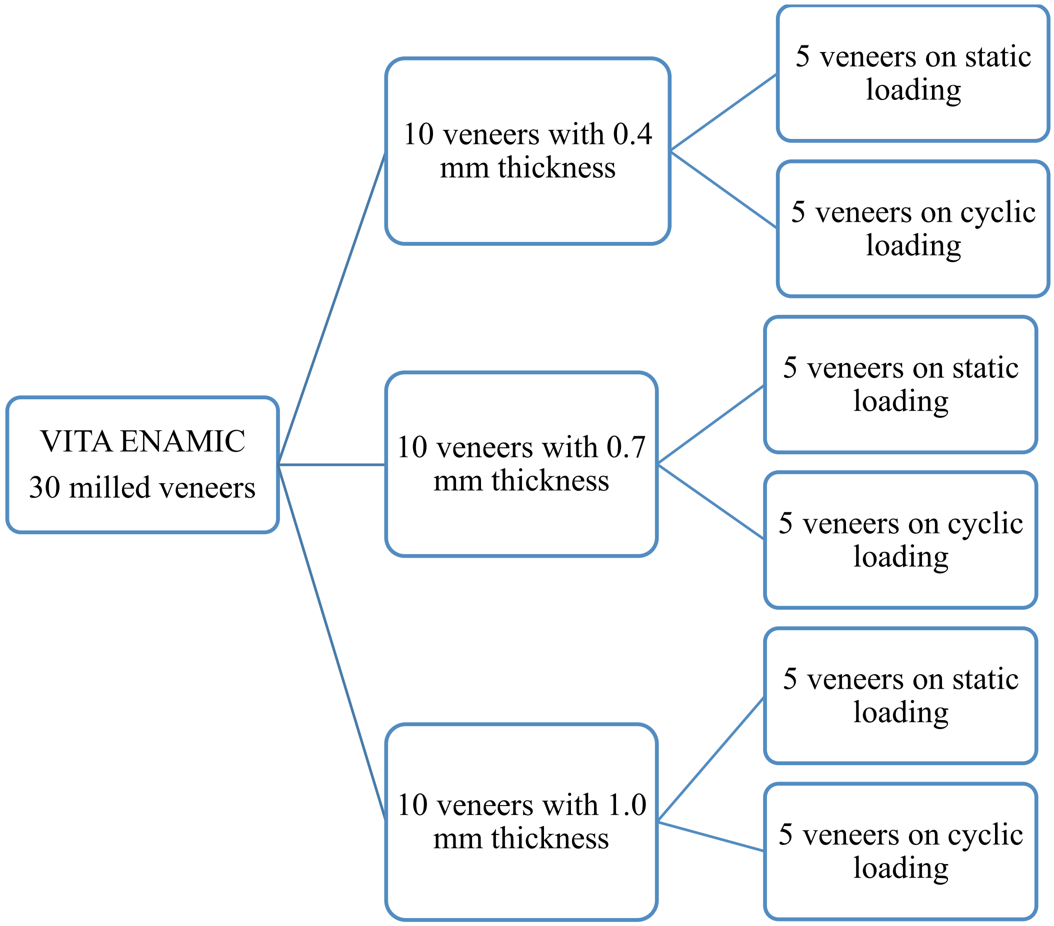
Material	Coefficient of Thermal expansion ($10^{-6} \cdot K^{-1}$)	Flexural Strength (MPa)	Fracture Toughness ($MPa \cdot m^{1/2}$)	Modulus of Elasticity (GPa)
IPS Empress CAD	100-400°C 16.6 100-500°C 17.5	160	1.3	62
IPS e. max CAD	100-400°C 10.2 100-500°C 10.5	360 - 400	2.25	95
VITA ENAMIC		150-160	1.5	30
Lava Ultimate		204	2.02	12.77



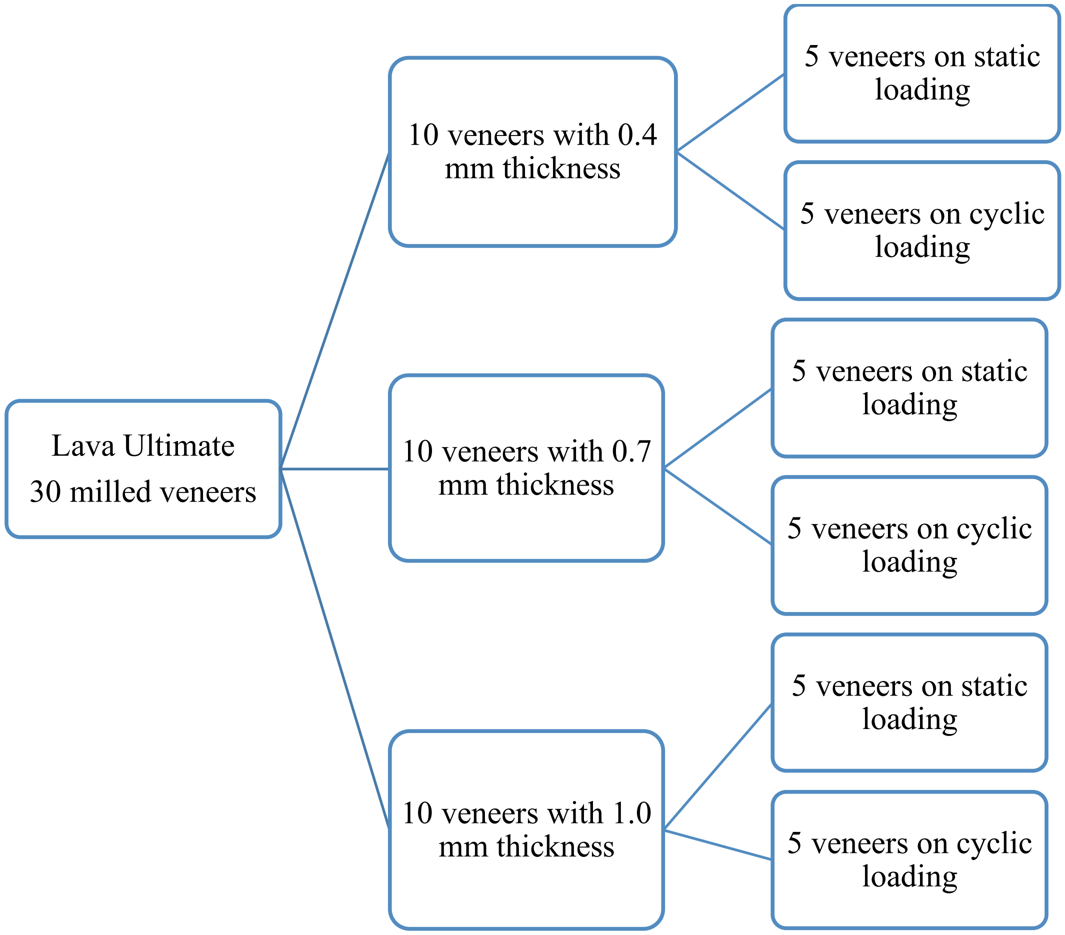
Graph 1: Study design, IPS Empress CAD



Graph 2: Study design, IPS e.max CAD



Graph 3: Study design, VITA ENAMIC



Graph 4: Study design, Lava Ultimate

Preparation of Anterior Veneers:

An ivorine typodont right central incisor (Model #D95SDP-200; Kilgore International, Inc., Coldwater, MI) (Figure 1) was selected to receive a veneer preparation. The tooth was prepared with a diamond rotary cutting instrument from a veneer preparation set (Brasseler USA® Dental, Savannah, GA). It was prepared with an incisal overlap preparation (IOP) having 0.5 mm depth reduction at the middle and incisal thirds and 0.3 mm chamfer margin placed 1.0 mm above the CEJ. The incisal edge was reduced 2.0 mm with a palatal chamfer and the interproximal finish line was located facially to the proximal contacts. All specimens were done by the same operator. The typodont tooth was sprayed with IPS contrast spray lab side (Ivoclar Vivadent, Liechtenstein) and scanned using an inEos Blue scanning camera (Sirona, Bensheim Germany) (Figure 2). Ceramic veneers were designed using Sirona InLab 3D software SW4 4.2.5 (Figures 3,4) and the designs were saved and used for all successive veneers. Four different ceramic materials were selected for the study; namely IPS Empress CAD (Ivoclar Vivadent, Liechtenstein), IPS e.max CAD (Ivoclar Vivadent, Liechtenstein), VITA ENAMIC (Vita Zahnfabrik, Germany) and Lava Ultimate (3M ESPE,USA) (Figures 5-8). Veneers were milled into three different thicknesses (0.4 mm, 0.7 mm and 1.0 mm) using a Sirona InLab MCXL milling machine. At the conclusion of the milling process, veneers were thoroughly cleaned and dried (Figure 9). Specimens were cut from their respective blocks using a diamond disc. Veneers from IPS e.max CAD were subjected to crystallization firing using a Programat P300/G2, (Ivoclar Vivadent, Liechtenstein) (Figure 10) following manufacturer's instructions (Table 3).

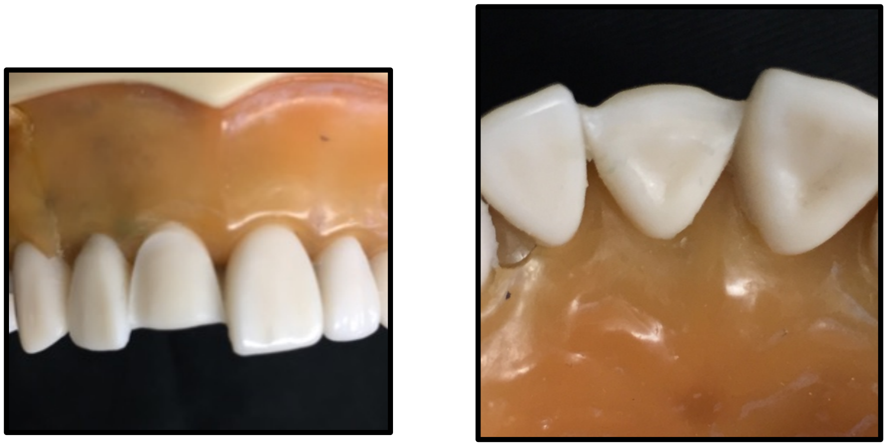


Figure 1: Right central incisor veneer preparation

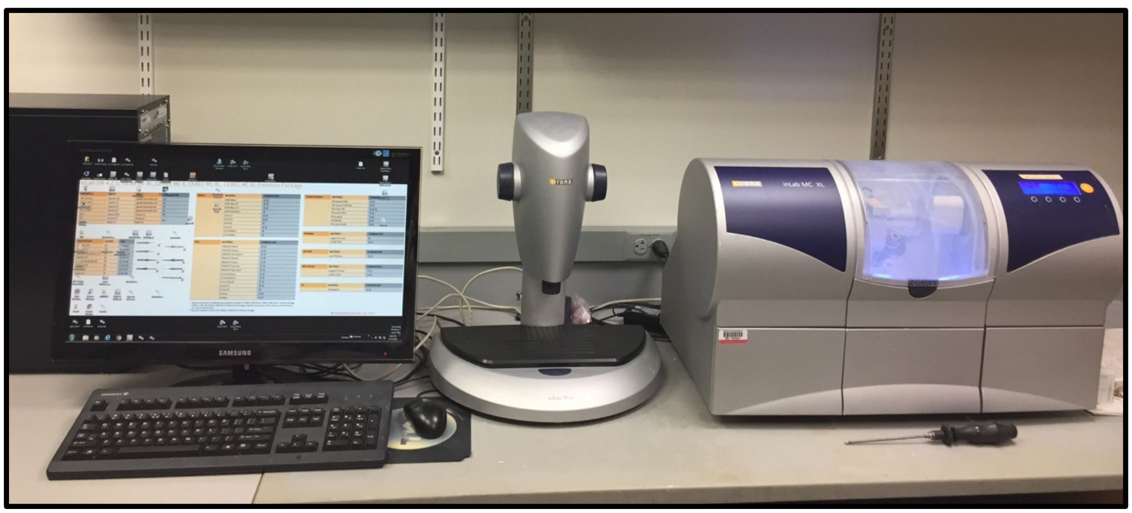


Figure 2: Sirona InLab Milling Machine and InEos Blue Scanner (Sirona, Bensheim Germany)

