IN VITRO EVALUATION OF FAILURE LOAD OF SELECTED ALL-CERAMIC CROWNS

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ABSTRACT

Objective: The purpose of this study was to assess the fracture resistance and failure mode of three different all-ceramic crowns; CEREC Blocs, IPS e.Max Press and Cercon. **Materials and Methods:** Thirty extracted maxillary premolars were prepared and randomly allocated to 3 test groups (A, B and C; n = 10 for each group). For group A, monolithic feldspathic crowns were fabricated (CEREC Blocs, Sirona Dental). Group B consisted of monolithic lithium disilicate crowns (IPS e.Max Press, Ivoclar Vivadent). Group C consisted of bilayered partially stabilized zirconia crowns (Cercon, Degudent Dentsply). All crowns were cemented to their representative teeth via dual-cured resin cement (ParaCore, Coltène/Whaledent). The specimens were then subjected to thermocycling (5-55 ˚C/ 500 cycles) and loaded to failure at an angle of 45˚ to the occlusal surface of the crown. Failure data was statistically analyzed using one-way (ANOVA) test at $\alpha = 0.05$. Fractoghraphic analysis was performed to determine the fracture modes of the failed specimens. **Results:** The mean fracture load values (N ± S.D.) for groups A, B and C were 387 ± 60 N, 452 ± 86 N, and 540 ± 171 N, respectively. Significant differences were found only between the failure loads of groups A and C ($P < 0.05$). Cracking that initiated from the cement layer surface resulting in bulk fracture was the major failure mode of group A. For group B & C, the major failure mode was similar, exhibiting catastrophic tooth fracture extending in a transverse plane from the buccal cervical area of crown to the palatal cervical area of root while the ceramic crown remained intact. **Conclusion:** Cercon crowns showed more fracture resistance than IPS e.Max Press crowns and CEREC Blocs crowns. IPS e.Max Press and Cercon crowns simulated similar major fractures; inducing severe distortion of the abutment teeth during occlusal loading. Furthermore, CEREC Blocs crowns showed catastrophic mode of ceramic fracture.

ABSTRAK

Objektif: Kajian ini dijalankan bagi menilai kerintangan terhadap fraktur dan mod kegagalan bagi tiga korona seramik yang berbeza; CEREC Blocs, IPS e.Max Press and Cercon. **Bahan dan kaedah kajian:** Tiga puluh gigi geraham kecil “maxillary” yang diekstrak telah disediakan dan dibahagikan secara rawak kepada tiga kumpulan (A, B dan C n = 10 bagi setiap kumpulan). Bagi Kumpulan A, korona feldspathic monolitik telah dibuat (CEREC Blocs, Sirona Dental). Kumpulan B terdiri dari pada monolitik korona litium disilicate (IPS e.Max Press, Ivoclar Vivadent). Kumpulan C terdiri dari pada korona dua lapisan zirkonia yang separa stabil (Cercon, Dentsply). Semua korona telah disimen kepada gigi menggunakan simen resin “dual-cured” (ParaCore, Coltène/Whaledent). Kemudian, spesimen melalui kitaran suhu (5-55 ˚C / 500 kitaran) dan dikenakan daya beban sehingga gagal pada sudut 45˚ dari permukaan korona. Data statistik telah dianalisis menggunakan ujian (ANOVA) sehala pada $\alpha = 0.05$. Analisis fraktographi telah dilaksanakan untuk menentukan mod fraktur spesimen yang telah gagal. **Keputusan:** Nilai beban fraktur purata (N ± S.D.) bagi Kumpulan A, B dan C adalah masing-masing, 387 N ± 60, 452 N ± 86, dan 540 N ± 171. Perbezaan yang bermakna hanya didapati antara kegagalan baban kumpulan A dan C ($P < 0.05$). Keretakan yang bermula dari permukaan lapisan simen hasil fraktur utama pukal adalah punca kegagalan utama bagi Kumpulan A. Bagi kumpulan B & C, punca kegagalan utama adalah sama, dimana gigi patah secara memanjang dalam satu permukaan melintang dari kawasan “buccal cervical” korona ke kawasan “palatal cervical” akar manakala seramik korona kekal utuh. **Kesimpulan:** Korona Cercon menunjukkan rintangan fraktur lebih banyak daripada IPS e.Max Press dan CEREC Blocs crown. IPS e.Max dan Cercon menunjukkan punca fraktur utama yang sama, menyebabkan penyelewengan teruk di struktur gigi semasa bebanan“occlusal”. Tambahan pula, CEREC menunjukkan kegagalan seramik fraktur yang sangat teruk.

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CHAPTER ONE

INTRODUCTION, AIMS AND OBJECTIVES

1.1 Introduction

Metal-ceramic restorations have been widely used in dentistry for more than 30 years. The significant reliance on such restorations was a result of the advantages that have been shown by this type of prosthesis, such as strength, performance and reasonable aesthetic (Heffernan et al., 2002). However, due to the demand for better aesthetic, in addition to concerns relating to the biocompatibility of the metal, all-ceramic restorations have been introduced into the dental field (Fischer et al., 2002).

All-ceramic restorations have a wide noticeable popularity among dental practitioners and patients because of their better aesthetics, biocompatibility and their excellent chemical stability (Powers & Sakaguchi, 2006). Nevertheless, dental ceramics are considered as brittle materials; the major concern of the clinical application of these materials is their low fracture resistance and toughness (Sadighpour et al., 2006).

Several techniques have been applied to develop stronger dental ceramic materials (Al-Makramani et al., 2009). All of these techniques have their own approaches in order to improve the mechanical properties of the dental ceramics and to get sufficient strength which is considered the greatest challenge in developing all-ceramic restorative materials (Seghi et al., 1995). Therefore, many types of all-ceramic restorations, with different systems, have recently become available for use in dentistry. These include lithium disilicate heat-pressed ceramics (IPS e.max Press, Ivoclar Vivadent, Liechtenstein), zirconium-oxide ceramics (Cercon, Degudent Dentsply, Germany), and feldspar CAD/CAM ceramics (CEREC Blocs, Sirona Dental, Germany).

CEREC Blocs is a fine-grained feldspar-based ceramic which was introduced in 2007 by Sirona Dental System. CEREC Blocs can be fabricated in a single visit using chairside CAD/CAM CEREC system. The feldspathic CEREC has been reported with a higher flexural strength in contrast to that of conventional low-fusing ceramic (Attia & Kern, 2004).

IPS e-max Press is a lithium disilicate heat-pressed ceramic which was introduced in 2005 as the updated version of IPS Empress II. A considerable strength could be achieved in lithium disilicate restorations; the remarkable strength of this type of ceramics could be referred to their chemical composition in which a crack could be trapped depending on distribution of Li-Si crystals inside the glass matrix (Guazzato et al., 2004; Kang et al., 2013). Therefore, lithium disilicate ceramics are considered a good choice for short-span fixed dental prosthesis fabrication (Blatz et al., 2003).

Cercon smart ceramics CAD/CAM system, which was introduced in 2001, utilizes a partially stabilized zirconia ceramic which relies on a special toughening process called transformation toughening that gives it superior strength compared with other types of ceramics (Tsalouchou et al., 2008). Cercon has been reported with a remarkable fracture strength value of 1140 N (Yilmaz et al., 2007).

In general, the fracture resistance is considered as a stable parameter and one of the most important mechanical properties through which the clinical performance of the restoration can be evaluated and improved (Quinn et al., 2005). Wang et al. (2008) reported that the evaluation of the longevity of a brittle material, such as dental ceramic, can be achieved through assessment of their fracture resistance and toughness.

The traditional fracture strength tests, such as uniaxial and biaxial flexural tests, are considered inappropriate methods to reflect the clinical situations in which other factors, rather than the material used, could contribute to the success of the all-ceramic restorations. These factors, such as the role of the cement, loading conditions, the restoration geometry and design, should be included in the fracture strength test design of the dental ceramic restoration (Kelly, 1999).

The crack propagation and fracture mode of all-ceramic restorations depend on the stress distribution through the ceramic-cement-tooth complex. According to Soares et al. (2006), the stress distribution through the different layers of the dental restoration was influenced mainly by the geometrical shape of the crown and loading direction, as well as the size and direction of the flaws inside the ceramic material. The masticatory stress cycles inside the mouth include a mixture of vertical and lateral forces. Thus, it is important to consider the influence of lateral forces during designing in vitro fracture tests of the dental restorations (Soares et al., 2006).

CEREC Blocs, IPS e.Max Press and Cercon all-ceramics, which have different compositions and fabrication techniques, are commonly used as dental crowns. Till now, we are not aware of any study performed to investigate and compare the flexural strength and the fracture mode of these systems considering the contribution of numerous clinically relevant factors; such as lateral forces, cement and restoration geometry. So, the aim and objectives of this study are drawn as follows:

1.2 Aim of the study

The aim of this study is to evaluate and compare in vitro the fracture load of CEREC Blocs (Sirona Dental, Germany), IPS e.Max Press (Ivoclar Vivadent, Liechtenstein) and Cercon (Degudent Dentsply, Germany) using one resin-bonded cement, ParaCore (Coltène/Whaledent, Switzerland).

1.3 Objectives

1. To determine the failure load of three different all-ceramic systems; CEREC Blocs, IPS e.Max Press and Cercon .
2. To investigate the mode of fracture of these dental ceramics cemented with one particular luting agent.

CHAPTER TWO

LITERATURE REVIEW

2.1 History of dental ceramics

The term "ceramic" was taken from the Greek name "keramos" which means "burnt earth" (Della Bona & Kelly, 2008). It refers to any product made from a non-metallic material that has been fired at a high temperature to enhance the properties of the product. The term "porcelain" refers to a ceramic material composed of feldspar, quartz, and kaolin, being fired at high temperature. Dental porcelain (also known as dental ceramic) is a porcelain used to fabricate biocompatible dental restorations, such as veneers, crowns and bridges (Powers & Sakaguchi, 2006).

Porcelain materials have been used in several forms over the centuries. The Chinese started working with porcelain in the ninth century. In 1700, refined porcelain was used in France for the fabrication of eating plates and artistic items. Later on, it was used for the same purpose in England (Leinfelder, 2000). The application of porcelain as a dental material was reported 200 years ago. Around 1774, the first successful porcelain denture was made by Alexis Duchateau, a French apothecary and a Parisian dentist named Nicholas Dubois de chemant (Ho & Matinlinna, 2011).

In 1808, porcelain teeth with embedded platinum pins were introduced in Paris by Fonzi (Jones, 1985). The continuous developments from the formulations of Elias Wildman in 1838 to vacuum firing in 1949 resulted in remarkable improvements in colour and translucency of dental porcelain (Vines & Semmelman, 1957). In 1903, Charles H Land introduced the all-porcelain (jacket) crown which showed a limited clinical application because of its retentive weakness (Rosenblum & Schulman, 1997). In 1965, Hughes and Mclean developed some formulations on aluminous porcelain compositions to enhance their fusion to certain gold alloys by elevating the coefficient of thermal expansion in order to make complete crowns and fixed partial dentures (FPD) (McLean & Hughes, 1965). In the 1980s, the introduction of the "shrink-free" all ceramic system (Sozio & Riley, 1983) and the castable glass-ceramic crown system

(Malament & Grossman, 1987) helped in obtaining aesthetics results and additional flexibility in all-ceramic systems.

The metal-ceramic crowns, since their implementation during the second half of the nineteenth century to date, are considered as the most common complete coverage dental restorations through which a proper strength can be obtained. However, the compromised aesthetic and the need for more reduction in tooth structure are the main disadvantages of these restorations (Al-Makramani et al., 2009). In 1723, Pierre Fauchard described the enameling of metal denture bases and initiated his research with porcelain to match and imitate the colour of the teeth and gingival tissues (Jones, 1985). The recent increase in the application of all-ceramic restorations was a result of the remarkable aesthetic that provided by this system. Unlike all-ceramics, the metal-ceramic system has shown less aesthetic properties because of the presence of a metal core (Seghi et al., 1995).

Several techniques of all-ceramic systems have been introduced during the last 30 years. The first technique was the castable glass ceramic system which is no longer preferred due to its high incidence of fracture and processing difficulties (Powers & Sakaguchi, 2006). In the late 1980s, high lecuite ceramic (Empress I) was introduced as the first pressable ceramic. The process of pressing heated leucite reinforced ceramic ingots using special pressing furnace made this system more popular than the castable ceramic which was fabricated using centrifugal casting technique. Regardless the remarkable strength recorded by leucite-reinforced Empress ceramic, using this system was limited because of the fracture possibility of such restoration in posterior area (Kelly et al., 1996). Shortly afterwards, the In-ceram system was introduced using slip-casting process. In-ceram aluminum copings are 80-82 % sintered aluminum oxide and the flexural strength of this glass-infused aluminium core is 352 MPa (Al-Makramani et al., 2009). In the mid 1990s, Procera AllCeram core was introduced by Nobel Biocare as a computer-aided design/computer-aided manufactured system (CAD/CAM). Procera AllCeram cores are 99.9% aluminium oxide (Conrad et al., 2007). The limited use of the early dental porcelain was a result of their lack of strength and large shrinkage (McCabe & Walls, 2009). In order to increase the strength, more recent lab-based CAD/CAM systems have used stabilized zirconium dioxide blocks. In 2001, Dentsply introduced zirconia ceramic CAD/CAM system (Cercon) with a flexural strength of 900 MPa, allowing it to be used for long-span posterior bridges (Ariko, 2003; Mantri & Bhasin, 2010).

In 1998, IPS Empress II was introduced by Ivoclar. IPS empress II is a lithium disilicate glass-ceramic with a flexural strength of 350 to 400 MPa (Marquardt & Strub, 2006). In 2005, Ivoclar introduced IPS e. max which had better physical and aesthetic properties (Guess et al., 2009). The CEREC CAD/CAM system of Sirona Dental Systems (previously Siemens Dental) has been used for clinical applications since 1986. A second generation of fine-grained feldspathic ceramic, called Vitablocs Mark II, has been available since 1991. In 2007, CEREC blocs were introduced by Sirona dental systems as chairside CAD/CAM restorations. CEREC blocs are high glass feldspar-based ceramics with similar properties of Vitablocs Mark II. Improving the strength of dental ceramics is still the biggest challenge in which the recent researches are heading (Giordano & McLaren, 2010).

2.2 Composition and properties of dental ceramics

Ceramics have two basic structure forms; crystalline and non-crystalline. Quartz is an example of crystalline ceramics which has a steady arrangement of atoms in lattice configuration. On the other hand, non-crystalline ceramics, such as granite, have undefined or amorphous structure (Einzelzahnversorgung & Präparation, 2008; Kunzelmann et al., 2008). The melting temperatures of ceramics are high as they arrange from 1100 ˚C to 1700 ˚C. However, all ceramics have low thermal and electrical conductivity. Synthetic ceramics also have superior biocompatibility as they are non-reactive due to their oxide nature (Rekow et al., 2011).

The main compositions of traditional feldspathic dental ceramics are silica (Quartz-SiO_2), kaolin (Clay-$Al_2O_3.2SiO_2.2H_2O$), soda feldspar ($K_2O.Al_2O_3.6SiO_2$) and potash feldspar (Holden et al., 2009). The formation of dental ceramics basically depends on the metallic/non-metallic components integration (Guess et al., 2008). Manufacturing process of traditional porcelain includes two prominent phases; the glass phase and the crystalline phase. However, certain structural ceramics may be processed with a partial glass fusion or produced as glass-free ceramics such as the newer polycrystalline ceramics which contain zirconia or alumina (Vagkopoulou et al., 2009).

2.3 Classification of dental ceramics

2.3.1 All-ceramics classification according to fusing temperature

This classification was made during the early 1940s and it is mainly for the ceramics that contain feldspar, quartz and clay. Low-fusing ceramics have a fusing temperature range from 870 ˚C - 1065 ˚C, while medium-fusing ceramics range from 1090 ˚C – 1260 ˚C. The fusing range of high-fusing ceramics is 1315 ˚C-1370 ˚C (Krishnan, 2010).

2.3.2 All-ceramics classification according to composition and glass content

Based on the glass content, dental ceramics could be classified into three categories; predominant glass ceramics, particle-filled glass ceramics and polycrystalline ceramics. Dental ceramics that belong to "predominant glass ceramics", such as leucite reinforced and high melting glass ceramics, have high glass composition with low content of filler particles. These highly filled glass ceramics are capable of producing remarkable optical properties similar to that of natural teeth (Özkurt & Kazazoğlu, 2010). "Particle-filled glass ceramics" category describes glass ceramics that have low glass content filled with high melting glass particles or crystalline in order to improve their mechanical properties (Guazzato et al., 2004). The last category "polycrystalline ceramics" are characterized by sintered crystalline structure with regular arrangement of the particles due to the lack of glass base which also makes them stronger than glass ceramics (Piconi & Maccauro, 1999). The examples of highly filled glass ceramics, particle-glass ceramics and polycrystalline ceramics are shown in Figure 2.1.

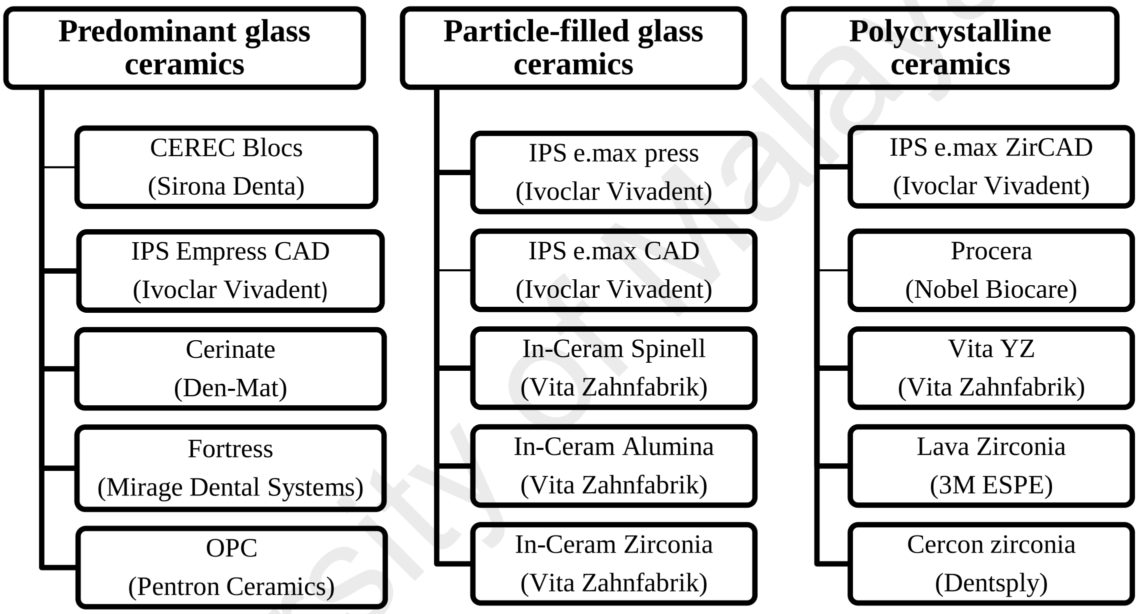

Figure 2.1: Examples of all-ceramics based on glass content

2.3.3 All-ceramics classification according to fabrication techniques

2.3.3.1 Sintered porcelains

"Leucite-reinforced feldspathic porcelain" is similar to conventional feldspathic porcelain but with high content of leucite and higher compressive strength. The existence of high content of leucite within the glassy material plays an important role in increasing the resistance to crack propagation (Kontonasaki et al., 2008). Unlike the conventional feldspathic porcelain that is used for metal-ceramics, Leucite-reinforced porcelain does not need special processing equipment (Rosenblum & Schulman, 1997). Optec HSP (Jeneric/Pentron Inc. WallingFord, USA), Fortune (Ivoclar. Williams, Amherst, New York) and Fortress (Mirage Dental Systems, USA) are the common examples of this group.

The first “aluminium-based core porcelain” was introduced in 1965 containing 40% to 50% alumina (McLean & Hughes, 1965) with a flexural strength of 131 MPa, which is twice that of feldspathic ceramic (Ozturk et al., 2008). Introducing alumina crystals into the glass matrix improves the hardness and the strength of the ceramic more than leucite. The key behind this improvement of the mechanical properties are the particle size and the high elastic modulus of alumina (Yilmaz et al., 2007).

“Magnesia-based core porcelain” was developed in 1985 through replacing the alumina with magnesia which has a high thermal coefficient similar to that of body and incisal porcelain used for metal ceramic (O'Brien et al., 1993). Unglazed magnesia core porcelain has the same flexural strength of alumina core porcelain. In addition, glazing can significantly increase the strength of the magnesia core material (Al-Makramani et al., 2009). In spite of the successful clinical testing of magnesia core ceramics, their use is limited because of their manufacturing using platinum foil technique, which has recently rejected in practice (Zarone et al., 2011).

Mirage II (Mirage Dental Systems, USA) is a “zirconia-based porcelain” with a modulus of rupture similar to that of conventional feldspathic ceramic (Anusavice, 2002). Yttria-stabilized zirconia has been added to conventional feldspathic porcelain through a mechanism called transformation toughening in order to improve the fracture strength and toughness (Kon et al., 2001).

2.3.3.2 Castable glass-ceramics

Castable ceramics are more homogenous than conventional feldspathic porcelain because of their fabrication method using lost-wax technique and casting via a special centrifugal machine. This technique has recorded a remarkable accuracy (Jalalian et al., 2010). After waxing and investing, which follow the same fabrication protocols used for some metal crowns, ceramic ingot is melted and casted with centrifugal casting machine producing a clear glass cast crown that must be heated in ceramic furnace in order to form a crystalline ceramic, which is a fluorine mica silicate. The interlocking of mica crystals within the glassy material plays an important role in fracture resistance of the glass ceramics (Burke et al., 2002; Denry & Holloway, 2010).

Dicor (Dentsply International Inc. York, PA) is a mica-based glass-ceramic which was introduced in 1982 as the first castable ceramic for dental application (Höland et al., 2006). Dicor is the most translucent ceramic material among all-ceramic systems and is indicated for use in the anterior restorations due to its low strength record with a flexural strength of 120 MPa (McCabe & Walls, 2009). Yttrium tetragonal zirconia polycrystals (Y–TZP) is one of the recent introduced castable core ceramics with highly reported flexural strength of 900 to 1200 MPa (McCabe & Walls, 2009; Raigrodski, 2004).

2.3.3.3 Heat-pressed ceramics

Heat pressable ceramics are available as ingots. After melting these ingots at high temperature (1150˚C), they are pressed into a custom mould using the lost wax technique (Gorman et al., 2000). In the early 1990s, Ivoclar Vivadent introduced IPS Empress I as “leucite reinforced glass-ceramic”. The glass material is reinforced by the leucite crystals which prevent crack propagation and, thus, increase the strength of the ceramic core; the translucency, however, is affected by this crystallinity (Heffernan et al., 2002). The flexural strength of IPS Empress I is around 125 MPa. Therefore, the use of this system is limited to single crowns, inlays, onlays, and veneers (Raigrodski, 2004).

IPS Empress II (Ivoclar Vivadent, Liechtenstein) is “lithium disilicate-based porcelain” with a flexural strength of 400 MPa. IPS Empress II has a crystal texture with a volume of 60% without compromising the translucency, as the refractive index of the crystals is almost similar to that of the glassy matrix (Qualtrough & Piddock, 2001). The high content of crystals forms an interlocked and tough structure which increases the fracture resistance of this material (Al-Makramani et al., 2009). Unlike IPS Empress I, IPS empress II is recommended for the fabrication of fixed partial dentures in the anterior and premolars regions (McCabe & Walls, 2009). In 2005, IPS e. max Press (Ivoclar Vivadent, Liechtenstein) was introduced as enhanced press reinforced glass ceramic. IPS e. max Press resembles IPS empress II with better aesthetic and physical properties (Altamimi et al., 2014; Giordano & McLaren, 2010; Guess et al., 2009).

2.3.3.4 Slip-cast ceramics

This technique depends on application of a slip to a gypsum refractory mould which was already designed in order to form a framework. The formed framework is then separated from the gypsum mould using partial sintering technique. The resulting ceramic is infiltrated with glass to increase the strength and reduce the porosity of the core material (McLean, 2001).

In-Ceram Alumina was introduced in 1989 by Vita Zahnfabrik, Germany. After the application of slurry Al_2O_3 on a plaster die, the alumina core is sintered at 1120 ˚C. The resulting porous alumina core must be fired again at 1100 ˚C for 4 hours to allow glass infiltration. This step is very important to reduce the porosity and increase the strength as well (Xiao-ping et al., 2002). Although In-Ceram Alumina has a lower level of translucency, it is a tough material with flexural strength of 600 MPa (Guazzato et al., 2004). In-Ceram Spinell (Vita Zahnfabrik, Germany) was revealed in 1994 as a modified In-Ceram depending on the magnesium spinel in order to overcome the translucency issues of In-Ceram Alumina. In-Ceram Spinell is recommended for anterior units due to its low strength which is around 250 MPa (Fradeani et al., 2002).

In-Ceram Zirconia (Vita Zahnfabrik, Germany) is the second modification of In-Ceram Alumina containing tetragonal zirconia and alumina to improve the strength of the core ceramic (Sundh et al., 2005). In-Ceram Zirconia has a great flexural strength of 700 MPa, however, its application is limited to posterior region because of its poor translucency (Raigrodski, 2004).

2.3.3.5 Machinable ceramics (CAD/CAM System)

In the mid 1990s, the first all-ceramic system using CAD/CAM technology was introduced by Nobel Biocare as substructure core, consisting of 99.9% alumina, which was layered by feldspathic ceramic (Walter, 2001). During the last decade, the production of direct ceramics restorations utilizing CAD/CAM system has become more favourable compared to traditional systems in which the final restoration takes longer process through many clinical and laboratory steps. An advantage of CAD/CAM technology is that a restoration can be fabricated and delivered in a single visit, which not only reduces the time consumed for making the final restoration; it can minimise the potential inaccuracies of the hand/lab traditional systems. As mentioned, it takes one visit to carry out the whole process in which the tooth is scanned, after preparation, using an optical scanner and the restoration is then designed by special computer software and milled via milling machine. Additionally, the flexural strength records of the core materials using this system are higher than conventional ceramics (Miyazaki et al., 2009). However, CAD/CAM demands expensive equipment and special training. Furthermore, this system produces larger internal and marginal gaps compared with conventional systems (Beuer et al., 2008). There are many CAD/CAM systems that are available in dentistry, such as CEREC System, Cercon smart ceramic System, LAVA TM System, Procera All Ceramic System and DCS System.

In 1980, the CEREC system was developed by Mörmann and Brandestini at Zurich University. The word CEREC refers to “computer-assisted CERamic REConstruction”. In 1985, CEREC I was used for the first time to produce the first chairside inlay from feldspathic ceramic material; namely Vita Mark I (Vita Zahnfabrik, Germany) (Mörmann, 2006). The launch of CEREC II in 1994 gave more options for partial and full restorations as it was provided with extra cylindrical diamond bur which enables form-grinding for partial and full copings and crowns. Unlike CEREC II, CEREC I used only a diamond-coated wheel. The software utilized in CEREC II was two-dimensional. In 2000, CEREC III was introduced with a two-bur system; cylindrical diamond and tapered burs instead of the diamond-coated wheel. The software used for CEREC III was developed to 3D display since 2003 which makes the handling much easier. The cylindrical bur was replaced in 2006 with a new modified bur called “step bur” which has smaller diameter tip to enable high precision form-grinding (Mörmann, 2006). In 2009, Sirona released CEREC AC (acquisition center) with a new imaging technology, the Bluecam, which is based on short-wave blue light. In 2011, the new Version 4.0 of the CEREC software was launched with new and simple intuitive user interface. Since then, it has also been possible to work on multiple restorations within a single process. CEREC Omnicam intraoral camera was launched in 2012 to facilitate powder-free digital impressions in natural colors.

The whole process to produce a ceramic restoration via CEREC CAD/CAM system is carries out in a single visit (Apholt et al., 2001). As mentioned, the fabrication process includes the following steps; scanning the prepared tooth via an optical probe, designing the restoration in a monitor screen and lastly, the final restoration is milled. There are many materials used with CEREC system such as; Vita Mark II, feldspathic ceramic (Vita Zahnfabrik, Germany), CEREC Blocs, felspathic ceramic (Sirona Dental, Germany), ProCAD leucite reinforced ceramic (Ivoclar Vivadent, Liechtenstein) and

Paradigm™ MZ100 composite block (3M ESPE, USA). There are also VITA In-Ceram® SPINELL™, ALUMINA™ and ZIRCONA™ (Vita Zahnfabrik, Germany) which are milled on CEREC inLab system.

Cercon smart ceramic system (Degudent Dentsply, Germany) uses conventional waxing technique for designing infrastructure copings with particular thickness. Cercon system is often considered as a CAM system as it does not include a CAD part (Liu, 2005). The first step is making a wax pattern of pontic or coping for the prepared die with a minimum thickness of 0.4 mm. The wax pattern is then scanned via a special Laser scanner and the data is saved in the CAM unit. The data is then used to produce the framework from partially sintered yttrium tetragonal zirconia polycrystals (Y-TZP) blanks. The time of the milling process is approximately 35 minutes for a single crown (Pilathadka et al., 2007; Pittayachawan, 2009). The zirconia coping is then sintered at 1350 ˚C in the Cercon heat furnace for six to eight hours (Liu, 2005). The strength of Cercon crown reached 1850 MPa for upper central incisor (Miura et al., 2005).

In 2002, Lava ™ All-Ceramic CAD/CAM System (3M ESPE, USA) was introduced to produce a high-strength sintered zirconia framework containing 3% yttrium partially stabilised zirconia polycrystal. The Lava system includes an optical scanner (Lava Scan), a computerized milling unit (Lava Form) and a sintering furnace (Lava Therm). After the scanning process, the crown is designed using CAD/CAM sofware and then milled from a partially sintered zirconia block (Piwowarczyk et al., 2005). This block, which is softer than sintered zirconia, reduces the milling time (approximately 35 minutes for crown coping) and minimizes the tool wear (Suttor et al., 2001). Finally, the sintering step is accomplished via Lava Therm in 8 hours. Yttria stabilised zirconia framework is used for the Lava system due to its high flexural strength that can exceed 1000 MPa (Pittayachawan et al., 2007).

Procera All Ceramic System is one of the common CAD/CAM systems used during the past years. Procera AllCeram (Nobel Biocare, Goteborg, Sweden) has one of the highest hardness records among the dental ceramics as it consists of 99.9% alumina (Pittayachawan, 2009). Procera AllCeram ceramics are available as crowns, veneers, inlays and onlays. The crown unit consists of densely sintered aluminium oxide core veneered with AllCeram porcelain (Pittayachawan, 2009). The prepared tooth is scanned and the data is transmitted to a milling machine to produce, through a CAD/CAM process, an enlarged die onto which the core ceramic is dry-pressed, sintered and veneered. The reported survival rates of Procera AllCeram after 5 and 10 years were 97.7 % and 93.5 %, respectively (Odman & Andersson, 2000). The fracture strength of the Procera alumina is 639 MPa while the Procera zirconia has a flexural strength of 1158 MPa (Itinoche et al., 2006).