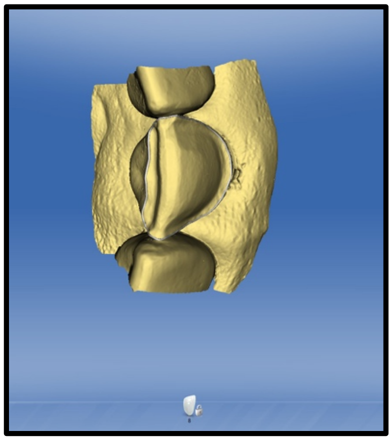


Figure 3: Typodont tooth scanned

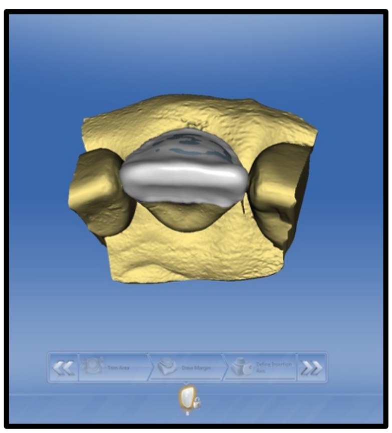


Figure 4: Veneer restoration design

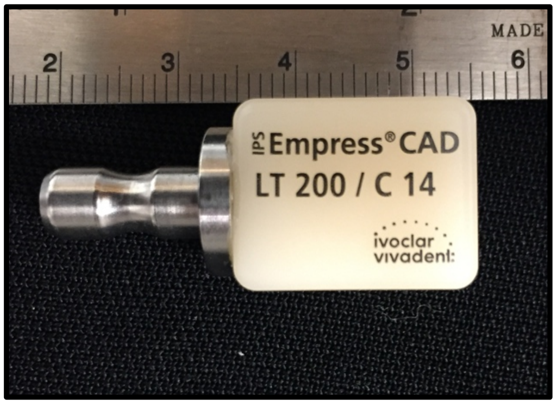


Figure 5: IPS Empress CAD block

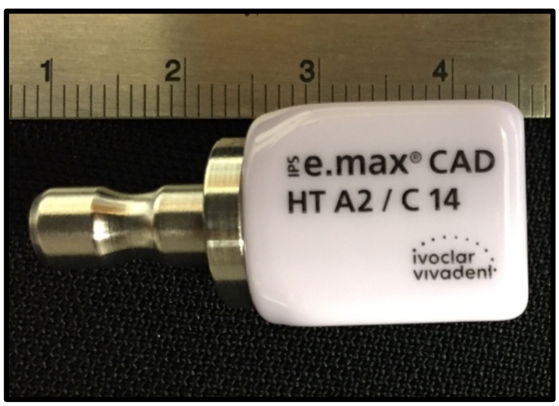


Figure 6: IPS e.max CAD block

Figure 7:VITA ENAMIC block

Figure 8: Lava Ultimate block

Figure 9: Milled veneer

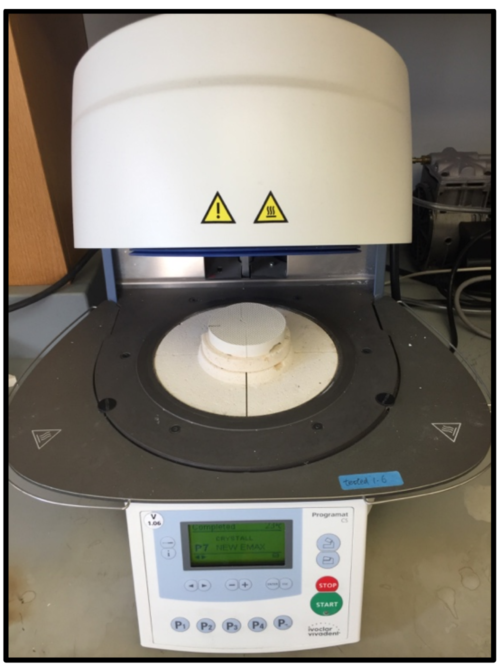


Figure 10: Programat CS furnace

Table 3: Crystallization firing steps for IPS e.max CAD

Stand-by temp. °C/°F	Closing Time min.	Heating rate °C/°F /min	Firing temp. °C/°F	Holding Time min.	Heating rate °C/°F /min	Firing temp. °C/°F	Holding time min.	Vacuum 1 1_1 °C/°F 1_2 °C/°F	Vacuum 2 2_1 °C/°F 2_2 °C/°F	Long term cooling °C/°F	Cooling rate °C/°F /min
403/757	6.00	90/162	820/1508	0:10	30/54	840/1544	7:00	550/820 1022/1508	820/840 1508/1540	700/1292	0

Marginal Chipping Measurement:

Milled veneers were inspected under the light microscope (IVS FSF Metallurgical Microscope, Zeiss, Germany) (Figure 11) by taking a series of images of the perimeter of the veneer to determine the marginal chipping. The chipping factor (CF) is an estimation of the degree of marginal chipping, which can be calculated by estimating the ratio of overall marginal chipping over the total marginal circumference of the restoration multiplied by 100 to give the percentage of chipping using the equation:

$$\mathbf{CF = \left[\frac{L}{P}\right] x100}$$

Where, L is the amount of marginal chipping and P is the marginal circumference of the restoration.

Eight samples from each group were inspected under the optical light microscope. The edge of each veneer was divided into four sections so that when the distance between two points was measured axially it would be a straight line. The samples were viewed with 10X magnification. The lengths of the chipped margins (L) of the veneers were measured with the x axis by calculating the mean of the chips for each veneer (Figures 12-15). The maximum veneer margin periphery (P) was measured and the chipping factor (CF) for each veneer was calculated using the equation above.

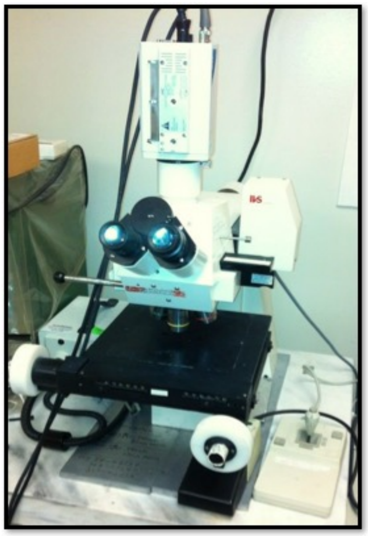


Figure 11: IVS FSF metallurgical light microscope

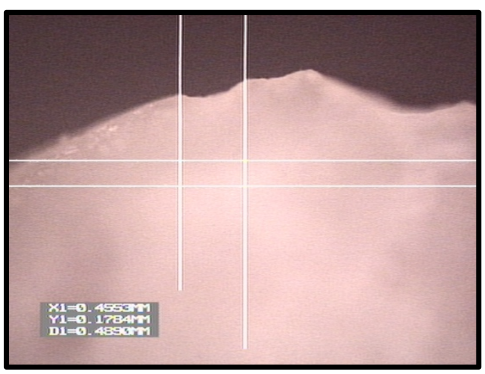


Figure 12: Measuring the length of the chipped margin of IPS Empress CAD 0.4mm thickness

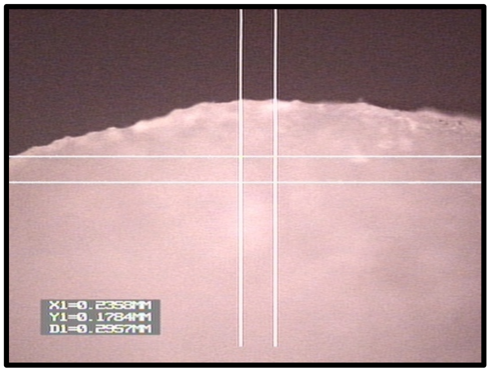


Figure 13: Measuring the length of the chipped margin of IPS e.max CAD 0.4mm thickness

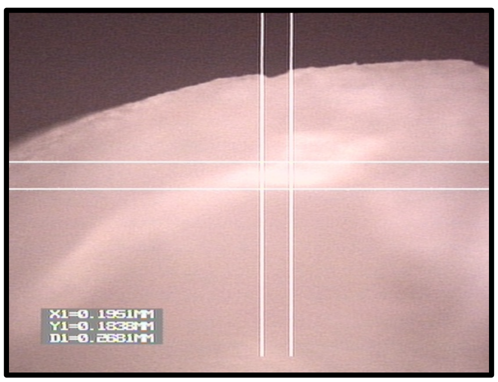


Figure 14: Measuring the length of the chipped margin of VITA ENAMIC 0.4mm thickness

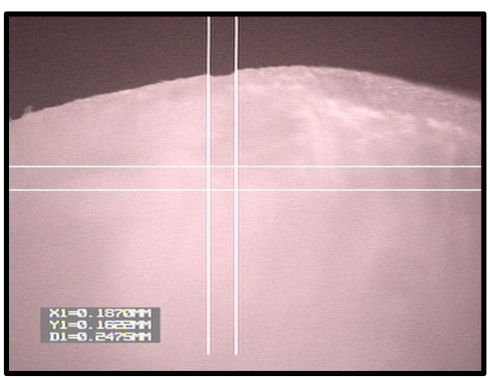


Figure 15: Measuring the length of the chipped margin of Lava Ultimate 0.4mm thickness

Fabrication of Abutments:

The prepared ivorine central incisor was used as the master tooth to fabricate 120 prepared tooth replicas using highly filled epoxy resin (3M™ Scotch-Weld™ Epoxy Adhesive 100FR, 3M ESPE, USA) (Figure 16). This material has a modulus of elasticity of 75 GPa which is similar to human enamel. An impression of the prepared tooth was made according to the manufacturer's instructions (Aquasil Ultra LV wash material regular set and Aquasil Ultra rigid tray material regular set, Dentsply Caulk, Milford, DE) (Figure 17). Epoxy resin was poured in the impression to fabricate the master die which was used to fabricate all 120 tooth replicas. The master die was fixed at a 125° angle between the long axis of the abutment and the horizontal plane of the abutment holder (Figure 18) to simulate the position at which forces are applied on a central incisor in the patient's mouth. Molds of the epoxy resin master die were fabricated using (PlatSil® 73-25 Silicone Rubber, Polytek Development Corp., Easton, PA) (Figure 19) (Table 4). After the molds were cured, epoxy resin was injected in the mold and left for 24 hours to reach its full cure (Figure 20-21). Each mold was used to fabricate four tooth replicas which result in 30 molds in total.

Table 4: Specifications of PlatSil® 73-25 Silicone Rubber Material

Mix Ratio	Shore Hardness	Pour Time	Cured Color	Mixed Viscosity	Specific Volume	Demold Time
1A:1B	A25	15 min.	Green	6,000 cP	24.3 in^3/lb	4-5 hr.

Figure 16: Highly filled epoxy resin adhesive

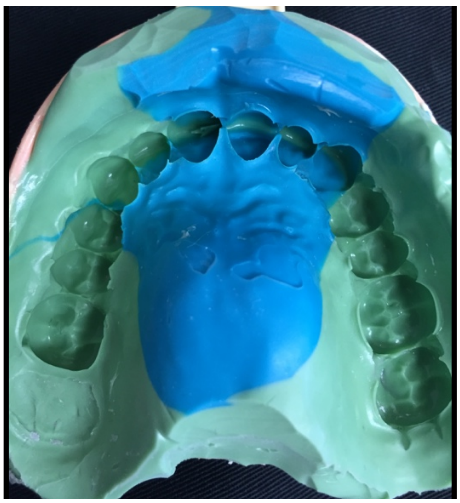


Figure 17: Impression of the prepared tooth using Aquasil ultra LV and heavy material

Figure 18: Epoxy resin master die fixed at 125° angle

Figure 19: PlatSil® 73-25 silicone rubber material

Figure 20: Silicone rubber material mold after curing

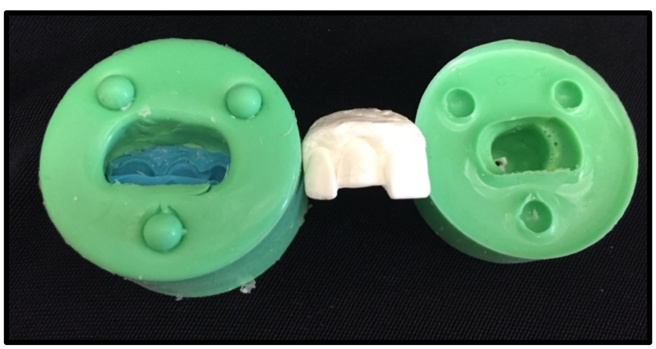


Figure 21: Cured epoxy resin abutment

Cementation of Veneers:

The internal surfaces of the veneers were etched with 5% hydrofluoric acid etching gel (IPS Ceramic Etch Gel, Ivoclar Vivadent, Liechtenstein) for 60 seconds. After that, the etched surfaces were rinsed with water spray for 60 seconds (Figure 22), cleaned in ultrasonic cleaner for 5 minutes then dried with compressed oil-free air for 20 seconds. Monobond plus was applied to the pre-treated surfaces with a brush and left to react for 60 seconds. Then it was dispersed with a strong stream of air. A thin layer of luting composite resin cement (Variolink Veneer, Ivoclar Vivadent, Liechtenstein) (Figure 23) was applied on the inner surfaces of the veneers and then seated on their respective epoxy resin replicas with finger pressure. A small area of the veneer was light-cured for a few seconds to tack the restoration in place and the excess cement was removed. Last, the veneer was cured from all areas for 40 seconds to complete the cure.