The Digitising Computer System (DCS) (DSC-dental; Allschwill, Switzerland) can be programmed to make a CAM restoration using 3D computer models. Many materials are available with DCS system, such as porcelain, In-Ceram, glass ceramic, dense zirconia and metals. DSC is capable of milling fully dense sintered zirconia as well as titanium (Liu, 2005).

Several ceramic materials are available as dental CAD/CAM restorations (Table 2.1). The machinable ceramics used earlier with CAD/CAM system were glass-ceramic, such as Vita Mark II and Dicor (Liu, 2005). They have been used as onlays, inlays, veneers and crowns. In-Ceram spinell is an excellent choice for single anterior crowns due to its high aesthetic properties with a reasonable strength of 350 MPa. Zirconia and alumina are the ideal choice for high stress posterior areas as they have remarkable strength records of 1000 MPa and 750 MPa, respectively (Liu, 2005). The most common all-ceramic materials used with CAD/CAM systems are shown in Table 2.1.

Table 2.1: Ceramic CAD/CAM Materials (Santos et al., 2015)

Product	Ceramic Material	Manufacturer	CAD/CAM System
Vita Mark II	Feldspathic ceramic	Vita Zahnfabrik, Germany	CEREC
CEREC Blocs	Feldspathic ceramic	Sirona Dental, Germany	CEREC
Dicor MGC	Fluoromica	Degudent Dentsply, Germany	CEREC
ProCAD	Leucite reinforced glass-ceramic	Ivoclar Vivadent, Liechtenstein	CEREC
IPS Empress CAD	Leucite reinforced glass-ceramic	Ivoclar Vivadent, Liechtenstein	CEREC inLab
In-Ceram Alumina	Glass-infiltrated With aluminium oxide	Vita Zahnfabrik, Germany	CEREC 3D, CEREC inLab
In-Ceram Spinell	Glass-infiltrated With Magnesium oxide	Vita Zahnfabrik, Germany	CEREC 3D, CEREC inLab
In-Ceram Zirconia	Glass-infiltrated With Zirconium oxide	Vita Zahnfabrik, Germany	CEREC 3D, CEREC inLab, DCS Precident
Procera AllCeram	Polycrystalline alumina	Nobel Biocare , Göteborg, Sweden	Procera
IPS e.max CAD	Lithium disilicate glass-ceramic	Ivoclar Vivadent, Liechtenstein	CEREC inLab
In-Ceram YZ	Polycrystalline zirconia (Y-TZP)	Vita Zahnfabrik, Germany	CEREC inLab
Cercon	Polycrystalline zirconia (Y-TZP)	Degudent Dentsply, Germany	Cercon
Lava Zirconia	Polycrystalline zirconia (Y-TZP)	3M ESPE, USA	Lava
Incoris TZI	Polycrystalline translucent zirconia (Y-TZP)	Sirona Dental, Germany	CEREC

2.4 Strength of dental ceramic materials

Ceramics are brittle materials with a low tensile strength due to the existence of inherent flaws within the ceramic materials. This also illustrates why ceramic restorations mostly fail in the stressed areas (Della Bona et al., 2003). For that reason, tensile strength is effectively considered as an important key to assess the failure probability of the ceramic restorations.

Strength is one of the most important mechanical properties that rule the clinical success of ceramic restorations. Typically, most specimens in practical sessions have complex stress distribution that are caused by tensile, compressive, and shear stresses. In general, it is easy to determine tensile strength for metals and other ductile materials. On the other hand, compressive strength is commonly measured for porcelains and other brittle materials, such as amalgams, cements, and composites (Al-Makramani et al., 2009).

2.4.1 Strengthening Methods for Dental Ceramics

Dental porcelain can effectively imitate natural tooth colour due to its high aesthetic properties, however, it has fracture susceptibility like other ceramics. Many methods have been applied to improve the strength of the dental ceramics. The basic principle of the strengthening methods is to produce compressive stress, which is more favourable than tensile stress, and decrease flaws in the dental ceramic material (O'Brien, 2000). Current mechanisms include surface treatment, dispersion strengthening, framework support, residual surface stressing and transformation toughening (Marinis et al., 2013).

Surface treatment includes polishing and glazing in order to reduce the surface flaws. Dispersion strengthening is carried out through incorporation a fine crystalline material within the glassy matrix, which prevents the crack propagation within the ceramic structure. This is accomplished via the compressive stress that is originated in the dispersion phase, as a result of coefficient of thermal expansion (CTE) variation between the fine particles and the glassy matrix. The compressive stress deflects the crack path around the particles (Marinis et al., 2013; O'Brien, 2000).

Ceramic material is supported by using a framework substructure, enabling the porcelain superstructure to resist high tensile stresses. In order to ensure desirable results, it is essential to assess the compatibility of coefficient of thermal expansion (CTE) as well as the bonding between the layering veneer porcelain and the framework (Marinis et al., 2013; O'Brien, 2000). Residual surface stressing is another method for strengthening the dental ceramics which relies on ion exchange on the surface of the ceramic material. Residual surface stressing is carried out through coating the porcelain with potassium salt. The coated porcelain is then heated at low temperature. As a result, smaller ions are replaced by larger ions and a layer of compressive stress is created on the surface of the ceramic material (Marinis et al., 2013; O'Brien, 2000).

Transformation toughening is a particular property of zirconia material (ZrO_2). When a crack is initiated inside the ceramic material, the molecular configuration of the material is subjected to phase transformation, resulting in volumetric changes. These changes create compressive stress that prevents the propagation of the cracks and increases the overall strength (Marinis et al., 2013; O'Brien, 2000).

2.4.2 In vitro strength testing for all-ceramics

2.4.2.1 Clinical significance

The long-term success of dental ceramics depends on their physical and mechanical properties which vary according to the composition and fabrication method. Flexural strength is one of the most effective properties through which the performance of a particular dental ceramic could be evaluated. It has been reported that the maximum functional biting forces are 200 N and 350 N on anterior and posterior reigns, respectively (Yilmaz et al., 2007). Therefore, the flexural strength of in vitro tested dental ceramics should withstand the occlusal loads that are usually created over the dental restoration inside the mouth. These loads could reach (150-665 N) up to (1000 N) in para-functional cases (Chaar et al., 2013; Chang et al., 2009; Shahrbaf et al., 2014)

2.4.2.2 Flexural strength test

Several methods have been applied to evaluate the strength of ceramic materials, such as flexural strength test, tensile strength test and compressive strength test. Typically, the fracture strength of ceramics is evaluated by using disc-shaped specimens tested in biaxial bending or bar-shaped specimens tested in uniaxial loading.

Tensile strength test is commonly used to assess the strength of metals more than brittle materials due to the difficulties related to specimens aligning and gripping into the testing machine (Sadighpour et al., 2006). Therefore, it is easier and more favourable to measure the strength of brittle materials via flexural strength test. Flexural strength refers to the capacity of restorations to resist the probable tensile forces. Restorations with high flexural strength are less susceptible to bulk fracture (Sunnegårdh-Grönberg et al., 2003). Different test methods are available to evaluate the flexural strength of ceramics; these methods are uniaxial flexural test, which includes three and four-point bending, and biaxial flexural strength test. For uniaxial strength test (three-point or four-point flexural test), the crack initiation is caused mainly by tensile stresses on the lower surfaces of the samples. Four-point bending test is a method that has been used to evaluate the strength of one-layered and bilayered ceramic specimens (Pittayachawan, 2009). According to (ISO 17565:2003), rectangular samples are used in this test and supported by two rods that are adjusted 21 mm apart. The specimens are loaded by two rods set 7 mm apart with 0.2 mm/min loading rate. Then, the ultimate tensile stress is measured (Quinn et al., 2009) (Figure 2.2).

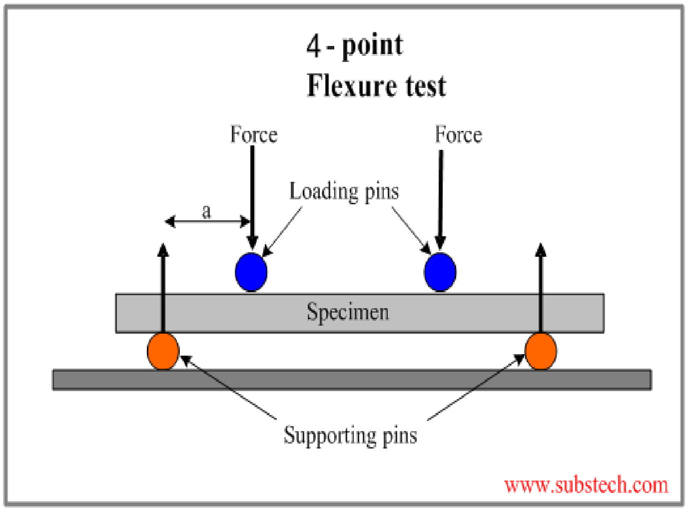

Figure 2.2: Four-point bending test, Adopted from (www.substech.com)

For instance, the 4-point flexural strength test was used by Aboushelib and Wang (2010) to investigate the effect of three different surface treatments on the flexural strength of zirconia using bar-shaped samples.

Another standardized test for strength evaluation of dental ceramic materials is three-point bending test, which might be influenced by edge fractures. Data variation in strength records from the actual values of the materials was reported (Seal et al., 2001). 3-point flexure test is shown in Figure 2.3.

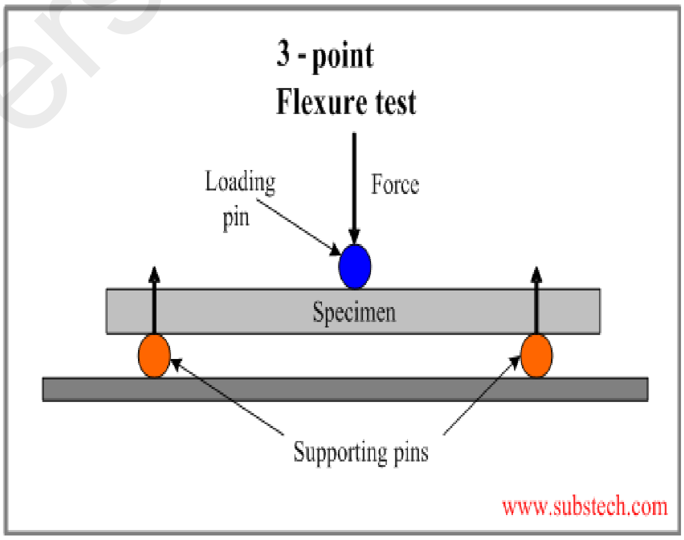

Figure 2.3: Three-point bending test, Adopted from (www.substech.com)

Wang et al. (2008) evaluated the influence of the CAD/CAM milling process and other surface treatments on the flexural strength of zirconia frameworks. Zirconia bars specimens were loaded via 3-point flexural strength test.

The maximum tensile stresses under biaxial strength test conditions are observed within the central loading surface; this clarifies why this method is more preferable than uni-axial flexural strength test, which is associated with undesirable edge failures (Guazzato et al., 2004). Additionally, this test is characterized by using discs specimens which are easier to be prepared and tested in a larger effective surface area (Seal et al., 2001) (Figure 2.4).

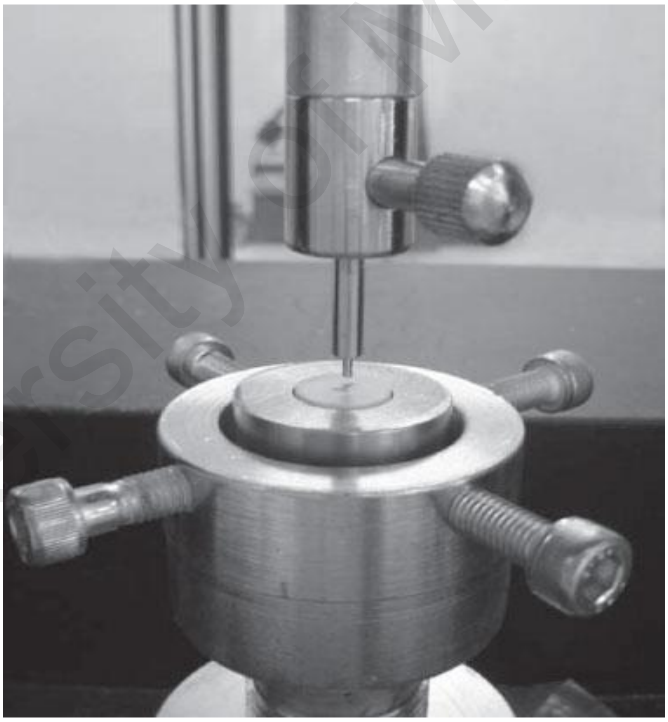

Figure 2.4: Biaxial flexural strength test, Adopted from (Al-Makramani et al., 2010)

As examples of utilizing biaxial strength test, there are two studies done by Yilmaz et al. (2007) and Al-Makramani et al. (2010). Yilmaz et al. conducted a comparative study using biaxial flexural strength method; disc-shaped specimens were used to compare the biaxial flexural strength of 6 different all-ceramic core materials (Cergo, Finesse, IPS

Empress, In-Ceram Zirconia, In-Ceram Alumina and Cercon Zirconia). The other study was conducted by Al-Makramani and co-workers to evaluate and compare the biaxial flexural strength of three ceramic core materials (Turkom-Cera, Vitadur-N and In-Ceram).

2.4.2.3 Clinically relevant test design

All-ceramic restorations, in service, consist of multi-layered structure including one or two layers of ceramic atop a cement layer and supported by dentine. This sophisticated structure is not well simulated by simple bar or disc-shaped specimens (Kelly, 1999). Therefore, there is no standardized test for measuring the strength of dental restorations due to their complex configurations and geometrical shapes. This may explain the discrepancies amongst the published data of strength values for a particular material (Powers & Sakaguchi, 2006)**.** In vitro tests should simulate a clinical failure mode in order to assess and predict the clinical performance of all-ceramic restorations through these tests (Scherrer et al., 2007). It is important to select a clinically relevant method to produce comparable fracture modes to those of clinical situations. Furthermore, specimen design should be carefully selected to mimic clinical crowns. In other words, the ceramic material should be tested within an entire restoration structure, which includes multi-layered specimen with veneering porcelain, core ceramic, luting agent and dentine, since the overall strength is significantly influenced by each layer (Fleming et al., 2006).

Kelly (1999) conducted an investigation on the most common failure tests of single-unit restorations in which specimens were loaded via spherical indenters. The clinical relevance of such failure tests was discussed. The characteristics of clinical failures were contrasted with failures induced by the traditional loading tests to show any discrepancies. It was drawn that traditional load-to-fracture tests are inappropriate for fracture testing of all-ceramic restorations, as they do not bring out fracture mechanisms similar to those seen in clinical situations. The author suggested the future need for validating such tests in order to illustrate the role of other variables in the success of all-ceramic prostheses. These variables include bonding, occlusion, cements and substructure materials (Kelly, 1999).