Figure 22: 5% hydrofluoric acid, IPS Ceramic etching gel

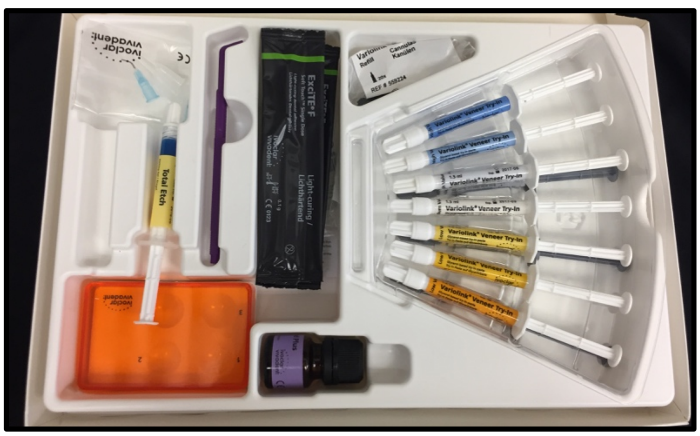


Figure 23: Luting composite resin cement, Variolink Veneer

Mechanical Testing:

Five specimens per group were loaded under compression with a 6mm diameter stainless steel ball using an Instron universal testing machine (Model 5566A, Instron Co., Canton, MA) at 0.5 mm/minute rate until fracture (Figures 24-25). The Instron machine was connected to a computer with a specifically designed program (BlueHill 3 software, Instron, Norwood, MA). This software controlled the testing machine and recorded the breakage load of the veneer. Failure was defined as occurrence of visible cracks, porcelain chipping, or audible events accompanied by a drop in the load by 20%.

Another five specimens were subjected to cyclic loading by pneumatic powered cylinder and an electronic control device (Pober Industries, Waban MA) (Figures 26-28). The peak load applied on each specimen represented 30% of the mean fracture load of each material for 30,000 cycles at a frequency of 1 Hz. The load was applied perpendicular to and at the center of the veneers by 6mm stainless steel balls. After cyclic loading was completed, the remaining samples were loaded in the universal testing machine under compression at 0.5mm/ minute until fracture occurred. Failure loads in Newtons were determined and compared. Failure modes; cohesive failure (veneer chipping), adhesive failure (veneer delamination) or catastrophic fracture (total fracture extending through the veneer and abutment) were observed and recorded after each test.

Figure 24: Universal testing machine with BlueHill software

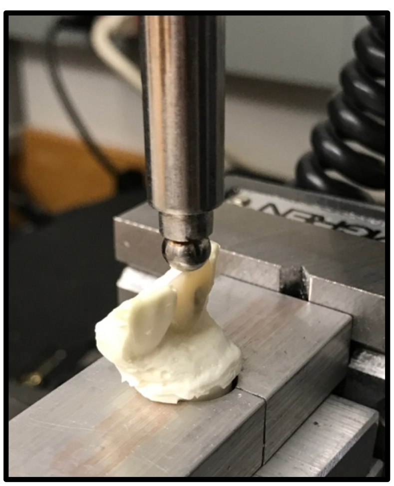


Figure 25: Testing setup at the universal testing machine

Figure 26: Plastic specimen holder for the cyclic loading

Figure 27: Cyclic loading apparatus, Pober Industries, Waban MA

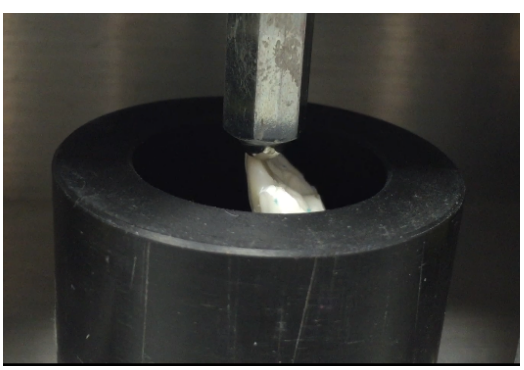


Figure 28: Testing setup at the cyclic loading machine

Microscopic Examination:

Optical Microscope:

Two specimens were randomly selected from each group, cleaned in ultrasonic cleaner for 5 minutes then then dried with compressed oil-free air for 20 seconds. Samples were examined under a light microscope (Ultra Swift Lite Illumination system, Carlsbad, CA) at different magnifications (Figure 29).

Figure 29: Ultra Swift Light microscope

Statistical Analysis:

Mean, standard deviation, and coefficient of variation for each group were calculated using Microsoft Excel software 2016 for Mac. The JMP Statistical Discovery from SAS software (SAS Campus Drive. Cary, NC, USA) was used for statistical analysis.

The failure load was analyzed with one-way ANOVA with material thickness as an independent variable while controlling other variables (fatigue and material type), comparisons for all pairs was done using Tukey-Kramer HSD. A significance level of 0.05 was used.

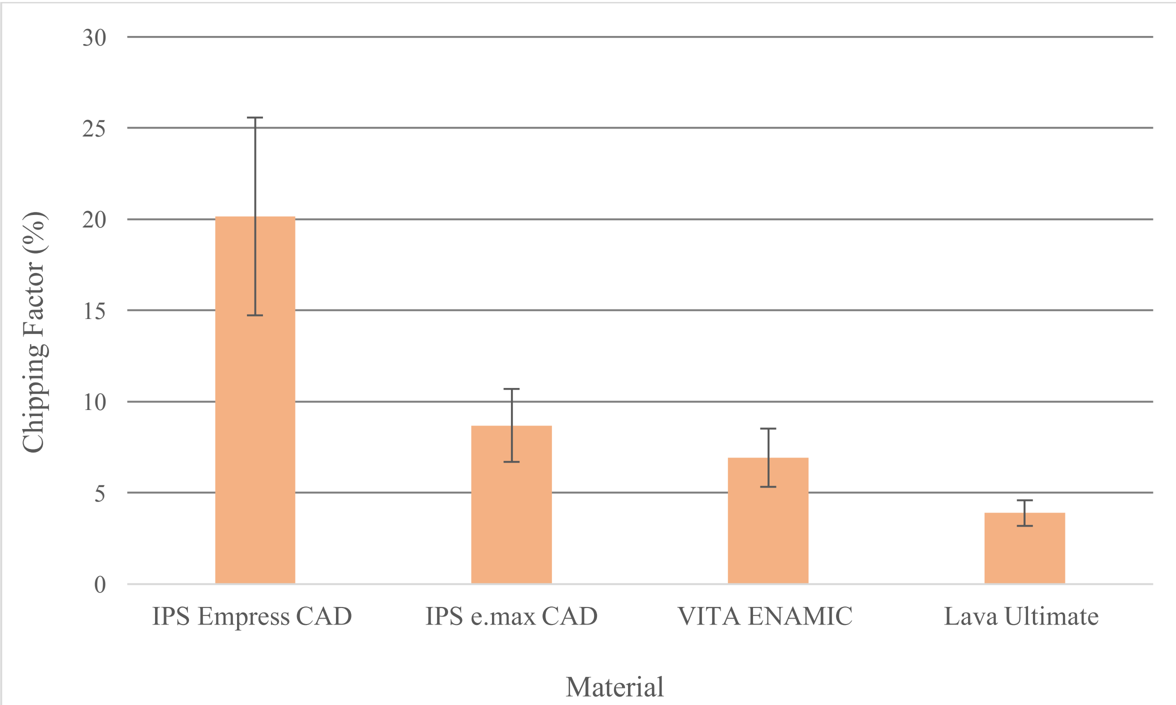
RESULTS

1. Chipping Factor:

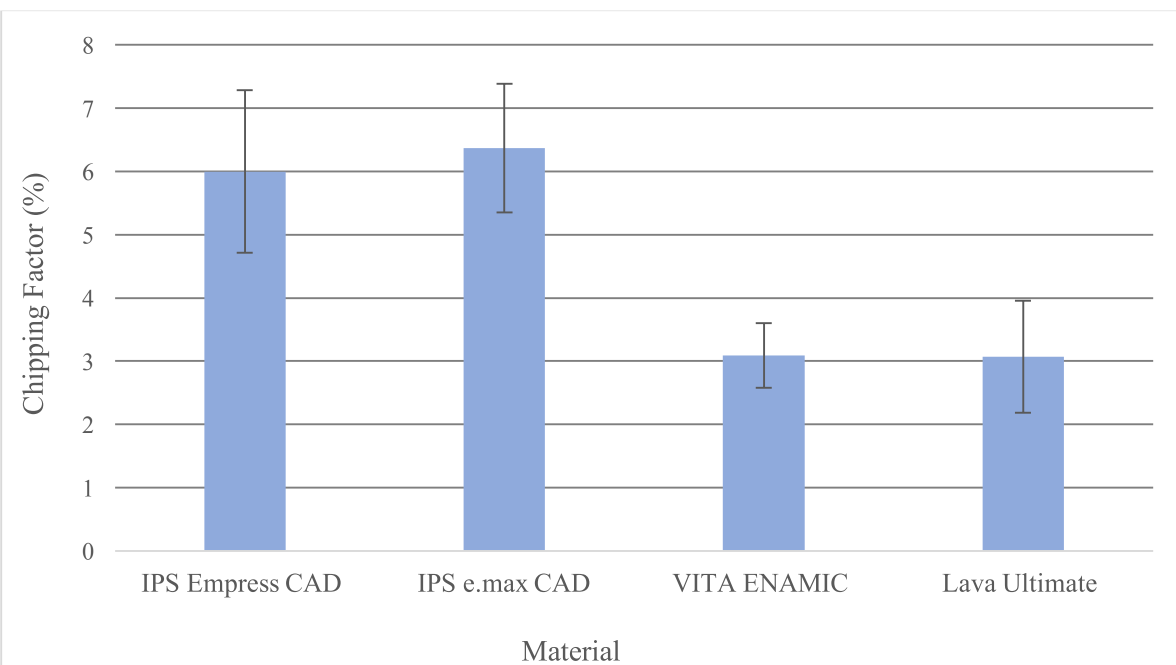
The chipping factor (CF) of four different materials with three different thicknesses (0.4mm, 0.7mm and 1.0mm) were tested in the study. The mean chipping factor (CF) and standard deviations (SD) of each material are given in (Table 5). The IPS Empress CAD 0.4mm marginal chipping was significantly greater than that of all other groups. Conversely, VITA ENAMIC 0.7mm and Lava Ultimate 0.7mm marginal chipping were significantly less than IPS Empress CAD 0.7mm and IPS e.max CAD 0.7mm. There was no significant difference between materials at 1.0mm thickness. (Graph 5-7). The null hypothesis, that there is no significant difference in the marginal chipping of veneers made with different ceramic materials by calculating the chipping factor (CF), was rejected. Levels not connected with same letter were significantly different (Table 6).