Several parameters should be considered before designing the strength test of all-ceramic restorations in order to give the test a clinical relevance. The first factor is the prosthesis design, which includes restoration geometry, thickness ratios of ceramic layer(s), teeth selection criteria and preparation design. The other parameters include simulation of periodontal ligament membrane, the influence of thermal conditions, vertical/oblique loading conditions, dry/wet environment and the selection of appropriate bonding system as well. Nevertheless, it is quite difficult to model all conditions in one experiment (Anusavice et al., 2007).

Lateral forces as well as vertical forces may effectively contribute to the oral masticatory cycles (Kim et al., 2013; Soares et al., 2006). Hou et al. (2011) confirmed that the structure of tooth can tolerate greater vertical loading than the inclined force loading. Therefore, the different loading directions may cause different fracture loads even for the same material because of the different stress distribution pattern for each approach. On that account, many studies suggested to concentrate on the influence of lateral force as a clinically associated status (Sornsuwan et al., 2011). Kalburge et al. (2013) studied the effect of different marginal ridge thickness on the fracture resistance of root canal treated upper premolars restored with two types of composites. Teeth were loaded at 45˚ angle to imitate the average angle of occlusion between upper and lower premolars. Sonza et al. (2014) evaluated the influence of the infrastructure material on the fracture mode of four different dental crowns. They suggested that a 30˚ angle load applied on lower premolar could produce the transverse loading simulated during mastication.

Cementation process plays a significant role in the success of all-ceramic restorations (Blatz et al., 2003). Many studies showed that using a strong resin-bonded luting agent gives high retention and increases the fracture resistance and toughness for both tooth structure and ceramic restoration (Pace et al., 2007). The nature of adhesive resin cements along with their remarkable mechanical properties inhibits the propagation of microcracks through blunting their internal surfaces; the fracture resistance of the restoration is thus increased (Borges et al., 2009; Shahrbaf et al., 2014; Yucel et al., 2012). Therefore, adhesive composite resin luting systems are the recommended choice for cementation of all-ceramic restoration. ParaCore (Coltène/Whaledent, Switzerland) is dual-cured resin cement using total etch or two-stages technique which was investigated in some studies and reported with the highest bonding properties and leakage resistance compared to other cements (Millar & Deb, 2014).

2.5 Studies on strength of CEREC Blocs, IPS e.Max Press and Cercon materials

Yilmaz et al. (2007) investigated the biaxial flexural strength of Cercon core and other commonly used five cores (Finesse, IPS Empress, Cergo, In-Ceram Zirconia, In-Ceram Alumina). In comparison, Cercon core showed greater value of flexural strength (1140.89 N) than the other cores used.

Sornsuwan et al. (2011) studied the effect of occlusal configuration of Cercon bilayered crowns on the fracture load through using different angles (0˚, 15˚ and 30˚ angles) in static flexural test with different core thickness (0.4, 0.6, 0.8 mm). All Cercon cores were veneered via (Cercon ceram Press) with a typical thickness of 1.5 – 3 mm using press-on technique. A high scatter of fracture load was established among groups. The lowest value was 376 N for 0.6 mm core thickness at 15˚ angle while the highest value was 2229 N for 0.8 mm core thickness at 0˚ angle. Delaminating of the veneer layer was the predominant failure mode on most cases in this study.

Zhao et al. (2012) evaluated the effect of veneer application on failure pattern of IPS e.Max Press crowns. The fracture loads as well as failure modes were established for IPS e.Max Press without veneer (full crown) and with veneer (bilayered crown). Using static vertical loading, the recorded values showed a significant difference in failure loads between two-layered crowns (1431 N) and full crowns (2665 N), thus it was concluded that veneer application decreases effectively the fracture resistance of IPS e.Max Press. Delaminating of veneer layer and cohesive veneer were the main failure modes that were observed in veneered crowns group, whereas most of full crowns group failed in catastrophic mode.

Schmitter et al. (2013) used CEREC Bloc as a veneer layer over zirconia crowns to assess the fracture load of the manual veneering technique compared to CAD/CAM veneering. 50 % of crowns were tested statically until failure at 30˚ angle; the other half of the crowns was subjected to artificial aging in terms of cyclic loading and thermocycling. The failure load of manual-layered veneer (1165 N) was significantly higher than CEREC Bloc veneer (395 N). On the other hand, no crowns veneered with CEREC Bloc failed during artificial aging, whereas 87.5 % of the other group had failed.

Kois et al. (2013) compared the fracture resistance of IPS e.Max Press partial posterior crowns to three different dental matreials (feldspathic ceramic, leucite-reinforced ceramic and indirect resin composite). All groups were subjected to vertical compressive load until failure. The failure load of IPS e.Max Press group (335 N) was significantly higher than other groups. The majority of IPS e.Max Press specimens presented a cohesive fracture mode within the ceramic crown; the root remained intact.

Zhao et al. (2014) studied the influence of cyclic loading on monolithic and bilayered IPS e.Max Press crowns. Using single loading, the fracture loads for both groups were estimated before and after fatigue testing. The mean failure loads for monolithic crowns before and after cyclic loading were 2686 N and 2133 N, respectively, whereas the fracture values for the second group before and after cyclic loading were 1443 N and 1464 N, respectively. According to the outcomes of this study, they concluded that cyclic loading has a significant influence on accelerating the fracture process for monolithic IPS e.Max Press crowns but not for the two-layered crowns.

Yang et al. (2014) compared the fracture resistance of CEREC Blocs to two machinable all-ceramic systems (IPS e.MaxCAD and inCoris ZI) after thermocycling and mechanical cycling. The mean fracture loads for CEREC Blocs before and after mechanical and thermal fatigue were 2281 N and 1226 N, respectively; thermocycling and mechanical fatigue had a significant effect on the failure loads for all groups. In comparison, CEREC Blocs had the lowest fracture loads among groups. However, there was no significant difference in failure load between the groups. The main fracture mode for all groups was noticed at dentine-cement interface.

Altamimi et al. (2014) conducted an in vitro study to evaluate and compare the fracture resistance of monolithic IPS e.Max Press crown and two bilayered zirconia/fluorapatite crowns; standard and anatomical copings. IPS e.Max Press crowns had the highest mean fracture strength value among groups (1360 N). All crowns were subjected to dynamic loading under water and then loaded under static loading. Catastrophic failure pattern was observed mainly for IPS e.Max Press crowns, while zirconia/fluorapatite crowns showed veneer fractures in most cases.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Collection and selection of the teeth

Fifty recently extracted human maxillary first premolars were collected. All teeth were collected within three months from one Malaysian orthodontic clinic. During the first week, the teeth were immersed in 0.5% Chloramine T trihydrate solution for disinfection purpose (ISO/TS 11405/2003). Calculus and soft deposits were removed via an ultrasonic scaler (Piezon® Master 400, Nyon, Switzerland). The teeth were kept hydrated until used by storing them at 4 ˚C in distilled water which was changed weekly (ISO/TS 11405/2003). The teeth were examined under a stereomicroscope (Kyowa Optical, Tokyo, Japan) at 10x magnification to select the appropriate teeth for this study. The inclusion criteria were teeth without defects, restorations, caries or cracks. Thirty intact premolars were selected for this study. The selected premolars had similar shape and size. The dimensions measurement was calculated using a digital caliper (Mitutoyo/Digimatic, Tokyo, Japan) as shown in Figure 3.1. The obtained average of teeth dimensions as follows; (9.5 - 10.5 mm), (7.5 - 8 mm) and (21.5 - 22.5 mm) for bucco-lingual width, mesio-distal width and occluso-apical length, respectively.

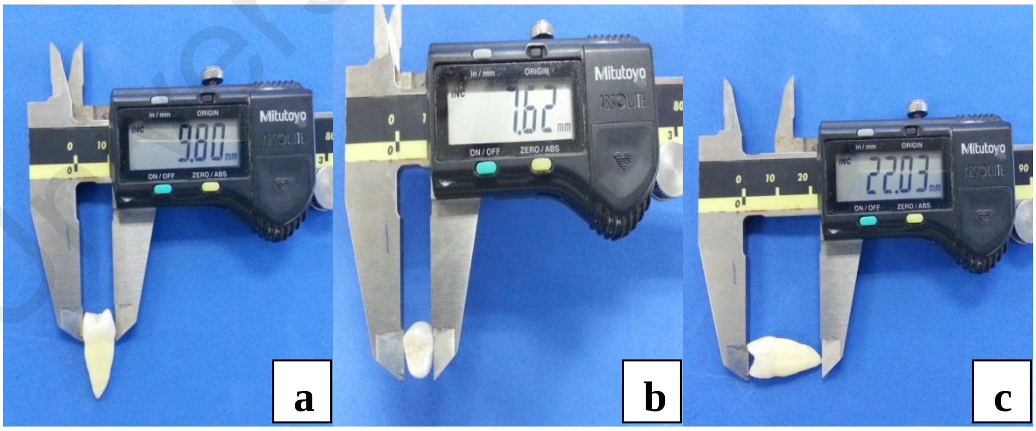

Figure 3.1: Measurement of teeth dimensions; a) bucco-lingual width, b) mesio-distal width, c) occluso-apical length

3.2 Periodontal membrane simulation

As an attempt to simulate the function of the periodontal membrane, the root surface of each tooth was coated by a delicate layer of light body silicon paste (Aquasil Ultra XLV Dentsply/Caulk) (Figure 3.2). The applied layer was 200 to 400 µm and 3 mm beneath the cement-enamel junction (CEJ) (Hou et al., 2011).

Figure 3.2: Periodontal membrane simulation

3.3 Teeth mounting

The teeth were stabilized vertically in cubic moulds using sticky wax. The teeth were then mounted 2 mm short of CEJ in cold-cured epoxy resin (Mirapox A and B, Miracon, Kuala Lumpur, Malaysia). All specimens were kept inside an incubator and given 24 hours for resin complete setting (Figure 3.3).

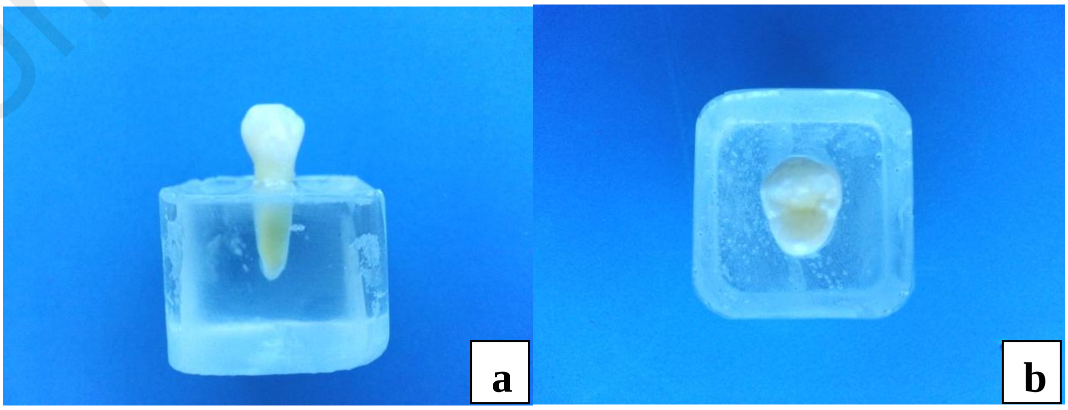

Figure 3.3: The tooth mounted in the epoxy resin; a) Buccal view, b) Occlusal view

3.4 Teeth preparation

In order to standardize the preparation, the teeth were prepared via a high speed handpiece fixed to a paralleling device. As described by Al-Makramani et al. (2009), this device consists of a specimen fixation plate in which the specimen can be clamped firmly and rotated against the mounted bur during the preparation. The paralleling device also has two arms; a vertical arm which holds the handpiece via customized jig and a horizontal arm with flexible joint (Figure 3.4). During the preparation, the handpiece angle was set at 6˚ angle to achieve a total convergence of 12˚ angle using special jig used before for the same purpose (Al-Makramani et al., 2009) (Figure 3.5).

Figure 3.4: The paralleling device used for teeth preparation

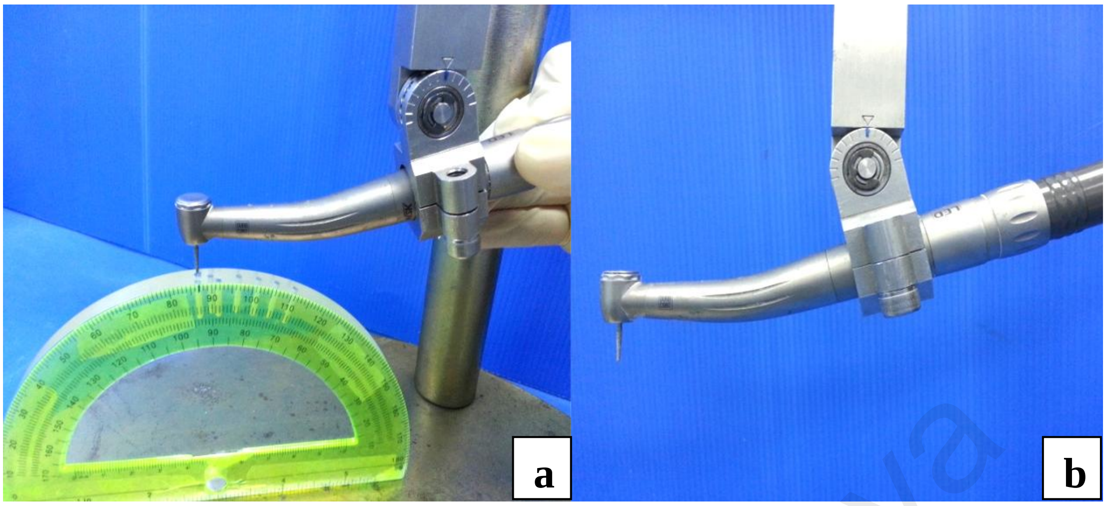

Figure 3.5: a) The jig used for setting the tapered angle, b) The jig used for fixation the handpiece at the oriented angle

The axial walls were prepared using a tapered flat-ended diamond bur (No.846C016, Alpen® Rotary instruments, Coltene®, Switzerland). A 1 mm shoulder finishing line was prepared 0.5 mm above CEJ using the same bur. The occlusal surfaces of teeth were prepared 4 mm above CEJ via a barrel diamond bur (No.811C033, Alpen® Rotary instruments, Coltene®, Switzerland) to produce the anatomical inclination of tooth cusps as shown in (Figure 3.6). Finishing the prepared surfaces was carried out using a fine grit diamond bur (No.846F016, Alpen® Rotary instruments, Coltene®, Switzerland). The burs set were changed after preparation of each five teeth.

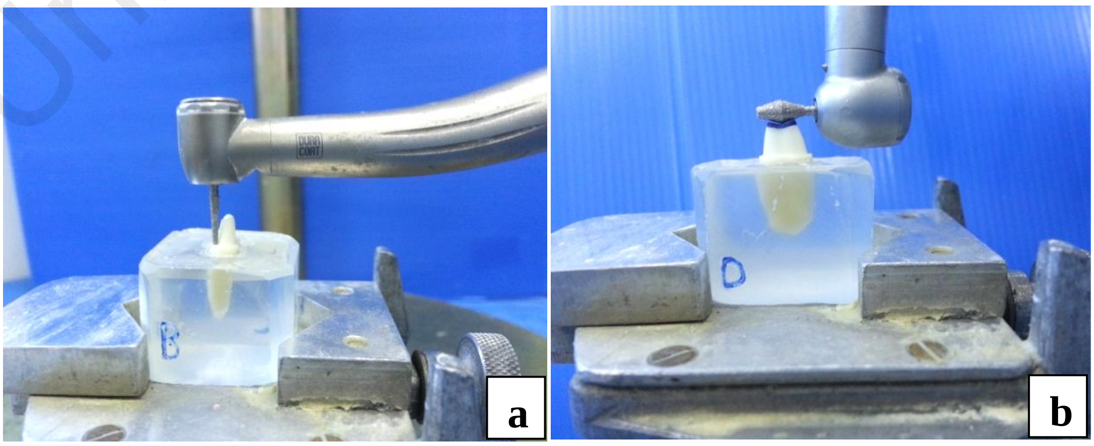

Figure 3.6: Tooth preparation; a) Axial walls reduction, b) Occlusal surface preparation

In summary, the final criteria of the prepared teeth were as follows; 4 mm coronal height, 6˚ axial tapering walls and 1 mm circumferential shoulder finishing line (Figure 3.7). This preparation matched the requirement of all-ceramic crowns used in this study as illustrated by the manufacturers.

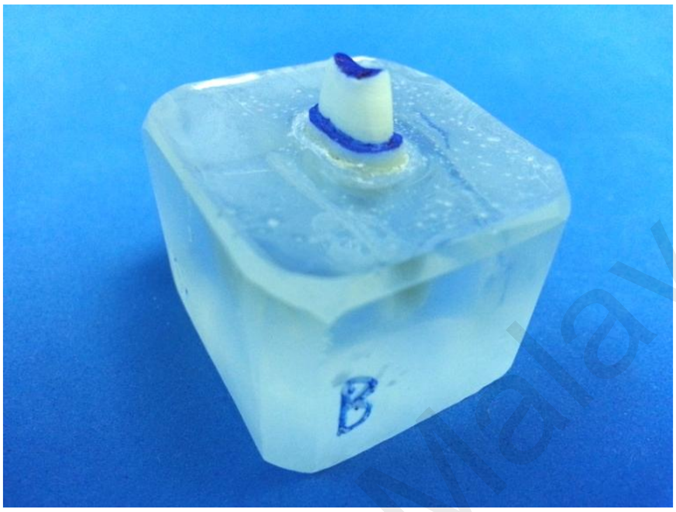

Figure 3.7: Finished tooth preparation

3.5 Teeth grouping

The prepared thirty teeth were divided randomly into three group (one group = ten teeth) to receive all-ceramic crowns chosen for this study; CEREC Bloc (group A), IPS e.Max Press (group B) and Cercon smart ceramic (group C).

3.6 Fabrication of all-ceramic specimens

3.6.1 CEREC Blocs crowns

A titanium dioxide powder was applied to the first group to give the required contrast for the optical scanner. Each tooth was scanned via an optical probe and the captured images were saved in the acquisition unit in which the final crowns were designed. A total of ten CEREC Blocs crowns were milled in the CEREC milling unit. The whole procedure was carried out at dental unit (chair-side) as illustrated in Figure 3.8 and Figure 3.9.

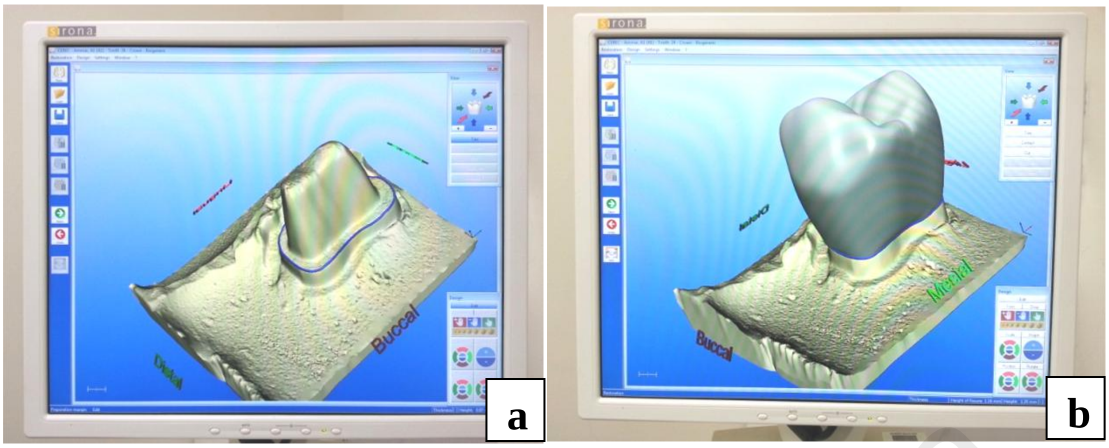

Figure 3.8: CEREC acquisition unit; a) Optical impression, b) Crown designing

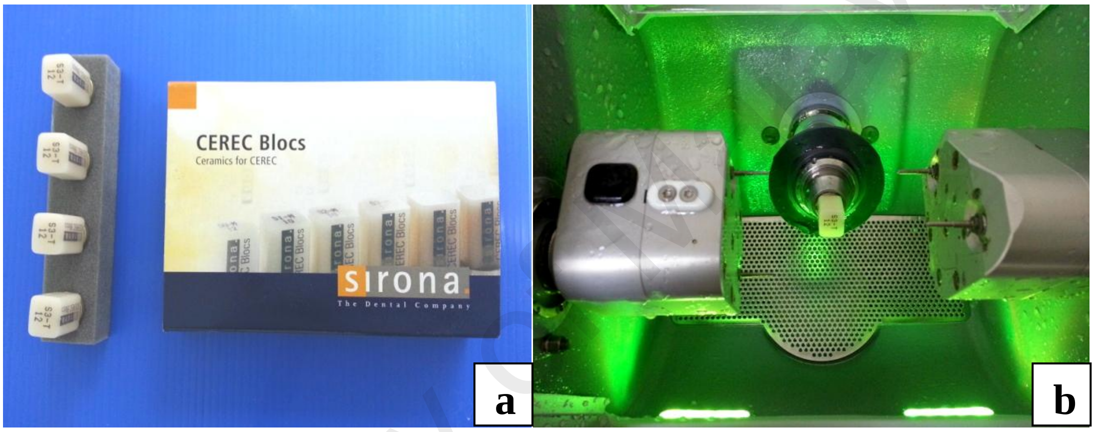

Figure 3.9: Milling Process; a) CEREC blocks, b) CEREC milling machine

3.6.2 IPS e.Max Press crowns

For the second group, ten impressions were taken for each tooth using polyether impression material (Impregum™ Penta™ Soft, 3M ESPE, USA). Wax boxing (Boxing In Wax, Metrodent Ltd, Huddersfield, England) was applied to ten bottle caps to represent the impression trays. The impressions were then poured with die stone (Densit, Shufo, Japan) (Figure 3.10). Ten wax patterns were made and invested in a phosphate-bonded investment material (Giroinvest Super, Amann Girrbach, Austria) followed by the burn out process. Then, IPS e-max Press ingots were pressed into the moulds using a custom furnace at 1050 ˚C as shown in Figure 3.11. Finally, crowns were finished and glazed according to the manufacturer's instructions, resulting in a total of ten fabricated IPS e-max Press crowns.

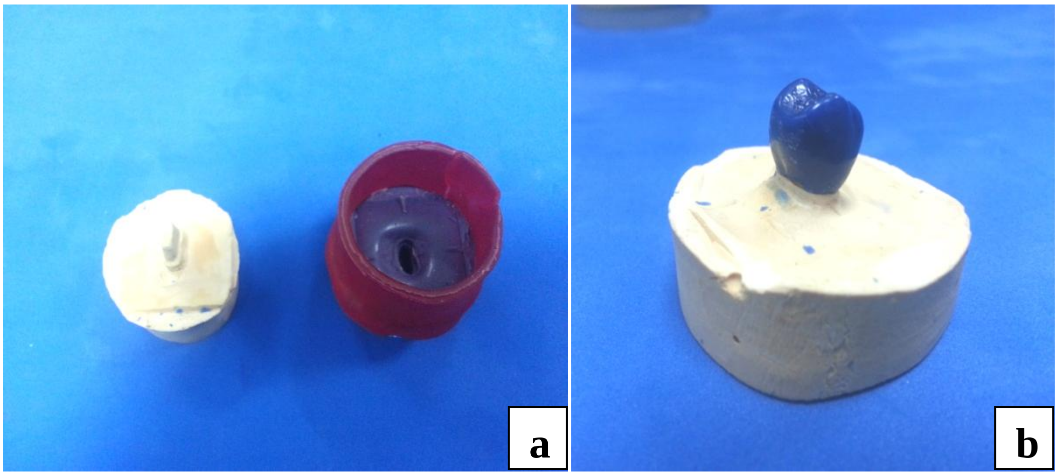

Figure 3.10: a) Customized impression tray, b) Adjusting the wax pattern

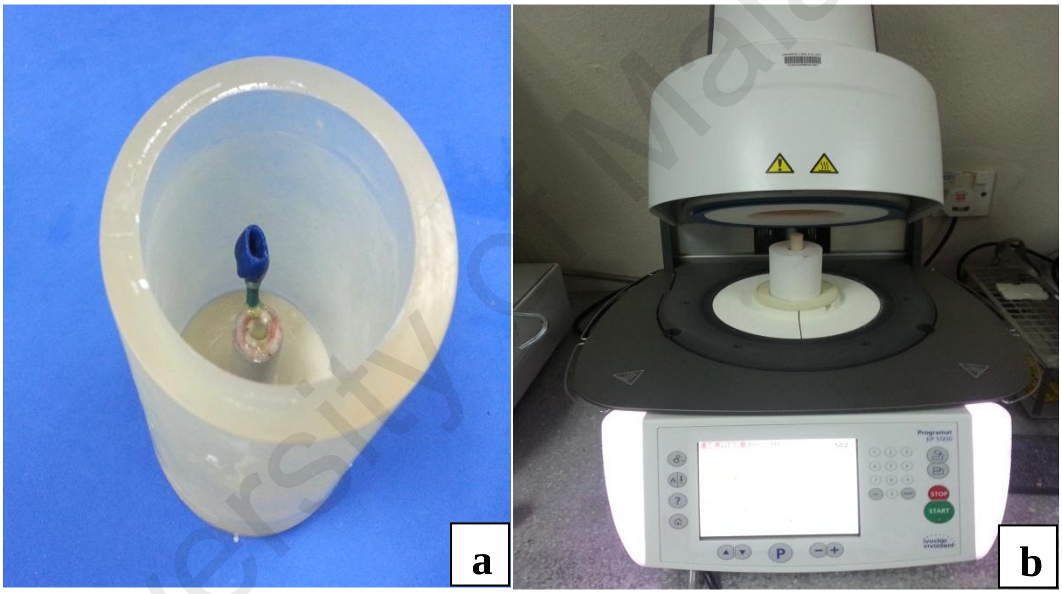

Figure 3.11: a) Spruing the wax pattern into the investment mould, b) Heat pressing of IPS e.Max Press ingot

3.6.3 Cercon crowns

The same impression technique used for the second group (B) was repeated for the last ten premolars to produce ten representative dies for the third group (C). The dies were then scanned using the scanning unit of the cercon system (Cercon eye). The final designing of the copings were processed via cercon CAD unit (Cercon Art). The Cercon copings were then milled from presintered zirconia blanks inside the milling unit (Cercon Brain) for a period of 35 minutes for each crown. Eventually, the tenth copings were sintered in the Cercon heat furnace at 1350 ˚C for 6-8 hours. The final veneering build up procedure was performed for all Cercon copings using Cercon Kiss material according to the manufacturer’s instructions.

Figure 3.12: a) Die scanning in Cercon eye, b) Coping designing

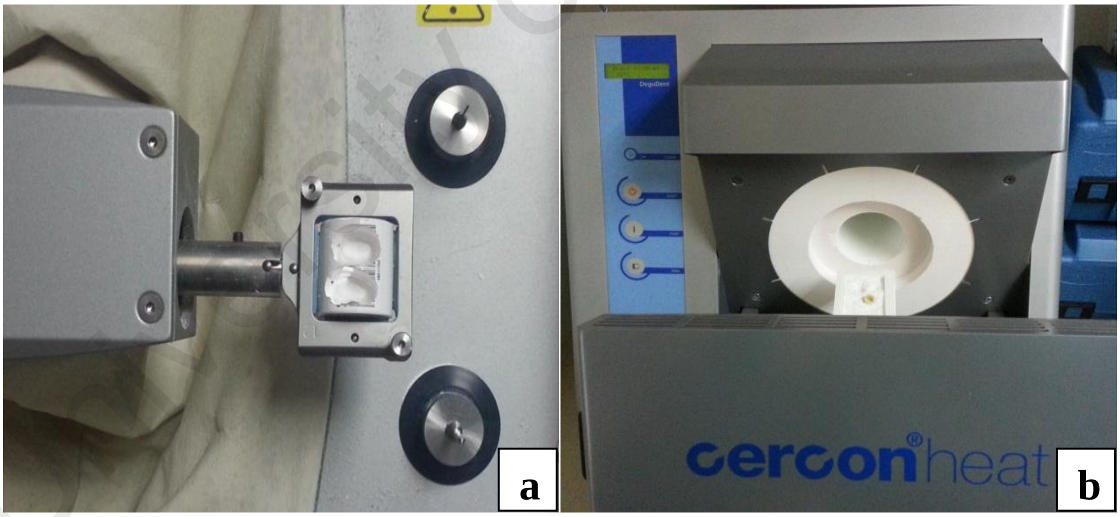

Figure 3.13: a) Cercon coping milling, b) Coping sintering

Figure 3.14: Veneering procedure (Cercon Kiss)

3.7 Crowns cementation

Paracore (Coltène/Whaledent, Switzerland), dual-cured resin cement, was selected to be used for crowns cementation in this study (Figure 3.15). All teeth with their respective crowns were cleaned with acetone and air dried prior to cementation. ParaBond non-rinse conditioner was applied onto the entire preparation using a brush for 30 s. The excess ParaBond non-rinse conditioner was dried using a gentle stream of air for 2 s. Next, ParaBond adhesive were applied to all prepared surfaces. The inner surfaces of the all-ceramic crowns were also conditioned according to the manufacturer’s instructions. Finally, the application of ParaCore cement was carried out into the inner surfaces of all crowns according to the manufacturer’s instructions. All cemented crowns were then subjected to a load of 5 kg for 10 minutes using a custom made apparatus “Al-Makramani Load” (Al-Makramani et al., 2008). After the completion of the cementation process, all specimens were stored in a sealed container filled with distilled water and placed in an incubator at 37 ˚C for 24 hours.

Figure 3.15: ParaCore cement

3.8 Thermocycling

The specimens were subjected to 500 thermal cycles between 55 ˚C and 5 ˚C in distilled water according to (ISO/TS 11405/2003). This process was carried out in thermocyling machine (ATDM T6 P D, Malaysia) as shown in Figure 3.16. The specimens were removed directly after the thermocycling procedure was completed and left at room temperature for the next 24 hours.