Table 5: Descriptive statistics of chipping factor (CF) of different veneer materials

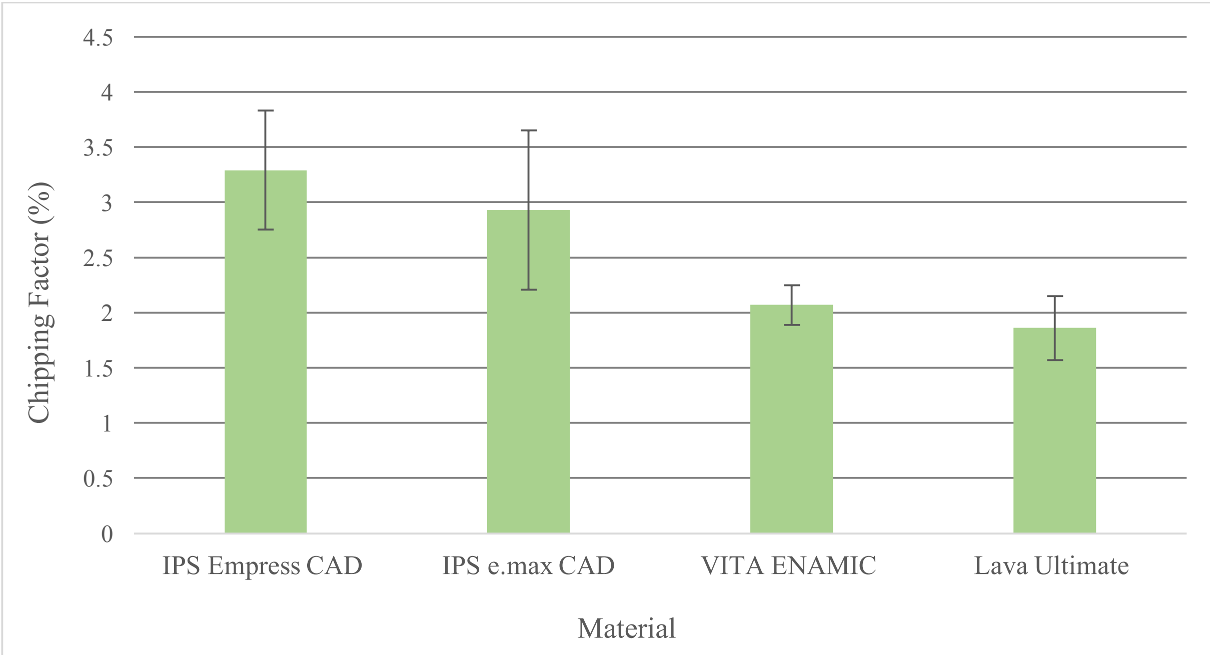
Material/Thickness	Mean CF (%)	Standard Deviation	COV
IPS Empress CAD 0.4mm	20.15	5.42	26.90
IPS Empress CAD 0.7mm	6	1.29	21.50
IPS Empress CAD 1.0mm	3.29	0.54	16.41
IPS e.max CAD 0.4mm	8.69	2.01	23.13
IPS e.max CAD 0.7mm	6.37	1.02	16.01
IPS e.max CAD 1.0mm	2.93	0.72	24.57
VITA ENAMIC 0.4mm	6.92	1.59	22.98
VITA ENAMIC 0.7mm	3.09	0.51	16.50
VITA ENAMIC 1.0mm	2.07	0.18	8.70
Lava Ultimate 0.4mm	3.9	0.7	17.95
Lava Ultimate 0.7mm	3.07	0.89	28.99
Lava Ultimate 1.0mm	1.86	0.29	15.59



Graph 5: Mean values of chipping factor(CF) of different veneer materials at 0.4 mm thickness



Graph 6: Mean values of chipping factor(CF) of different veneer materials at 0.7 mm thickness



Graph 7: Mean values of chipping factor(CF) of different veneer materials at 1.0 mm thickness

Table 6: Comparison of chipping factor of all materials using Tukey-Kramer HSD

Level	Significant Difference	Mean CF (%)
IPS Empress CAD 0.4mm	A	20.15
IPS e.max CAD 0.4mm	B	6
VITA ENAMIC 0.4mm	B C	3.29
IPS e.max CAD 0.7mm	B C D	8.69
IPS empress CAD 0.7mm	B C D E	6.37
Lava Ultimate 0.4mm	C D E F	2.93
IPS Empress CAD 1.0mm	D E F	6.92
VITA ENAMIC 0.7mm	E F	3.09
Lava Ultimate 0.7mm	E F	2.07
IPS e.max CAD 1.0mm	E F	3.9
VITA ENAMIC 1.0mm	F	3.07
Lava Ultimate 1.0mm	F	1.86

2. Mechanical Testing:

Four different CAD/CAM materials milled at three different thicknesses (0.4 mm, 0.7 mm, 1.0 mm) and subjected to static and cyclic loading were used in this study. Failure loads in Newtons and failure modes were registered.

IPS Empress CAD

The mean failure load (with standard deviation) values for IPS Empress CAD at different thicknesses (0.4mm, 0.7mm, 1.0mm) under static loading were as follows: 435.43(112.42), 740.51(105.69), 656.60 (85.83). There was a significant difference between 0.4mm thickness and 0.7mm thickness and between 0.4mm thickness and 1.0mm thickness. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under static loading, was rejected.

The mean failure load (with standard deviation) values for IPS Empress CAD at different thicknesses (0.4mm, 0.7mm, 1.0mm) under cyclic loading were as follows: 487.04 (110.93), 704.68 (219.83), 741.11 (126.71). There was no significant difference in the cyclic fatigue of IPS Empress CAD at different thicknesses. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under cyclic loading, was accepted.

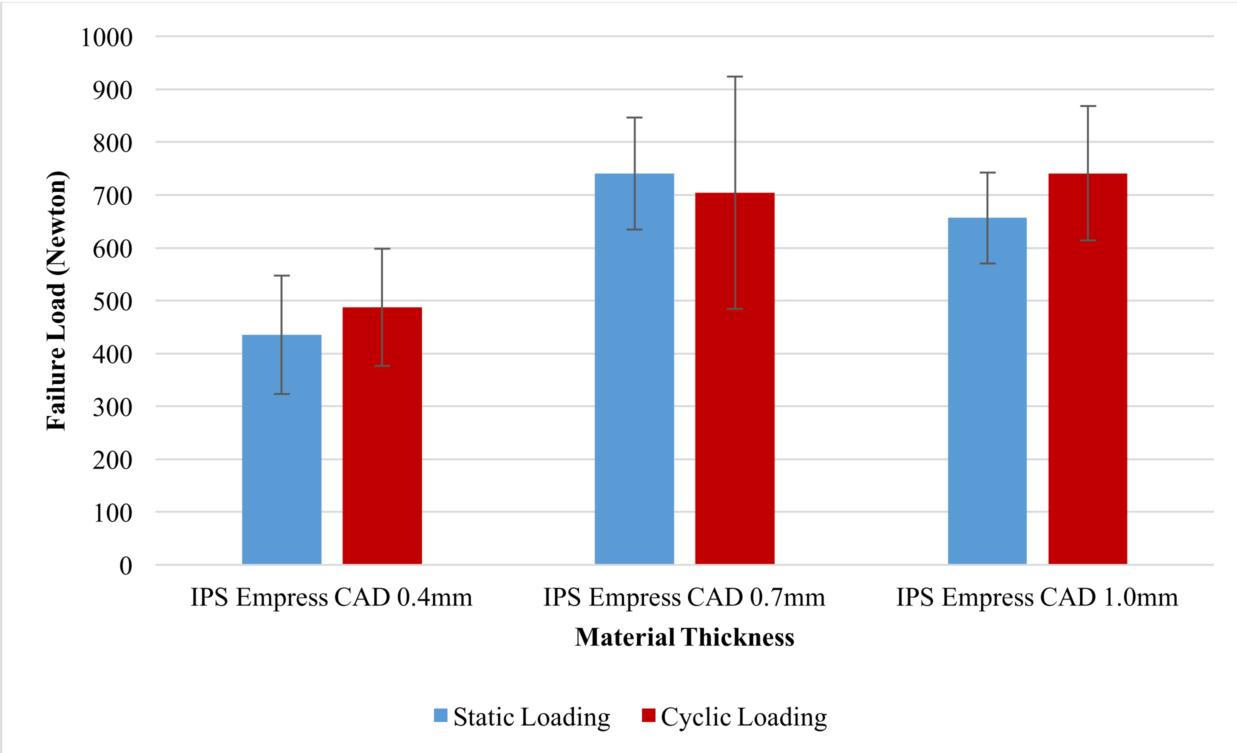
20% of IPS Empress CAD at 0.4 mm and 60% at 0.7 mm were cracked or fractured during cyclic loading.

Descriptive statistics for all groups are available in Table 7.

Table 7: Descriptive statistics of failure loads of different thicknesses of IPS Empress CAD under static and cyclic loading

Material	Loading Type	Mean Failure load (Newton)	Standard Deviation	Coefficient of Variation
IPS Empress CAD 0.4mm	Static Loading	435.43	112.42	25.81
	cyclic fatigue	487.04	110.93	22.77
IPS Empress CAD 0.7mm	Static Loading	740.51	105.69	14.27
	cyclic fatigue	704.68	219.68	31.19
IPS Empress CAD 1.0mm	Static Loading	656.60	85.83	13.07
	cyclic fatigue	741.11	126.71	17.09

Graph 8: Mean values of failure loads of different IPS Empress CAD thickness under static and cyclic loading



Comparing the data of static and cyclic fatigue within the same group, there is no significant difference between static and cyclic fatigue. The null hypothesis, that cyclic fatigue has no significant effect on the failure load of different veneering materials and thicknesses, was accepted. However, comparing the data between groups, there is a significant difference between 0.4mm thickness (static and cyclic) and 0.1mm thickness (cyclic) and between 0.4mm thickness (static and cyclic) and 0.7mm thickness (static) (Graph 6). Levels not connected by the same letter are statistically different (Table 8).

Table 8: Comparison of all IPS Empress CAD thicknesses under static and cyclic loading using Tukey-Kramer HSD

Level			Mean
IPS Empress CAD 1.0mmC	**A**		741.11
IPS Empress CAD 0.7mm	**A**		740.51
IPS Empress CAD 0.7mmC	**A**	**B**	704.68
IPS Empress CAD 1.0mm	**A**	**B**	656.6
IPS Empress CAD 0.4mmC		**B**	487.04
IPS Empress CAD 0.4mm		**B**	435.43

IPS e.max CAD

The mean failure load (with standard deviation) values for IPS e.max CAD at different thicknesses (0.4mm, 0.7mm, 1.0mm) under static loading were as follows: 676.66 (152.83), 854.65 (142.87), 905.33 (101.56). There was a significant difference between 0.4mm thickness and 1.0 thickness and there were no significant differences between 0.4 mm and 0.7 mm thickness or between 0.7 and 1.0 mm thickness. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under static loading, was rejected.

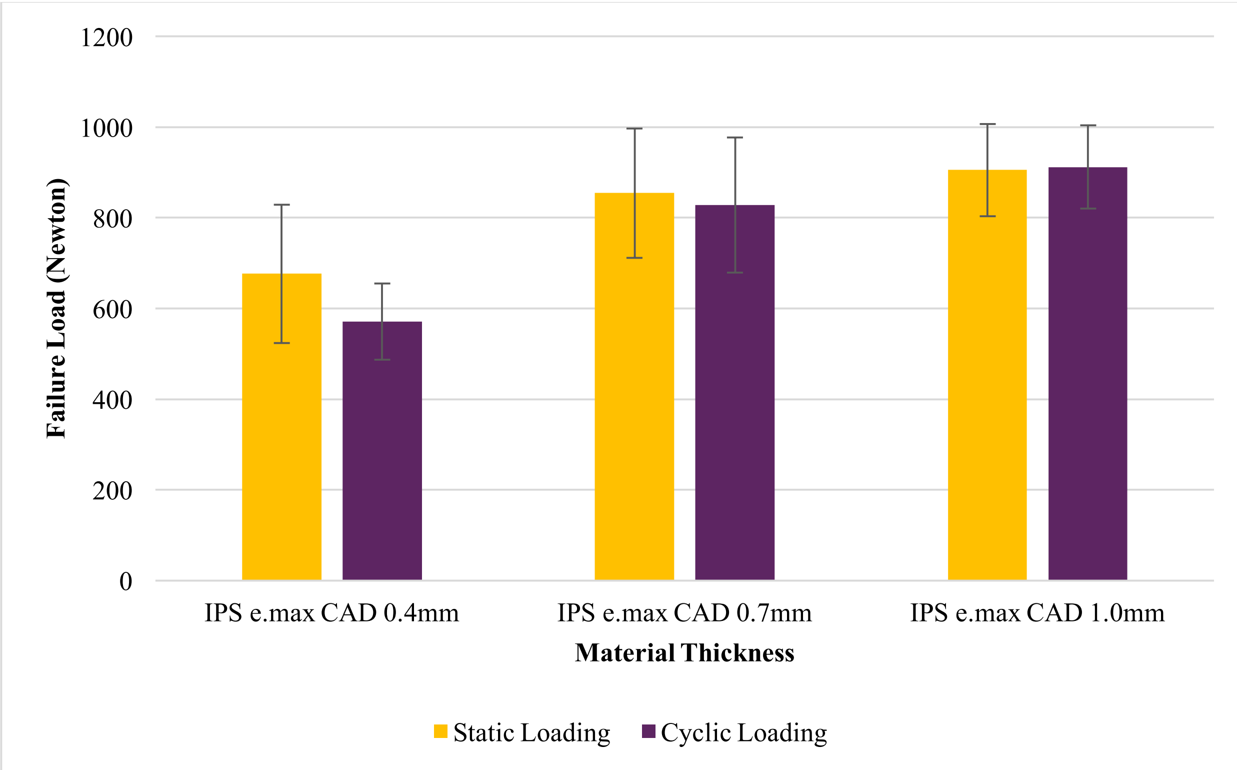
The mean failure load (with standard deviation) values for IPS e.max CAD at different thicknesses (0.4mm, 0.7mm, 1.0mm) under cyclic loading were as follows: 571.90 (84.18), 828.07 (148.57), 911.97 (92.10). There was a significant difference between 0.4 mm and 0.7 mm thickness and between 0.4 mm and 1.0 mm thickness after cyclic fatigue whereas there was no significant difference between 0.7 mm and 1.0 mm thickness. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under cyclic loading, was rejected.

Descriptive statistics for all groups are available in Table 9.

Table 9: Descriptive statistics of failure loads of different thicknesses of IPS e.max CAD under static and cyclic loading

Material	Loading Type	Mean Failure load (Newton)	Standard Deviation	Coefficient of Variation
IPS e.max CAD 0.4mm	Static Loading	676.66	152.83	22.58
	cyclic fatigue	571.07	84.18	14.71
IPS e.max CAD 0.7mm	Static Loading	854.65	142.87	14.15
	cyclic fatigue	828.07	148.57	17.51
IPS e.max CAD 1.0mm	Static Loading	905.33	101.56	11.21
	cyclic fatigue	911.97	92.10	10.09

Graph 9: Mean values of failure loads of different IPS e.max CAD thickness under static and cyclic loading



Comparing the data of static and cyclic fatigue within the same group, there is no significant difference between static and cyclic fatigue. The null hypothesis, that cyclic fatigue has no significant effect on the failure load of different veneering materials and thicknesses, was accepted. However, comparing data between groups, there is a significant difference between 0.4 mm thickness (cyclic) and 0.7 mm thickness (static and cyclic). Moreover, there is a significant difference between 0.4 mm thickness (cyclic) and 1.0 mm thickness (static and cyclic) (Graph 7). Levels not connected by the same letter are significantly different (Table 10).

Table 10: Comparison of all IPS e.max CAD thicknesses under static and cyclic loading using Tukey-Kramer HSD

Level			Mean
IPS e.max CAD 1.0mmC	**A**		911.97
IPS e.max CAD 1.0mm	**A**		905.33
IPS e.max CAD 0.7mm	**A**		854.65
IPS e.max CAD 0.7mmC	**A**		828.07
IPS e.max CAD 0.4mm	**A**	**B**	676.66
IPS e.max CAD 0.4mmC		**B**	571.9

VITA ENAMIC

The mean failure load (with standard deviation) values for VITA ENAMIC at different thicknesses (0.4mm, 0.7mm, 1.0mm) under static loading were as follows: 734.67 (43.07), 672.88 (118.43), 759.26(149.94). There was no significant difference in the static fatigue of VITA ENAMIC at the different thicknesses. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under static loading, was accepted.

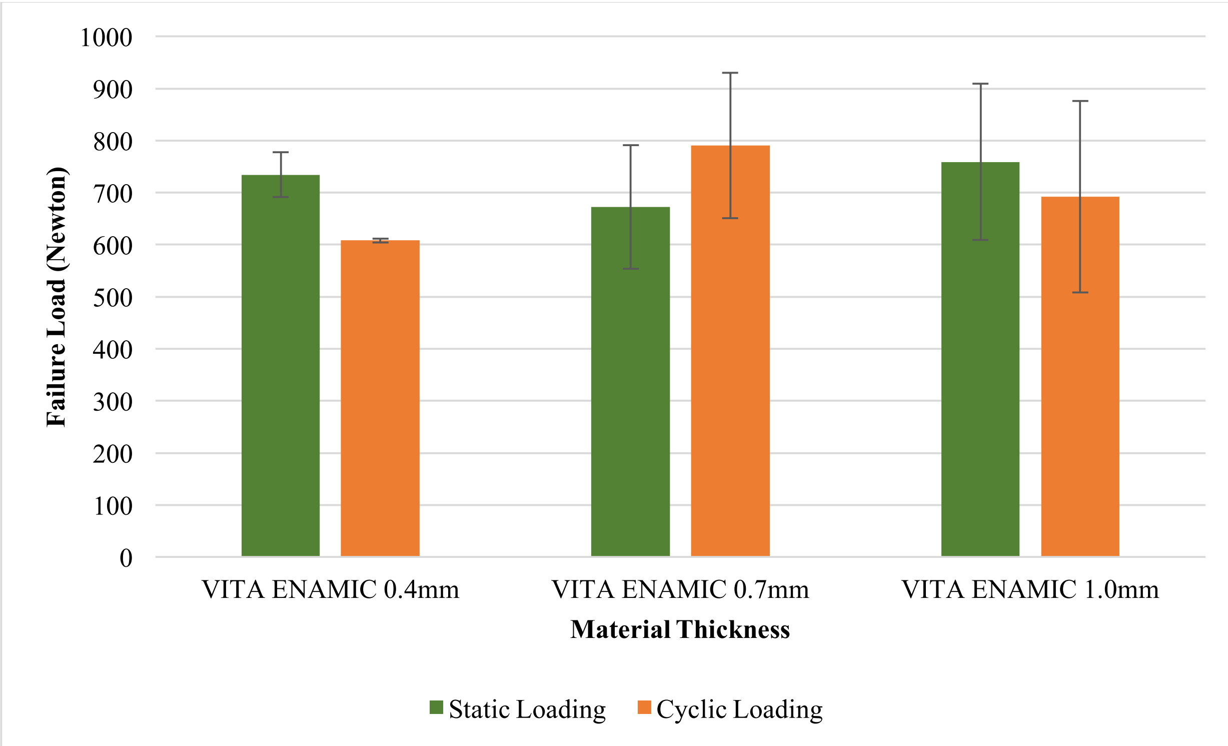
The mean failure load (standard deviation) values for VITA ENAMIC at different thicknesses (0.4mm, 0.7mm, 1.0mm) under cyclic loading were as follows: 608.06 (3.66). 790.68 (139.35), 692.62 (183.99). There was no significant difference in the cyclic fatigue of VITA ENAMIC at the different thicknesses. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under cyclic loading, was accepted.

40% of VITA ENAMIC at 1.0 mm were cracked or fractured during cyclic loading. Descriptive statistics for all groups are available in Table 11.

Table 11: Descriptive statistics of failure loads of different thicknesses of VITA ENAMIC under static and cyclic loading

Material	Loading Type	Mean Failure load (Newton)	Standard Deviation	Coefficient of Variation
VITA ENAMIC 0.4mm	Static Loading	734.67	43.07	32.4
	cyclic fatigue	608.06	3.66	0.69
VITA ENAMIC 0.7mm	Static Loading	672.88	118.43	17.6
	cyclic fatigue	790.68	139.35	17.62
VITA ENAMIC 1.0mm	Static Loading	759.26	149.94	19.74
	cyclic fatigue	692.62	183.99	26.56

Graph 10: Mean values of failure loads of different VITA ENAMIC thickness under static and cyclic loading



Comparing the data of static and cyclic fatigue of VITA ENAMIC show that cyclic loading had no statistically significant effect on the material (Graph 8). The null hypothesis, that cyclic fatigue has no significant effect on the failure load of different veneering materials and thicknesses, was accepted. Levels not connected by same letter are significantly different (Table 12).

Table 12: Comparison of all VITA ENAMIC thicknesses under static and cyclic loading using Tukey-Kramer HSD

Level		Mean
VITA ENAMIC 0.7mmC	**A**	790.68
VITA ENAMIC 1.0mm	**A**	759.26
VITA ENAMIC 0.4mm	**A**	734.67
VITA ENAMIC 1.0mmC	**A**	692.62
VITA ENAMIC 0.7mm	**A**	672.88
VITA ENAMIC 0.4mmC	**A**	608.06

Lava Ultimate

The mean failure load (with standard deviation) values for Lava Ultimate at different thicknesses (0.4mm, 0.7mm, 1.0mm) under static loading were as follows: 489.25(66.18), 565.86(83.95), 546.26(92.51). There was no significant difference in the static fatigue values of Lava Ultimate at different thicknesses. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under static loading, was accepted.

The mean failure load (with standard deviation) values for Lava Ultimate at different thicknesses (0.4mm, 0.7mm, 1.0mm) under cyclic loading were as follows: 556.21(143.97), 420.15(35.98), 565.0(89.29). There was no significant difference in the cyclic fatigue measurements of Lava Ultimate at different thicknesses. The null hypothesis, that there is no significant difference in the failure load of different veneering materials and thicknesses under cyclic loading, was accepted.

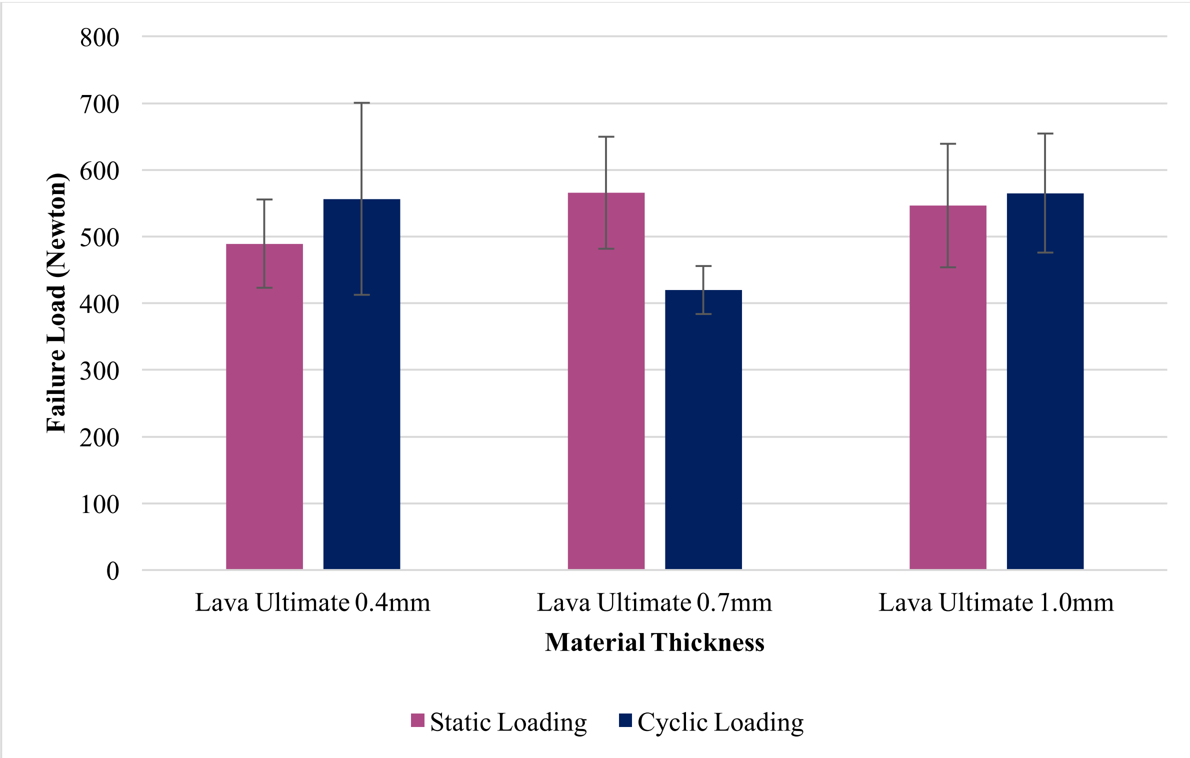
20% of Lava Ultimate at 0.4 mm, 0.7 mm and 1.0 mm thicknesses were cracked or fractured during cyclic loading.