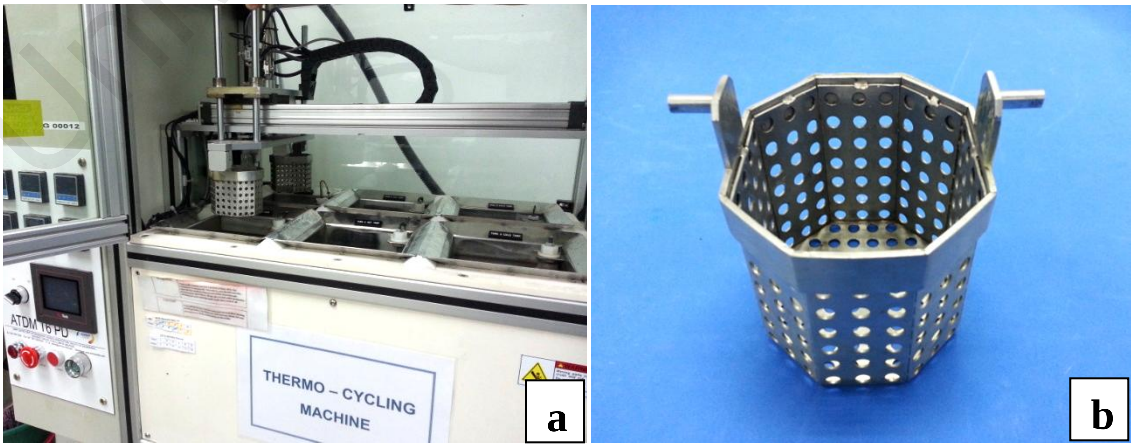

Figure 3.16: a) Thermocycling machine, b) Specimens holder (mesh)

3.9 Fracture Testing

3.9.1 Fracture resistance

Each specimen was secured into a special designed jig in order to be subjected to testing on the universal testing machine (Shimadzu, Shimadzu Corp., Japan) (Figure 3.17). A 3 mm stainless steel bar will was mounted on the Shimadzu machine to apply a compressive load obliquely at an angle of 45˚ to the occlusal surface of the crown and 135˚ angle to the long axis of the tooth as shown in Figure 3.18. The stainless steel bar was applied on the palatal cusp (2 mm away from the central groove) at a crosshead speed of 1 mm/min until fracture obtained. The maximum force value to produce fracture was established in Newton.

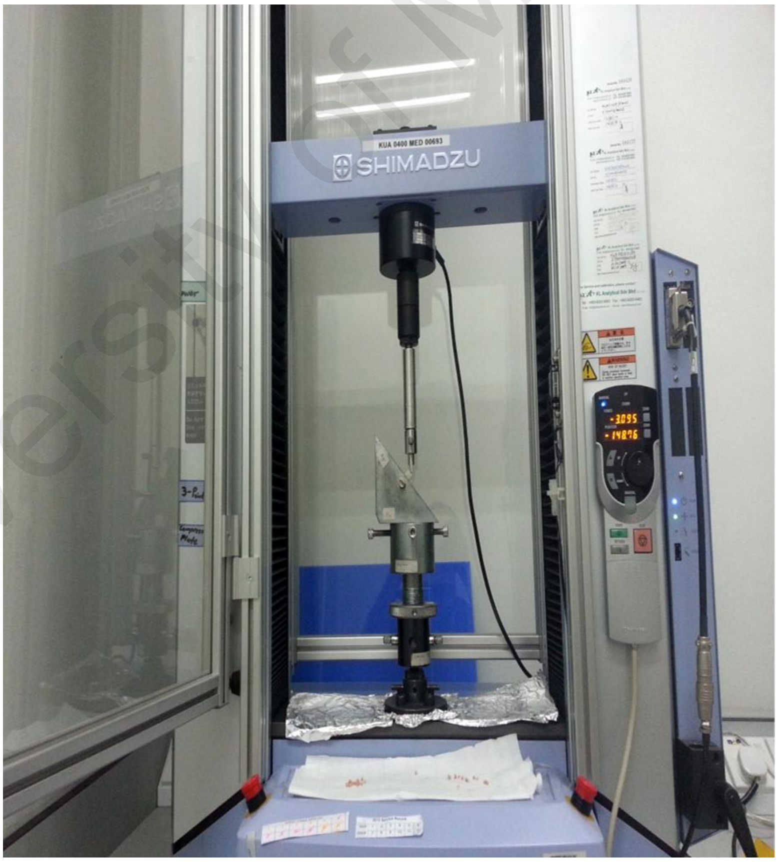

Figure 3.17: Shimadzu universal testing machine

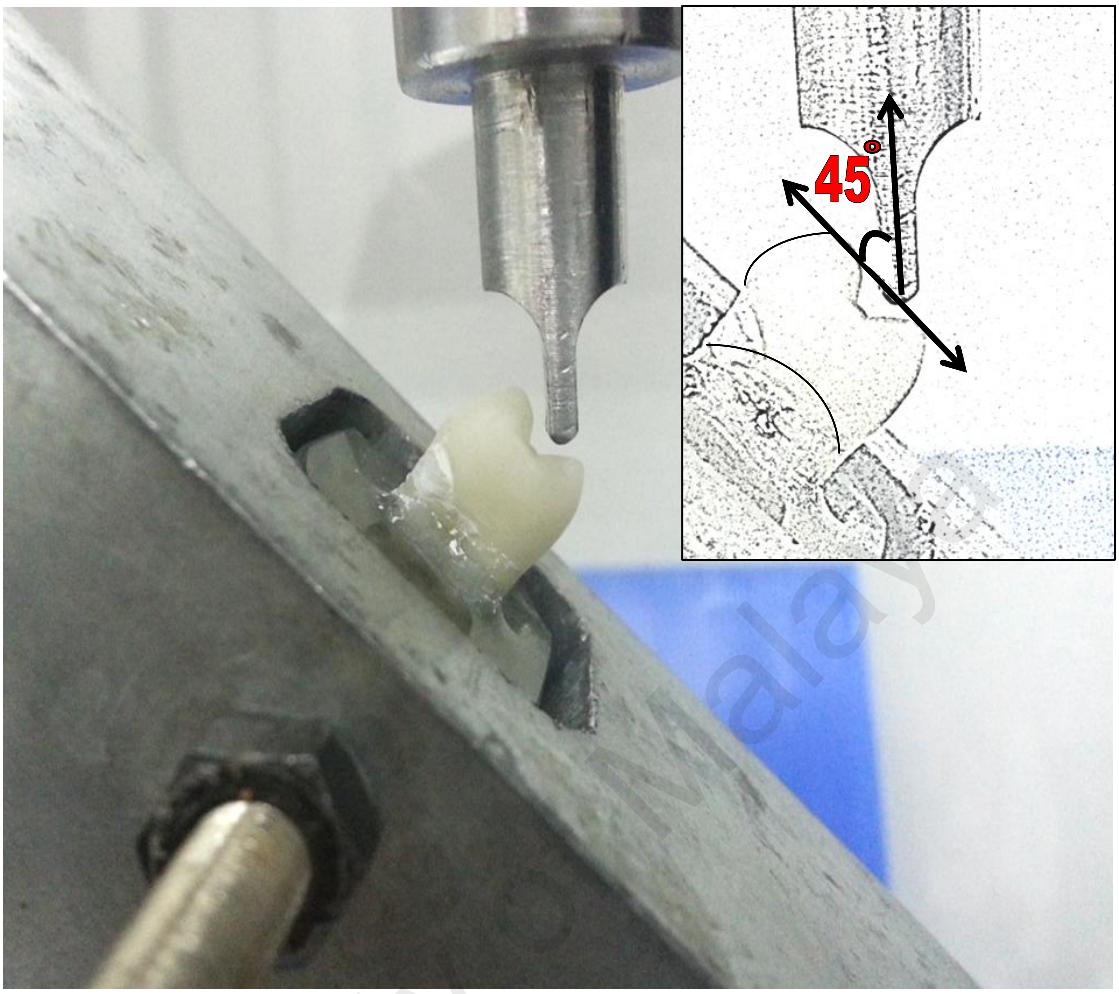

Figure 3.18: Specimen during the test (oblique loading)

3.9.2 Failure mode

First, the specimens were visually examined to classify the failure modes. Then the specimens were assessed under a stereomicroscope (Kyowa Optical, Tokyo, Japan) to confirm the first findings. Furthermore, three specimens (one per group) were selected for fractography investigation via scanning electron microscope (FEI Quanta 200 SEM, FEI Co.Eindhoven, Netherlands). The mode of failure was classified into favourable (repairable) and non-favourable (non repairable) fracture modes. The favourable failures were described as restorable failures, including fractures within the restoration and unfavourable failures were defined as non-restorable failures including fractures within the tooth structure (Abdulmunem et al., 2016).

3.10 Data Analysis

The data were statistically analyzed using SPSS software, version 12 (SPSS Inc., Chicago, USA). The normal distribution of fracture loads between the groups was established using Shapiro-Wilk test. The mean fracture resistance of multiple groups was analyzed using the one-way analysis of variance test (ANOVA), at $\alpha = 0.05$. Subsequently, Turkey's HSD post hoc test was conducted for comparison among groups. The statistics of the failure modes were descriptively established and analyzed.

CHAPTER FOUR

RESULTS

4.1. Fracture load

The recorded mean failure load of CEREC crowns was (387.24 ± 60.20 N) with maximum and minimum fracture loads of 475.81 N and 298.46 N, respectively. The frequency of fracture resistance for CEREC group is shown in Figure 4.1.

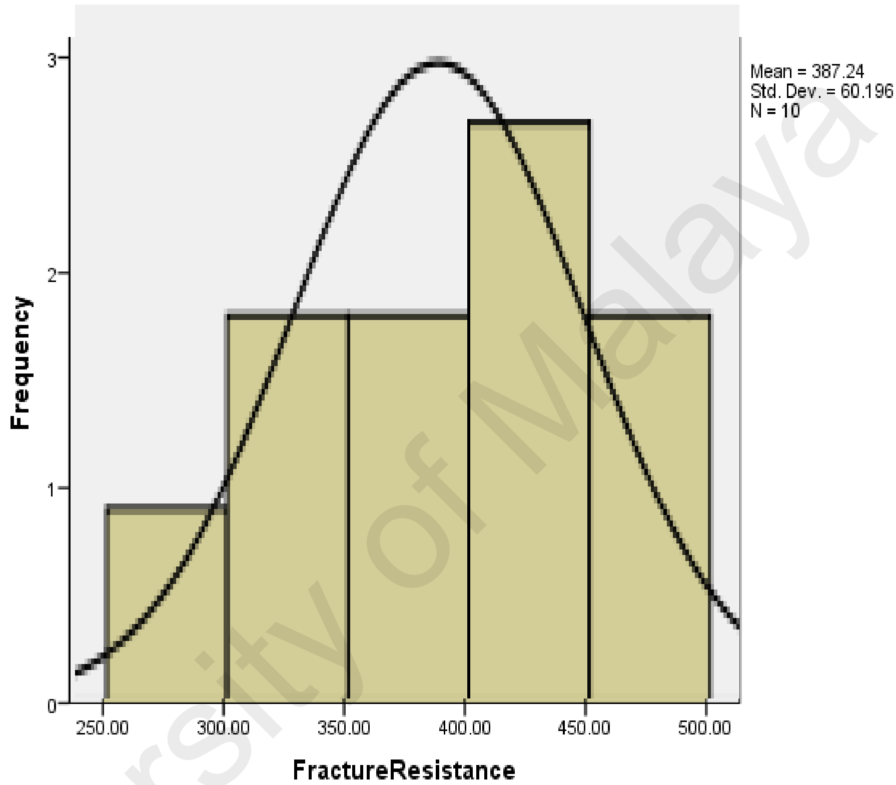

Figure 4.1: Fracture loads for CEREC group

The mean fracture resistance for IPS e.Max Press crowns was (452.25 ± 86.76 N) with maximum and minimum fracture loads of 602.00 N and 360.61 N, respectively. The frequency of fracture resistance for IPS e.Max Press group is shown in Figure 4.2.

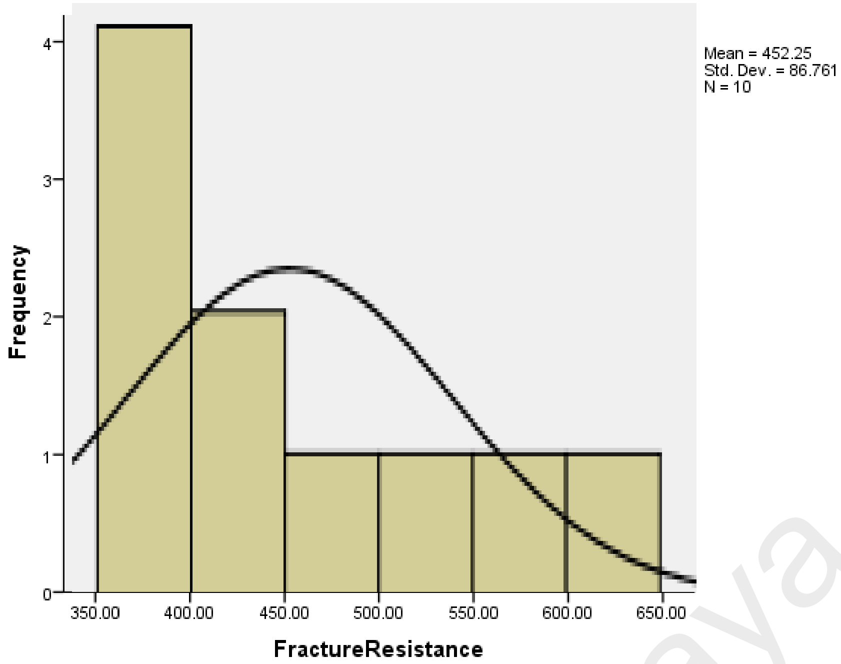

Figure 4.2: Fracture loads for IPS e.Max Press group

The mean fracture load for Cercon crowns was (540.81 ± 171.06 N) with maximum and minimum fracture loads of 780.73 N and 265.63 N, respectively. The frequency of fracture resistance for Cercon group is shown in Figure 4.3.

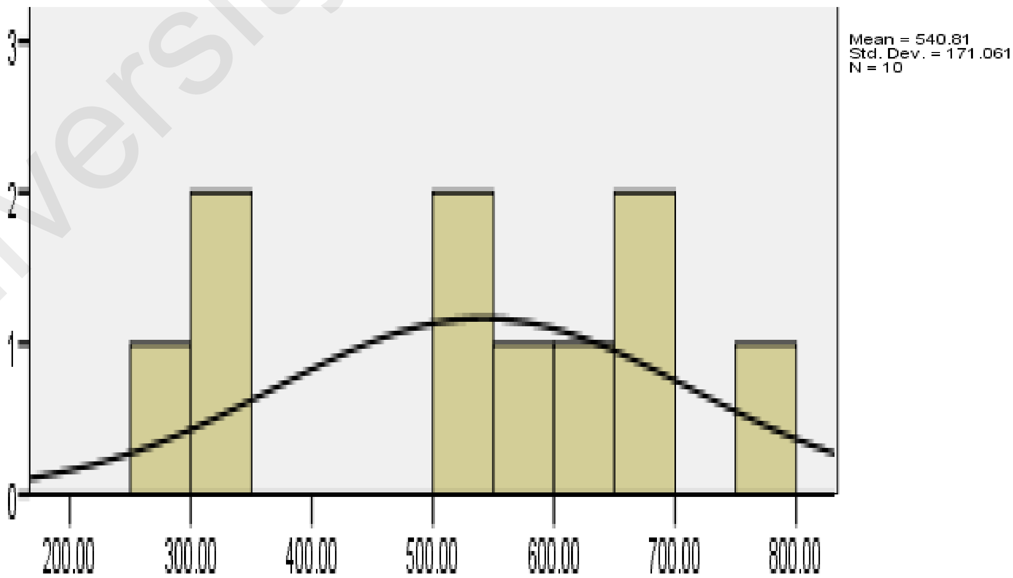

Figure 4.3: Fracture loads for Cercon group

For all groups, the summary of the mean fracture loads is shown in Table 4.1. The mean fracture resistance for Cercon crowns was the highest compared to the other groups; while CEREC Blocs group showed the lowest records. The fracture loads among groups are further shown in Figure 4.4.

Table 4.1: Mean fracture loads for all groups

Group	Samples No.	Mean (Newton)	Std. Deviation	Minimum	Maximum
CEREC Blocs	10	387.24 N	60.20	298.46	475.81
IPS e.Max Press	10	452.25 N	86.76	360.61	602.00
Cercon	10	540.81 N	171.06	265.63	780.73

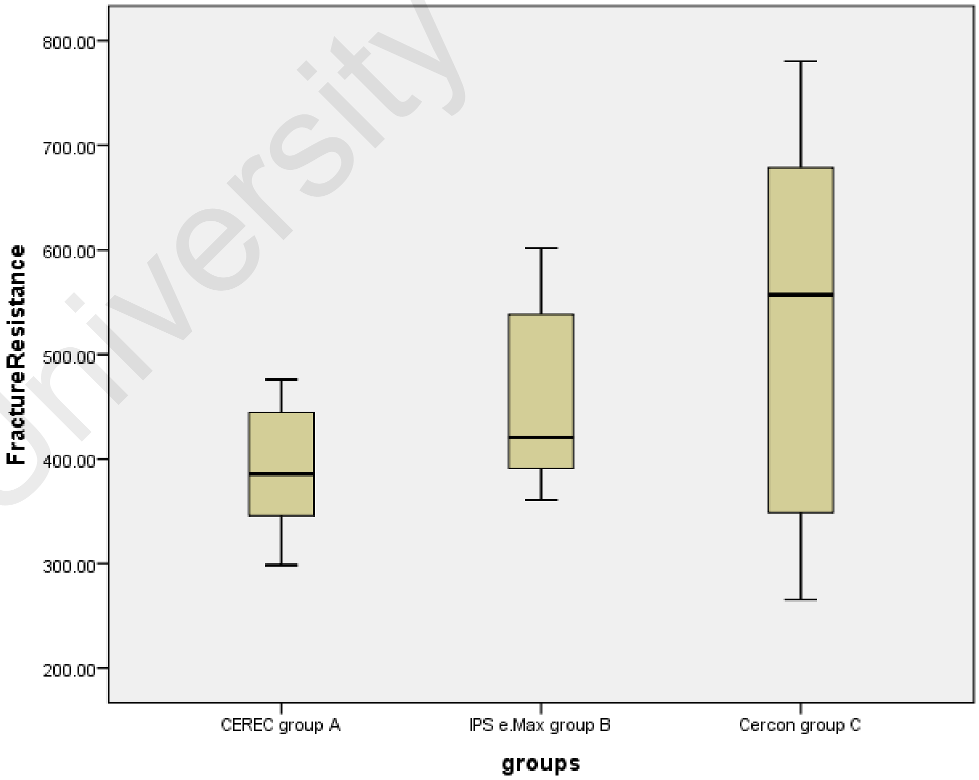

Figure 4.4: Fracture loads for all groups

The data distribution was checked using the Shapiro-Wilk test which indicated normal distribution for all groups, $p > 0.05$. One-way analysis of variances (ANOVA) was conducted and indicated a significant difference amongst the different groups ($p < 0.05$) as shown in Table 4.2.

Table 4.2: Result of One-way ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	118853.534	2	59426.767	4.411	0.022
Within Groups	363717.059	27	13471.002		
Total	482570.593	29			

Tukey HSD Post Hoc test was established for multiple comparisons between groups. The mean fracture load of Cercon crowns (540.81 ± 171.06 N) was significantly higher than CEREC Blocs crowns (387.23 ± 60.20 N) at $p < 0.05$. Despite that the mean fracture resistance of Cercon group was higher than that for IPS e.Max Press crowns (452.25 ± 86.76 N), there was no significant difference between these two groups ($p > 0.05$). Furthermore, no significant difference was detected between CEREC group and IPS e.Max group ($p > 0.05$) as shown in Table 4.3.

Table 4.3: Tukey HSD Post Hoc test

(I) groups	(J) groups	Mean Difference (I-J)	Sig.
CEREC group A	IPS e.Max group B	-65.01630	0.434
	Cercon group C	-153.57710(*)	0.017
IPS e.Max group B	CEREC group A	65.01630	0.434
	Cercon group C	-88.56080	0.221
Cercon group C	CEREC group A	153.57710(*)	0.017
	IPS e.Max group B	88.56080	0.221

(*) Significant Difference, $p < 0.05$

4.2 Fracture modes

The fracture patterns were determined visually using stereomicroscope at 30 X magnification. The different failure modes of test groups are shown in Table 4.4

Table 4.4: Fracture modes distribution per group

Ceramic group	Failure modes		Total
	Favourable (Ceramic fracture)	Non-favourable (Tooth fracture)	
CEREC Blocs	8	2	10
IPS e.Max Press	-	10	10
Cercon	2	8	10

4.2.1 Fracture modes of CEREC Blocs group

Examination of failure modes revealed that 80 % of CEREC Blocs crowns exhibited ceramic crown failure mode (tooth was intact). Whereas, severe fracture of tooth was observed within 20 % of this group (Figure 4.5).

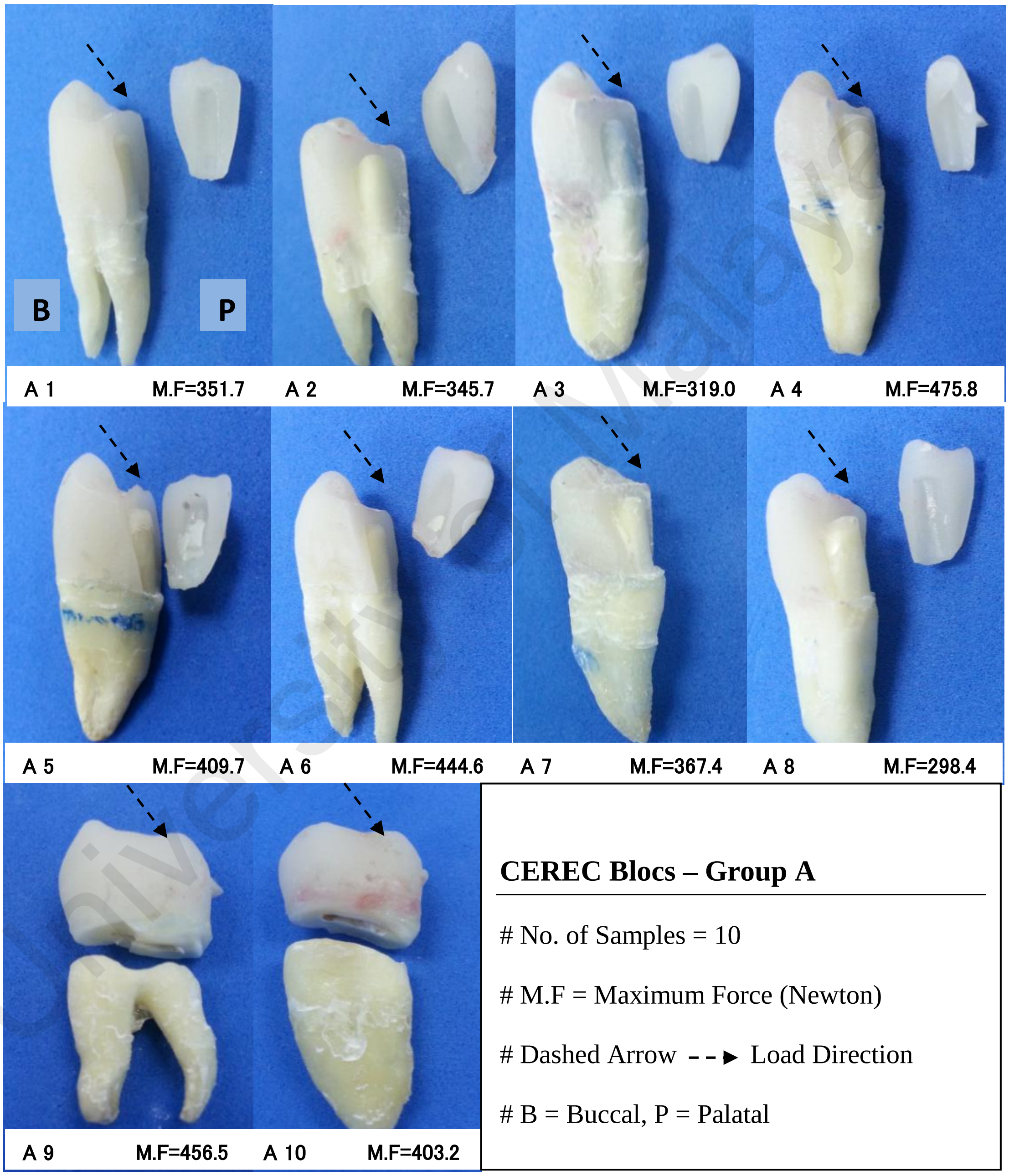

Figure 4.5: Failure patterns of CEREC Blocs specimens; ceramic crown fracture (A 1 to A 8) and severe tooth fracture (A 9 and A 10)

4.2.2 Fracture modes of IPS e.Max Press group

For IPS e.Max Press group, all the crowns exhibited severe tooth fracture extending in a transverse plane from the buccal cervical area of crown to the palatal cervical area of root and ultimately separated the tooth into two pieces while ceramic crown remained intact; as shown in Figure 4.6.

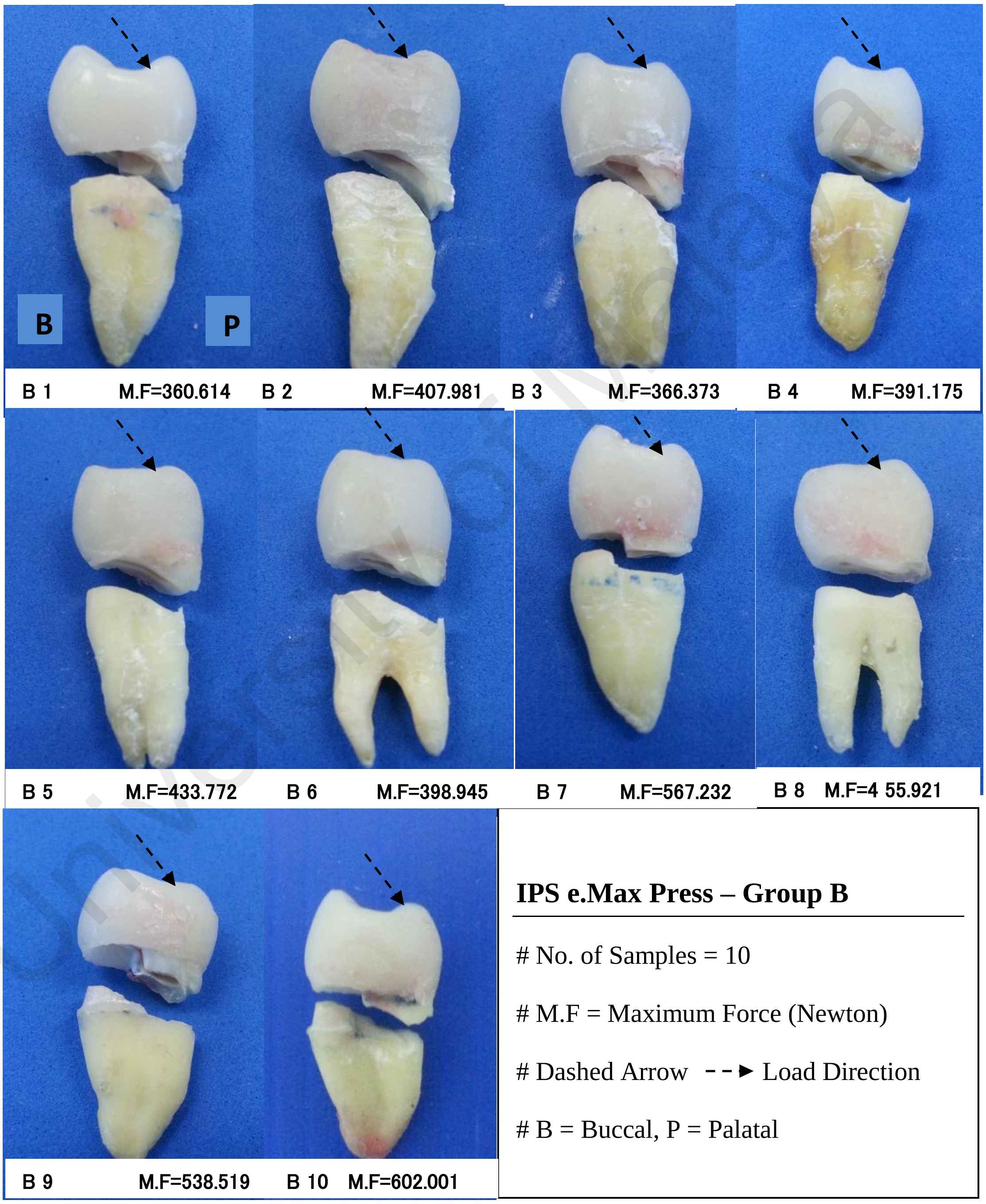

Figure 4.6: Failure pattern of IPS e.Max Press specimens (Severe tooth fracture)

4.2.3 Fracture modes of Cercon group

For Cercon group; 80 % of crowns exhibited the same mode that has been observed in group B; tooth fracture involving the root, whereas the ceramic crown remained intact. The rest of crowns (20%) showed favourable fracture mode (fracture within the ceramic only) as shown in Figure 4.7.