Descriptive statistics for all groups are available in Table 13.

Table 13: Descriptive statistics of failure loads of different thicknesses of Lava Ultimate under static and cyclic loading

Material	Loading Type	Mean Failure load (Newton)	Standard Deviation	Coefficient of Variation
LAVA ULTIMATE 0.4mm	Static Loading	489.25	66.18	13.52
	cyclic fatigue	556.21	143.97	11.41
LAVA ULTIMATE 0.7mm	Static Loading	565.86	83.95	14.83
	cyclic fatigue	420.15	35.98	8.56
LAVA ULTIMATE 1.0mm	Static Loading	546.26	92.51	16.93
	cyclic fatigue	565.00	89.29	15.8

Graph 11: Mean values of failure loads of different Lava Ultimate thickness under static and cyclic loading



Comparing the data of static and cyclic fatigue of Lava Ultimate shows that cyclic loading had no statistically significant effect on the material (Graph 9). The null hypothesis, that cyclic fatigue has no significant effect on the failure load of different veneering materials and thicknesses, was accepted. Levels not connected by same letter are significantly different (Table 14).

Table 14: Comparison of all Lava Ultimate thicknesses under static and cyclic loading using Tukey-Kramer HSD

Level		Mean
Lava Ultimate 0.7mm	**A**	565.86
Lava Ultimate 1.0mmC	**A**	565
Lava Ultimate 0.4mmC	**A**	556.21
Lava Ultimate 1.0mm	**A**	546.26
Lava Ultimate 0.4mm	**A**	489.25
Lava Ultimate 0.7mmC	**A**	420.15

A statistically significant difference was observed in the failure load between groups under static loading (Graph 10). Failure load of IPS e.max CAD and VITA ENAMIC was significantly higher than IPS Empress CAD and Lava Ultimate. Levels not connected by same letter are significantly different (Table 15).

Graph 12: Mean values of failure load of different veneer materials of various thickness under static loading

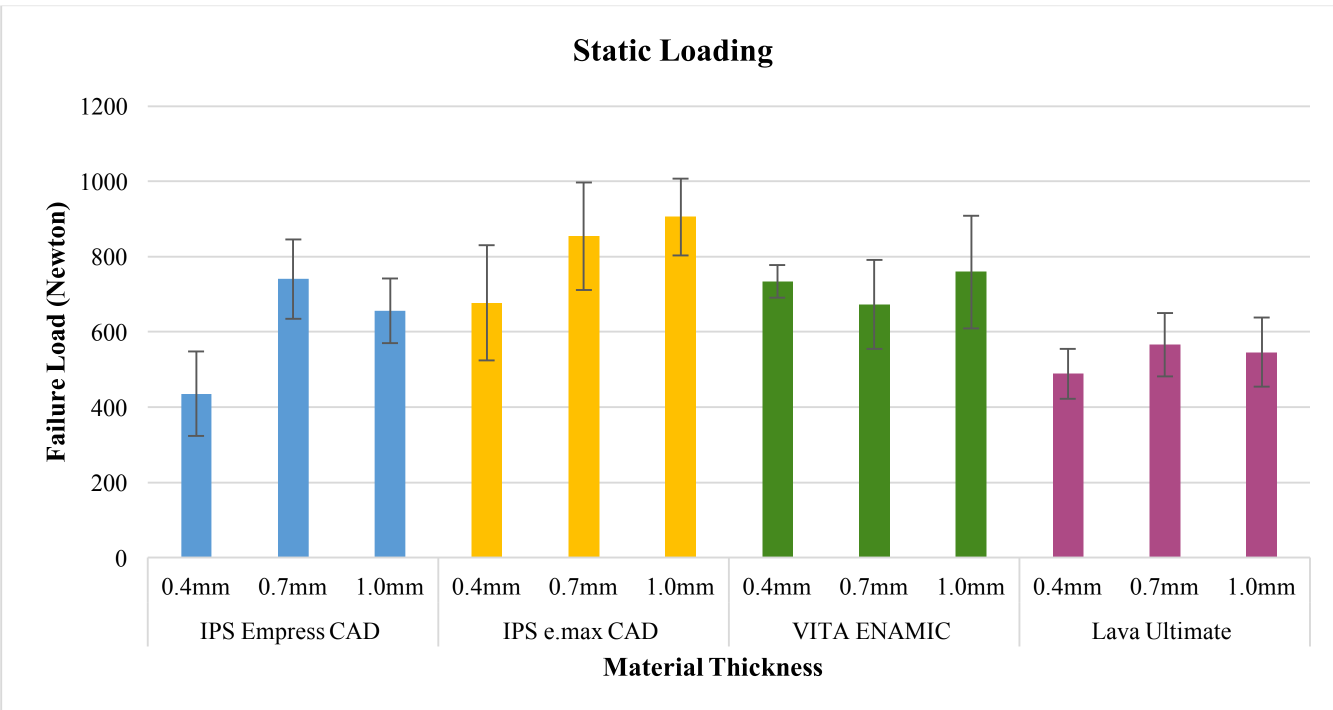


Table 15: Comparison of all veneer materials and thicknesses under static loading using Tukey-Kramer HSD

Level		
IPS e.max CAD 1.0mm	**A**	905.33
IPS e.max CAD 0.7mm	**A B**	854.65
VITA ENAMIC 1.0mm	**A B C**	759.26
IPS Empress CAD 0.7mm	**A B C**	740.51
VITA ENAMIC 0.4mm	**A B C**	734.67
IPS e.max CAD 0.4mm	**A B C D**	676.66
VITA ENAMIC 0.7mm	**A B C D E**	672.88
IPS Empress CAD 1.0mm	**A B C D E**	656.6
Lava Ultimate 0.7mm	**C D E**	565.86
Lava Ultimate 1.0mm	**C D E**	546.26
Lava Ultimate 0.4mm	**D E**	489.25
IPS Empress CAD 0.4mm	**E**	435.43

A statistically significant difference was observed in the failure load between groups under cyclic loading (Graph 11). Failure load of IPS e.max CAD, VITA ENAMIC and IPS Empress CAD was significantly higher than the load for Lava Ultimate. Levels not connected by same letter are significantly different (Table 16).

Graph 13: Mean values of failure load of different veneer materials of various thickness under cyclic loading

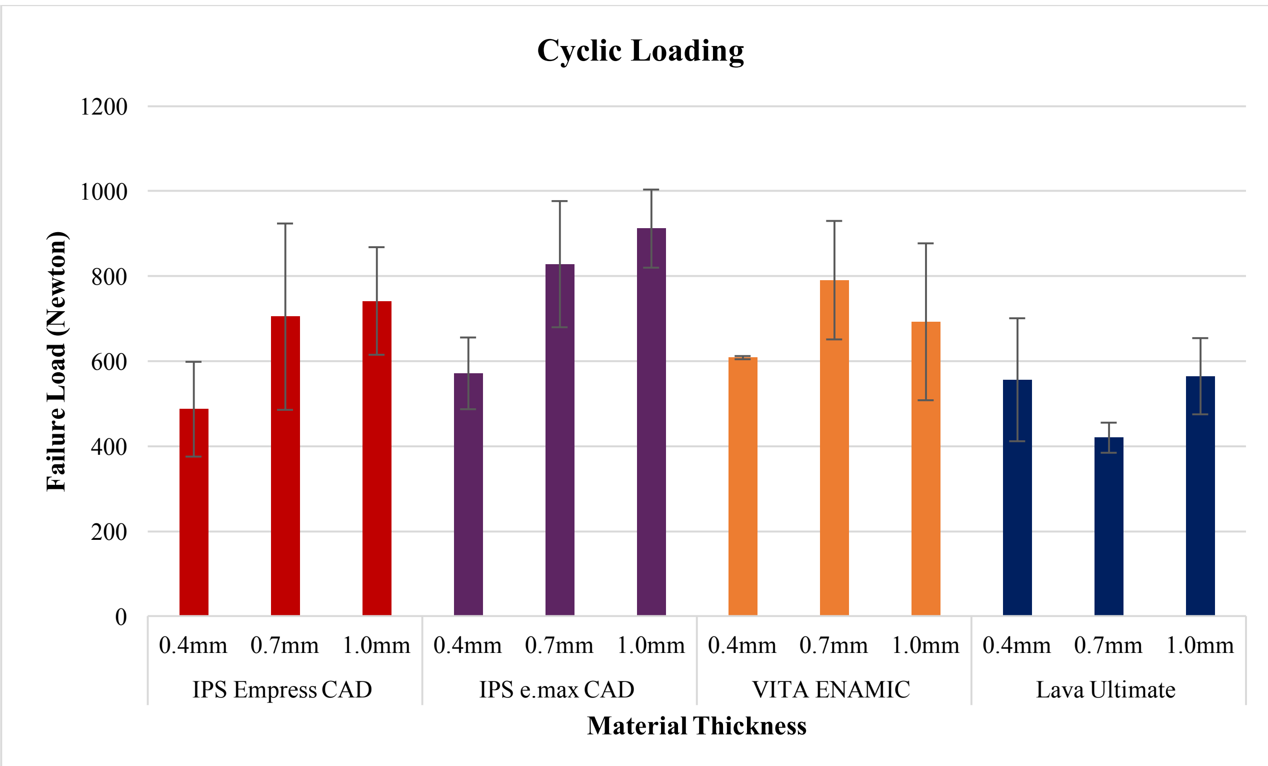


Table 16: Comparison of all veneer materials and thicknesses under cyclic loading using Tukey-Kramer HSD

Level					
IPS e.max CAD 1.0mmC	A				911.97
IPS e.max CAD 0.7mmC	A	B			828.07
VITA ENAMIC 0.7mmC	A	B			790.68
IPS Empress CAD 1.0mmC	A	B	C		741.11
IPS Empress CAD 0.7mmC	A	B	C	D	704.68
VITA ENAMIC 1.0mmC	A	B	C	D	692.62
VITA ENAMIC 0.4mmC		B	C	D	608.06
IPS e.max CAD 0.4mmC		B	C	D	571.9
Lava Ultimate 1.0mmC		B	C	D	565
Lava Ultimate 0.4mmC		B	C	D	556.21
IPS Empress CAD 0.4mmC			C	D	487.04
Lava Ultimate 0.7mmC				D	420.15

Comparison of all veneer materials of various thickness under static and cyclic loading was done with Tukey-Kramer HSD (Graph 12). Levels not connected by same letter are significantly different (Table 17).

Graph 14: Mean values of different veneer materials of various thickness under static and cyclic loading

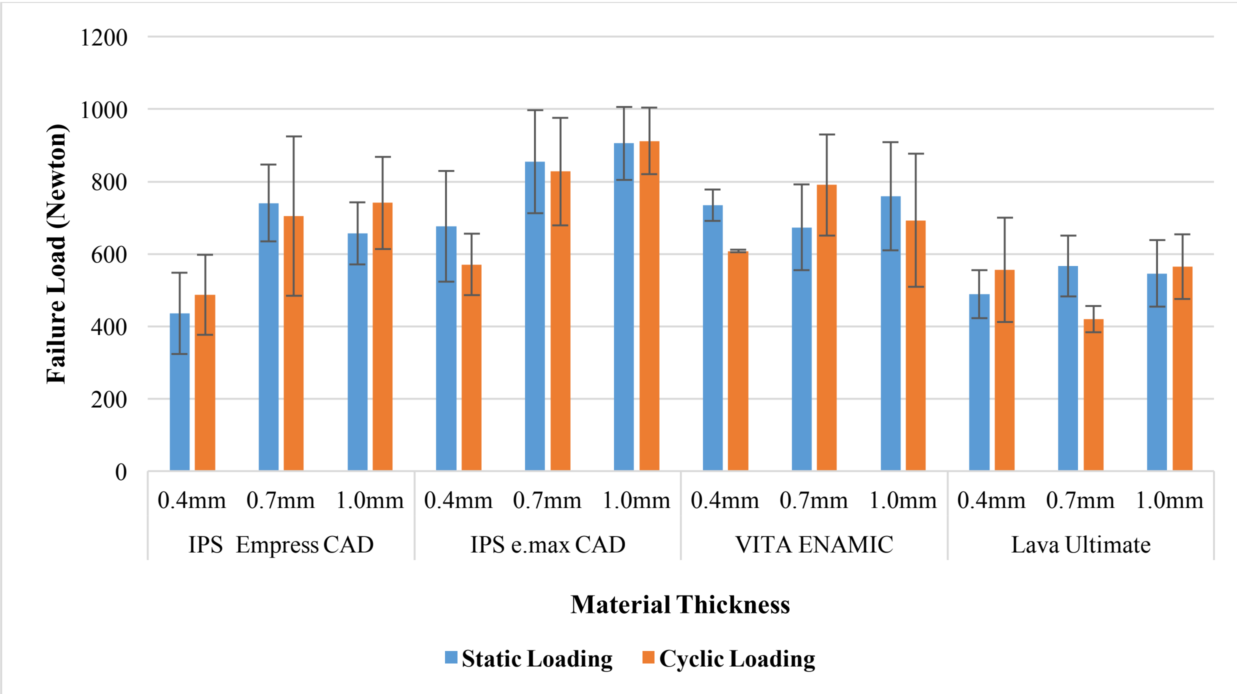


Table 17: Comparison of all veneer materials and thicknesses under static and cyclic loading using Tukey-Kramer HSD

Level		Mean
IPS e.max CAD 1.0mmC	**A**	911.97
IPS e.max CAD 1.0mm	**A**	905.33
IPS e.max CAD 0.7mm	**A B**	854.65
IPS e.max CAD 0.7mmC	**A B C**	828.07
VITA ENAMIC 0.7mmC	**A B C D**	790.68
VITA ENAMIC 1.0mm	**A B C D E**	759.26
IPS Empress CAD 1.0mmC	**A B C D E F**	741.11
IPS Empress CAD 0.7mm	**A B C D E F**	740.51
VITA ENAMIC 0.4mm	**A B C D E F**	734.67
IPS Empress CAD 0.7mmC	**A B C D E F G**	704.68
VITA ENAMIC 1.0mmC	**A B C D E F G**	692.62
IPS e.max CAD 0.4mm	**A B C D E F G**	676.66
VITA ENAMIC 0.7mm	**A B C D E F G**	672.88
IPS Empress CAD 1.0mm	**A B C D E F G**	656.6
VITA ENAMIC 0.4mmC	**B C D E F G**	608.06
IPS e.max CAD 0.4mmC	**C D E F G**	571.9
Lava Ultimate 0.7mm	**C D E F G**	565.86
Lava Ultimate 1.0mmC	**C D E F G**	565
Lava Ultimate 0.4mmC	**C D E F G**	556.21
Lava Ultimate 1.0mm	**D E F G**	546.26
Lava Ultimate 0.4mm	**F G**	489.25
IPS Empress CAD 0.4mmC	**E F G**	487.04
IPS Empress CAD 0.4mm	**G**	435.43
Lava Ultimate 0.7mmC	**G**	420.15

Failure Mode Evaluation:

Regarding mode of failure, some materials failed adhesively (complete delamination of the veneer), cohesively (chipping of the veneer) or catastrophically which is fracture of both the veneer and the composite abutment (Table 18).

Table 18: Mode of failure of materials used in the study

Material	Adhesive	Cohesive	Catastrophic
IPS Empress CAD 0.4 mm		5	4
IPS Empress CAD 0.7 mm		4	3
IPS Empress CAD 1.0 mm		3	7
IPS e.max CAD 0.4 mm	2		8
IPS e.max CAD 0.7 mm	2		8
IPS e.max CAD 1.0 mm	2		8
VITA ENAMIC 0.4 mm		6	4
VITA ENAMIC 0.7 mm	4	1	5
VITA ENAMIC 1.0 mm	1	4	3
Lava Ultimate 0.4 mm	6	2	1
Lava Ultimate 0.7 mm	7	2	
Lava Ultimate 1.0 mm	8	1	

IPS Empress CAD: (Figure 30-31)

At 0.4mm thickness, some samples show a crack in the porcelain veneer with the epoxy resin die still covered with the porcelain veneer (cohesive failure, porcelain chipping). Other samples show a crack that extends full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

At 0.7mm thickness, some samples show a crack in the porcelain veneer with the epoxy resin die still covered with the porcelain veneer (cohesive failure, porcelain chipping), and other samples show a crack that extend full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

At 1.0mm thickness, samples show a crack that extends the full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

IPS e.max CAD: (Figure 32-33)

At 0.4mm thickness, samples show a crack that extends the full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

At 0.7mm thickness, samples show a crack that extends the full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

At 1.0mm thickness, samples show a crack that extends the full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

VITA ENAMIC: (Figure 34-35)

At 0.4mm thickness, samples show several cracks in the porcelain veneer with the epoxy resin die still covered with the porcelain veneer (cohesive failure, porcelain chipping).

At 0.7mm thickness, most samples show a crack that extends the full depth of the porcelain veneer to the epoxy resin die. At the area of fracture, part of the epoxy resin die was attached to the porcelain veneer (catastrophic failure).

At 1.0mm thickness, samples show several cracks in the porcelain veneer with the epoxy resin die still covered with the porcelain veneer (cohesive failure, porcelain chipping).

Lava Ultimate: (Figure 36-37)

At 0.4mm thickness, samples show a fracture in the porcelain veneer and the epoxy resin was completely exposed (adhesive failure).

At 0.7mm thickness, samples show a fracture in the porcelain veneer and the epoxy resin was completely exposed (adhesive failure).

At 1.0mm thickness, samples show a fracture in the porcelain veneer and the epoxy resin was completely exposed (adhesive failure).

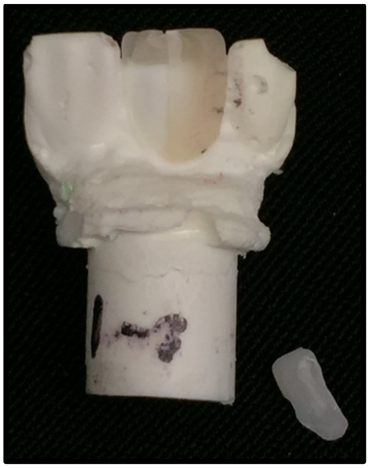


Figure 30: Mode of failure of IPS Empress CAD at 0.4mm and 0.7mm, Cohesive failure

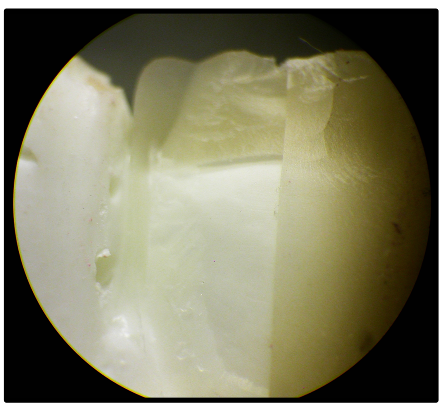


Figure 31: IPS Empress CAD under light microscope 15X

Figure 32: Mode of failure of IPS e.max CAD at 0.4mm, 0.7mm and 1.0mm, Catastrophic failure

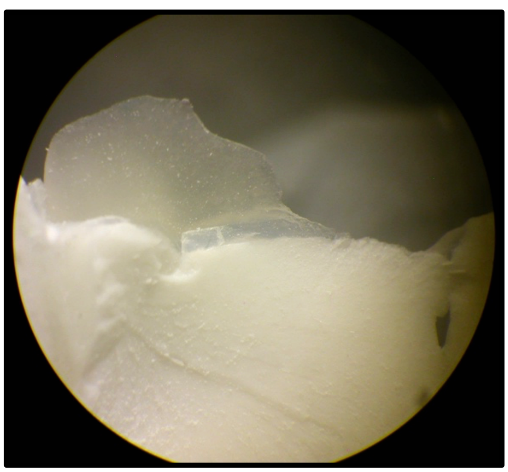


Figure 33: IPS e.max CAD under light microscope 15X

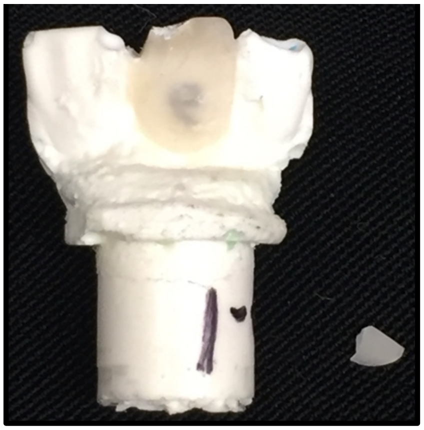


Figure 34: Mode of failure of VITA ENAMIC at 0.4mm, 0.7mm and 1.0mm, Cohesive failure

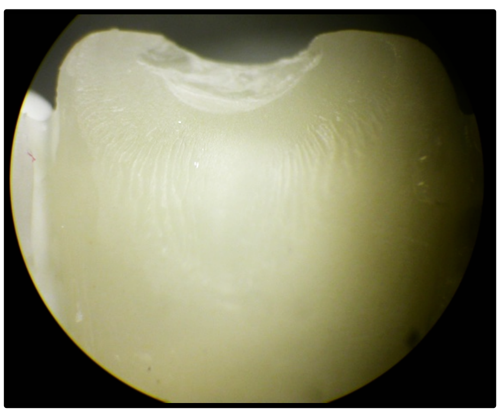


Figure 35: VITA ENAMIC under light microscope 15X

Figure 36: Mode of failure of Lava Ultimate at 0.4mm, 0.7mm and 1.0mm, Adhesive failure

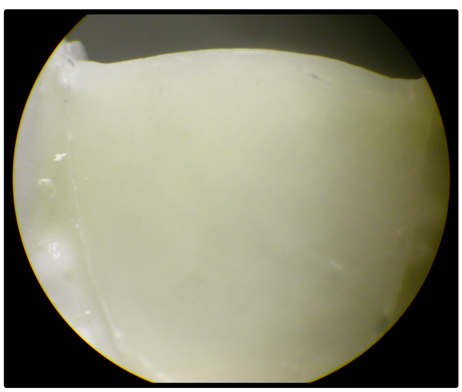


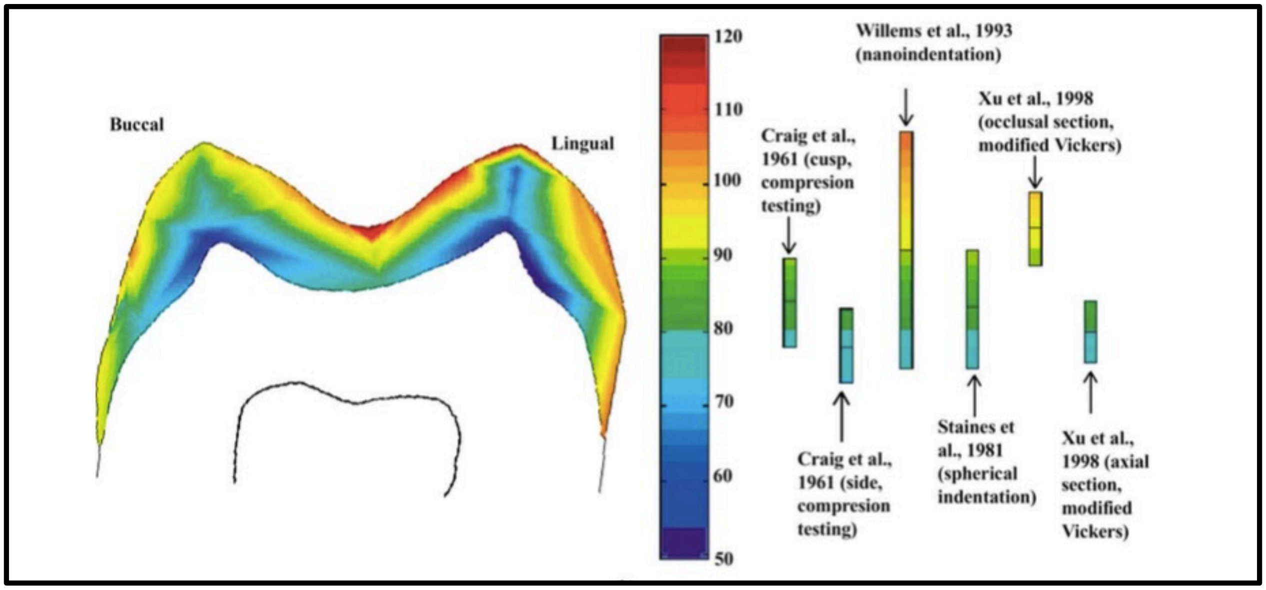
Figure 37: Lava Ultimate under light microscope X15

DISCUSSION

Load to failure laboratory tests usually investigate variables that are thought to affect the clinical success of restorations, and to evaluate new materials or designs under controlled conditions.[33] Using extracted natural teeth optimally represents clinical conditions more closely than artificial abutments.[14,27] However, standardization of human teeth is difficult because of their large variations in size, shape, anatomy, storage time after extraction and fracture during loading due to elastic modulus changes in the extracted teeth.[14,27] Free hand preparation may result in variable depths of preparation with different veneer dimensions and the possibility of dentin exposure than can affect the restoration bonding. Therefore, using artificial teeth as abutments means that the material can be easily standardized.[14] In the current study, highly filled epoxy resin abutments (3M™ Scotch-Weld™ Epoxy Adhesive 100FR, 3M ESPE, USA) were used instead of natural teeth because of their closer elastic modulus ($E=75$ GPa) to enamel-dentin junction ($E<70$ GPa). Cuy et al. reported that the range of enamel elastic modulus is ($E>115$ GPa) and it significantly decreases when going from the enamel surface towards dentin as seen in (Figure 38).[34]

Regarding veneer preparation design, an even reduction of 0.5mm enables sufficient space for porcelain veneers to be fabricated without bulk and with excellent color. Excessive reduction will increase the dependence on the bonding agent system to seal and retain the restoration.[35] Highton et al. stated that incisal overlap preparation distributes the incisal load and eventually lowers stress concentration on the veneer restoration.[36] Furthermore, some authors found better results with incisal edge coverage as it enhances veneer survival, esthetics, adequate seating of the restoration and provides the veneer with greater bulk of porcelain, which can reduce the incidence of fractures on the palatal surface.[37]

Figure 38: Mechanical properties variation between the enamel surface and the enamel-dentin junction. Average values of E that have been reported by other authors are included for comparison



1) Chipping Factor (CF)

CAD/CAM ceramic materials specifically available for machining potentially suffer from chipping defects. Many parameters can be considered to measure machinability of ceramic materials including tool wear, surface roughness, cutting force, cutting energy, drilling rates, etc.[21] Boccaccini proposed the brittleness index as another parameter for estimating machinability. Brittleness is the measure of a material susceptibility to deformation and fracture, involving hardness (H) which quantifies resistance to deformation, and toughness (K_{Ic}) which quantifies resistance to fracture.[24] However, it is hard to find a way for measuring machining of ceramic materials other than direct experimentation.

In the present study, chipping factor (CF) was the method used to measure marginal chipping of the materials. The results showed that the chipping factor (CF) varies according to the material used. It was found that the nano ceramic material (Lava Ultimate) and the hybrid ceramic (VITA ENAMIC) had the lowest chipping factor while the leucite-reinforced glass ceramic (IPS Empress CAD) had the highest chipping factor. These results were consistent with a previous study done by Tsitrou et al. that showed the composite material (Paradigm MZ100) had the lowest chipping factor when compared with the other ceramic materials used. They also concluded that there was a positive correlation between the chipping factor and the brittleness index of the material. Their results showed that the composite material had the lowest brittleness index and that it has better machinability compared to ceramic materials.[21]

Additionally, marginal discrepancy may arise from software limitations in designing restorations such as veneers, and hardware limitations of the camera, scanning equipment and milling systems could generate errors in the CAD/CAM technique especially during milling the fine details like the finish lines of the restoration.[20] Moreover, marginal chipping may result from overgrinding of the bur which may be of a larger diameter than some parts of the tooth preparation, by the brittle nature of the material used, and by milling vibration.[10,20] Giannetopoulos et al. showed that CEREC inEOS system uses an abrading procedure (milling) to fabricate restorations. This procedure is called the "subtractive method" because the material is usually subtracted from a block to produce the desired shaped restoration, and that can possibly affect the quality of the margins.[38]

The present study showed that the chipping factor (CF) varies with the thickness of the material used. As the thickness of a material increases, the chipping factor decreases. Veneers fabricated at 1.0mm thickness had marginal defects less than those fabricated at 0.4mm thickness.

To the best of our knowledge, there are limited studies in the literature that test the marginal chipping of CAD/CAM fabricated veneers. Applying minimally invasive procedures with CAD/CAM is relatively new and not many studies have been found in the literature examining the performance of these types of restorations.[38]

2) Mechanical Testing

Fracture strength is considered one of the main criteria for the long-term success of restorations. The values that are reported in the previous studies about fracture strength of all ceramic systems are extremely variable. Fracture strength depends on the modulus of elasticity of the die structure, type of luting agent used, design of tooth preparation and restoration thickness.[39]

The recommendations described by Kelly for clinically relevant in vitro load to failure tests for all ceramic restorations were followed in the current study. This included the type of die material used, preparing teeth according to clinical guidelines and utilizing a commonly used luting agent.[33]

In the present study, there was a significant difference between 0.4 mm, 0.7 mm, and 1.0 mm thickness in IPS Empress CAD and IPS e.max CAD but not in VITA ENAMIC and Lava Ultimate under static loading. A study by Johnson et al. compared the effect of different thicknesses, 0.3, 0.6, and 1.0mm, on the fracture strength of posterior occlusal veneers. They found that restoration thickness had no significant effect on the fracture strength and suggested that restorations as thin as 0.3mm can be used in areas subjected to masticatory forces.[30] The mean failure load of IPS Empress CAD and IPS e.max CAD veneers at 0.4mm thickness were significantly lower than in 0.7mm and 1.0mm thickness. The null hypothesis that different thickness has no significant effect on the fracture load of different veneers materials is rejected. These results coincide with Chunling et al. who concluded that increasing the porcelain thickness significantly raised the failure loads needed to cause catastrophic failure of bonded porcelain veneers.[12]

Regarding material type, flexural strengths of IPS e.max CAD and VITA ENAMIC were significantly higher than those of IPS Empress CAD and Lava Ultimate. A study by Stawarczyk et al. revealed that lithium disilicate (IPS e.max CAD) had the highest flexural strength values when compared to CAD/CAM composites, VITA ENAMIC and IPS Empress CAD. Lithium disilicate materials show high initial flexural strength but can succumb to spontaneous fracture due to the brittle behavior of dental ceramics.[40]

VITA ENAMIC is a hybrid dental ceramic that includes both properties of ceramics and composites. It has high flexural strength as well as better elastic properties than ceramics. VITA ENAMIC has elastic modulus values close to human tooth structure and its considered to be a very homogenous material with very good reliability.[40] Presence of polymer in the microstructure of VITA ENAMIC has added some plasticity to the material and subsequently has made this material resistant to crack propagation and prevents it from unexpected brittle fracture.[41]

All of the composite resin abutments were fabricated 125° to the long axis and fixed in place in the Instron machine to load all specimens in the same direction as the occlusal forces directed against maxillary anterior dentition. [14,42]

Static loading to fracture is a test that is commonly used to give an indication whether a material or a type of restoration can be considered a feasible option clinically. However, this test can also show the strength of the restoration immediately after bonding and show values of fracture resistance that do not indicate long-term success of a restoration. On the other hand, restorations in the oral cavity are loaded in their lifetime with many cycles which can result in a major reduction of the material's strength due to fatigue.[7]

During chewing simulation, several tested veneers from IPS Empress CAD, VITA ENAMIC and Lava Ultimate were cracked or fractured. Veneers fabricated from IPS e.max CAD survived cyclic fatigue with no fracture. Failure load of the veneers that survived artificial aging were not significantly affected by cyclic loading. Several factors can affect the variations in the fracture strength of ceramic restorations such as: restoration thickness, tooth preparation and luting agent. A more important factor than contributes to failure of ceramic restorations is the environment.[43] In the present study, specimens were fatigued under dry conditions and that might explain why there was no significant difference between static and cyclic loading of the specimens. Kelly et al. have shown that dental ceramics are sensitive to water under static and cyclic loading. It has been found that water can decrease the strength of ceramics by acting chemically at the crack tips. Cyclic loading under dry conditions do not seem to lead to any cementation surface damage and cannot be used alone to cause failure.[33] Moreover, water in the current study decreased the strength of the epoxy resin abutments which could affect the veneer load to failure. Sobrinho et al. stated that there was a decrease in strength of In-Ceram, optimal pressable ceramic (OPC) and IPS Empress when tested under wet conditions.[43]

In the present study, there was a significant difference between groups of IPS Empress CAD and IPS e.max CAD 0.4mm and (0.7 and 1.0mm) thicknesses but not in VITA ENAMIC and Lava Ultimate. That might be due to their low elastic moduli which allow more absorption of functional stresses through deformation.[44] Additionally, the presence of polymer in their composition adds plasticity to the materials which makes them resistant to crack propagation.[41]

The ability of ceramic restorations to survive chewing forces is compromised by the presence of surface cracks, defects on the surface as a result of machining and grinding.[7] Several veneers fractured during masticatory stimulation in this study. This can be influenced by materials thickness and machining defects. Generally, some fractured specimens involved the veneer material only and others extended to involve the epoxy resin abutment as well. This may be explained by the difference in the elastic modulus of ceramic materials, resin cement, and epoxy resin abutments. Tensile stresses usually develop at the cement interface in ceramic materials. Theses stresses are more sensitive to the variation in the elastic moduli of ceramic veneer, cement and composite abutment than to the thickness of the material.[10,27]

To the author's knowledge, data from previous studies regarding fracture tests of anterior CAD/CAM veneers using epoxy resin as abutments cannot be compared to this study due to different test conditions, including the die material used, ceramic materials, load direction and preparation design. Additionally, the mean failure load values in the present study ranged from 420 to 912 N, reaching higher levels than the average masticatory forces in the anterior dentition (20 to 160 N).[10]

Increasing the veneer failure strength may be usually considered as a favorable outcome. However, if such increase is accompanied by increasing the incidence of tooth damage during failure, then achieving those high veneer strengths may not be worth it. In this study, the failures of anterior veneers were mostly within the restorative material and did not cause damage to the composite abutment, which coincides with previous studies that the main cause of failure of facial veneers is chipping or fracture of the veneer.[31]

In this study, fracture loads after cyclic loading for some groups were slightly higher than their counterpart with no cyclic fatigue but are not significantly different. There might be two explanations of this result. First, the higher failure load is an effect of the small sample size. Second, wearing during cyclic fatigue at the contact points adjusted the fit of the stainless steel ball in the consequent ultimate load testing.

According to the mode of failure in this study, a majority of IPS Empress CAD and IPS e.max CAD samples fractured at the veneer with the abutment (Catastrophic failure). Total fractures might be due to the high modulus of elasticity in IPS Empress CAD and IPS e.max CAD (62,95 GPa) respectively. Additionally, IPS e.max CAD has a high flexural strength (360-400 MPa), and that may explain the catastrophic failure in these samples. A few samples failed within the veneer material only (cohesive failure).

Cohesive failure was seen in VITA ENAMIC samples which may indicate the existence of a good interfacial bond between the veneer and the underlying die structure.[45] A majority of Lava Ultimate samples showed adhesive failure and that may be due the weak bonding of Lava Ultimate. The manufacturer removed the crown indication for this material because crowns are debonded at a higher than expected rate.

CONCLUSIONS:

From this in vitro study, the following conclusions were drawn within the scope of current test conditions:

1) The chipping factor decreases as the material thickness increases and can be used as an indicator of a material's machinability.
2) IPS Empress CAD had the highest chipping factor when compared to other materials used.
3) IPS e.max CAD at 1.0mm thickness showed the highest failure load values under static loading.
4) Cyclic loading had no significant effect on the failure load of the veneers tested.
5) When comparing static and cyclic fatigue of the same material, IPS Empress CAD and IPS e.max CAD at 0.4mm were significantly lower than in 0.7mm and 1.0mm thickness.
6) IPS e.max CAD and VITA ENAMIC showed the highest failure load values when compared to other materials used.
7) Considering mode of failure, the majority of IPS Empress CAD and IPS e.max CAD specimens showed catastrophic failure. VITA ENAMIC showed cohesive failure while Lava Ultimate showed adhesive failure.

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CURRICULUM VITAE

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