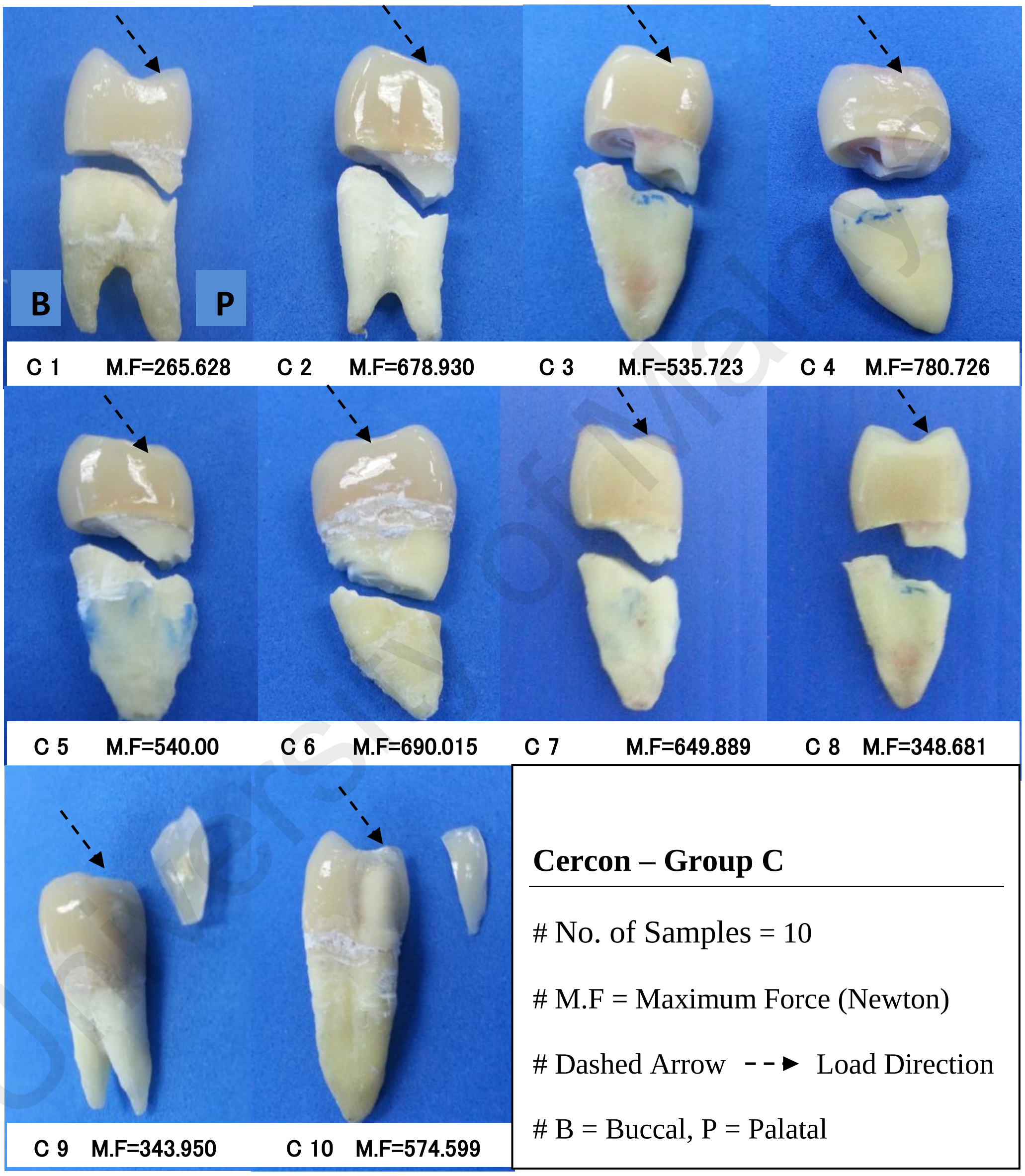

Figure 4.7: Failure patterns of Cercon; Severe tooth fracture (C 1 to C 8) and ceramic crown fracture (C 9 and C 10)

4.3 Fractography

Using scanning electron microscope (SEM), fractography was conducted on three random specimens to represent each group in order to determine the crack origin and its propagation path as well.

4.3.1 Fractography of CEREC

Figures 4.8 (a) and (b) show the optical images of the fractured sample A5. It is noticeable that the bulk fracture occurred within the ceramic while the tooth remained intact. In SEM image (Figure 4.8, c), the crack can be clearly seen at the axial wall of the crown. Additional SEM micrographs (Figure 4.9, a, b, c) show in detail the point of crack origin and the direction of crack propagation as well. The crack originated at the cement-ceramic interface and propagated toward the outer surface of ceramic resulting in catastrophic failure. This is further illustrated in the schematic diagram shown in Figure 4.10; the star represents the crack origin while dashed arrow indicates the direction of crack propagation.

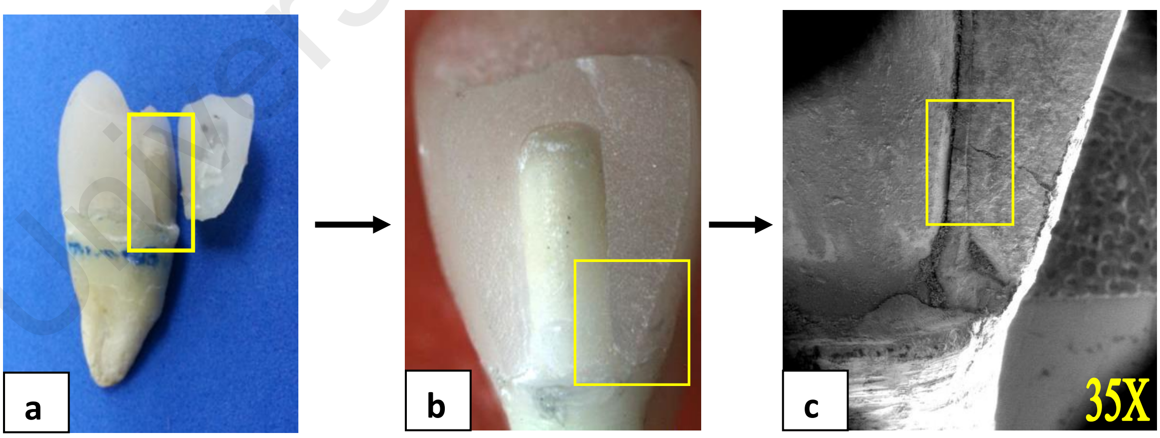

Figure 4.8: Optical (a,b) and SEM (c) images of fractured CEREC specimen; proximal (a) and palatal (b,c) view

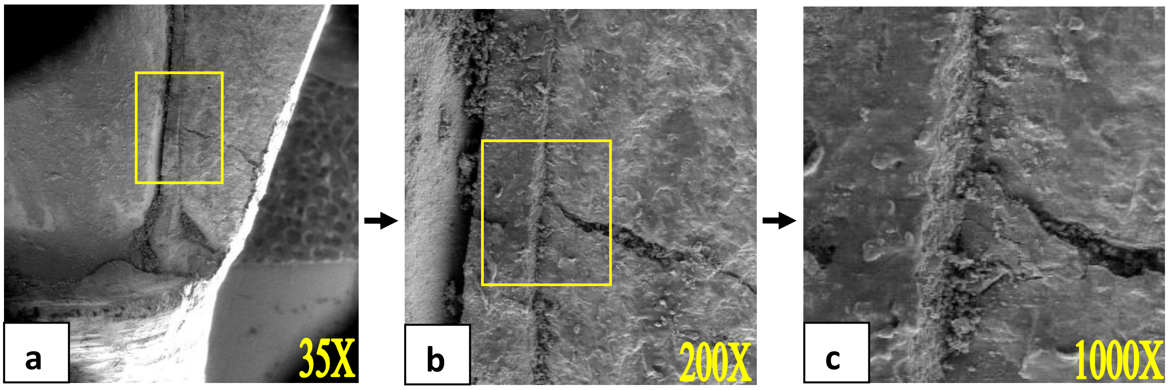

Figure 4.9: SEM micrographs of fractured CEREC specimen at different magnifications

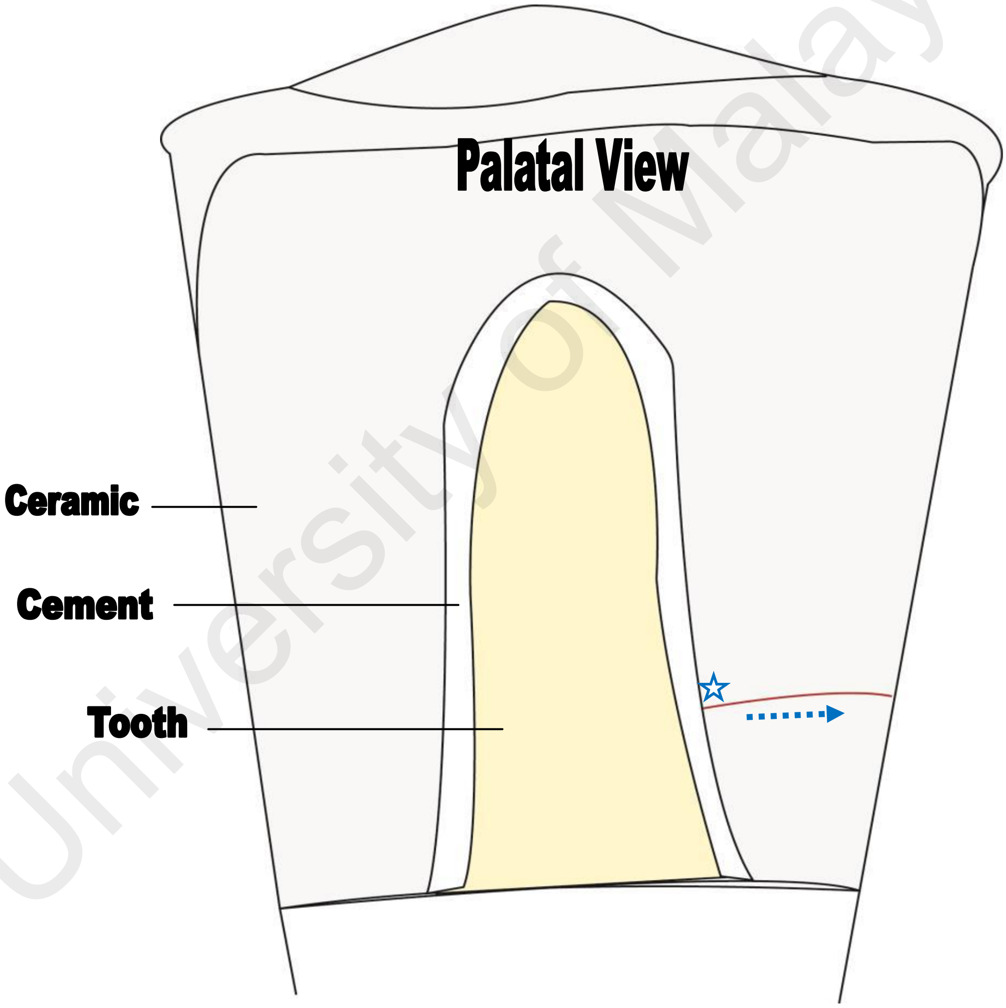

Figure 4.10: Schematic representation of the fractured surface for CEREC specimen. Star represents the crack origin. Dashed arrow indicates the direction of crack propagation.

4.3.2 Fractography of IPS e.Max Press

In IPS e.Max Press group, all specimens showed catastrophic fracture of tooth structure with the ceramic part remaining intact. Each tooth was fractured into two pieces; upper and lower (Figure 4.11, a). The SEM images, as shown in figure 4.12, reveal the main characterization of the fractured surface of IPS e.Max Press sample B4. Figures 4.12 (a,b) show the crack origin and the direction of the crack propagation within the buccal half of the fractured surface. Two cracks can be seen, originating at the internal wall of the root and propagated horizontally through the surface in bucco-palatal direction. One minor crack was arrested at one point on the surface close to the internal margin of the tooth. The main crack extended bucco-palatally in semi-circular approach within the palatal half of the fractured surface, as shown in Figure 4.12 (c). Figure 4.12 (d) shows hackle features that were observed on the fracture surface which can indicate the propagation path of crack as well. Generally, homogenous fracture surface was observed in this group. The general fracture features are further illustrated in the schematic diagram shown in Figure 4.13. The stars point out the cracks origins while the dashed arrows show the propagation path of the cracks within the whole surface. Furthermore, the solid arrows indicate the presence of hackle lines.

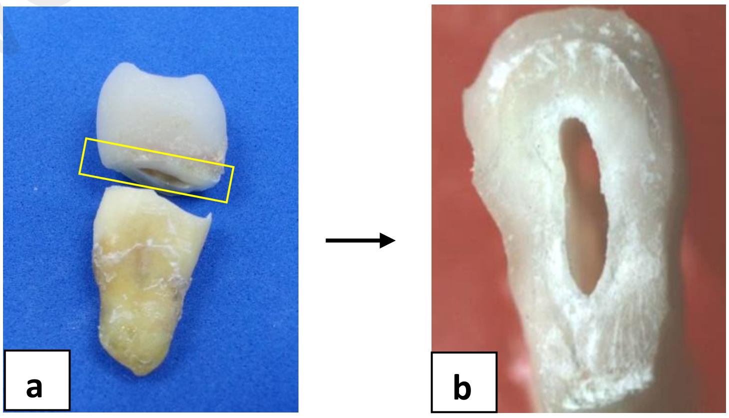

Figure 4.11: Optical images of fractured tooth in IPS e.Max Press group; proximal (a) and cross-sectional (b) view

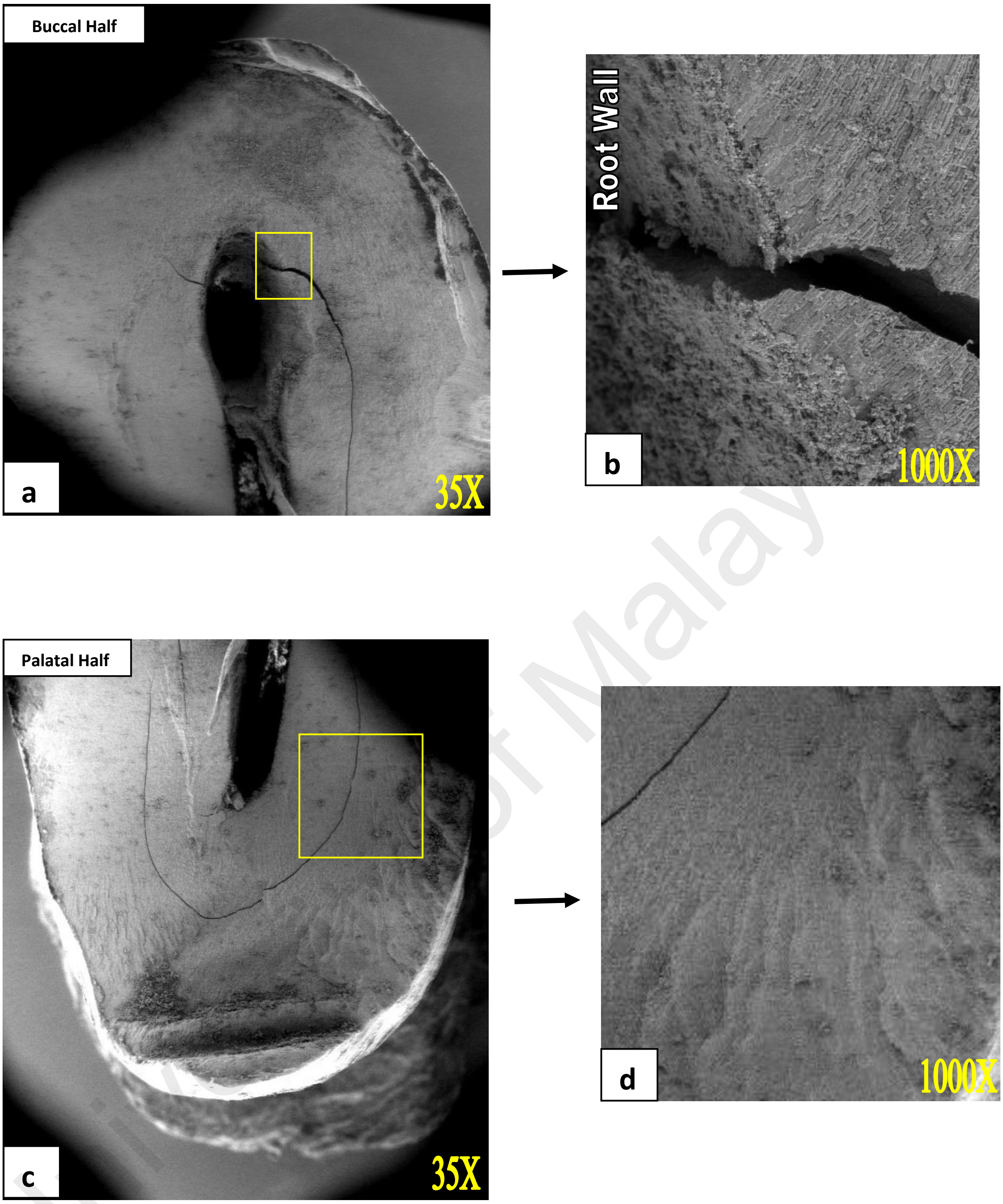

Figure 4.12: Cross-sectional SEM view of fractured tooth of IPS e.Max Press group

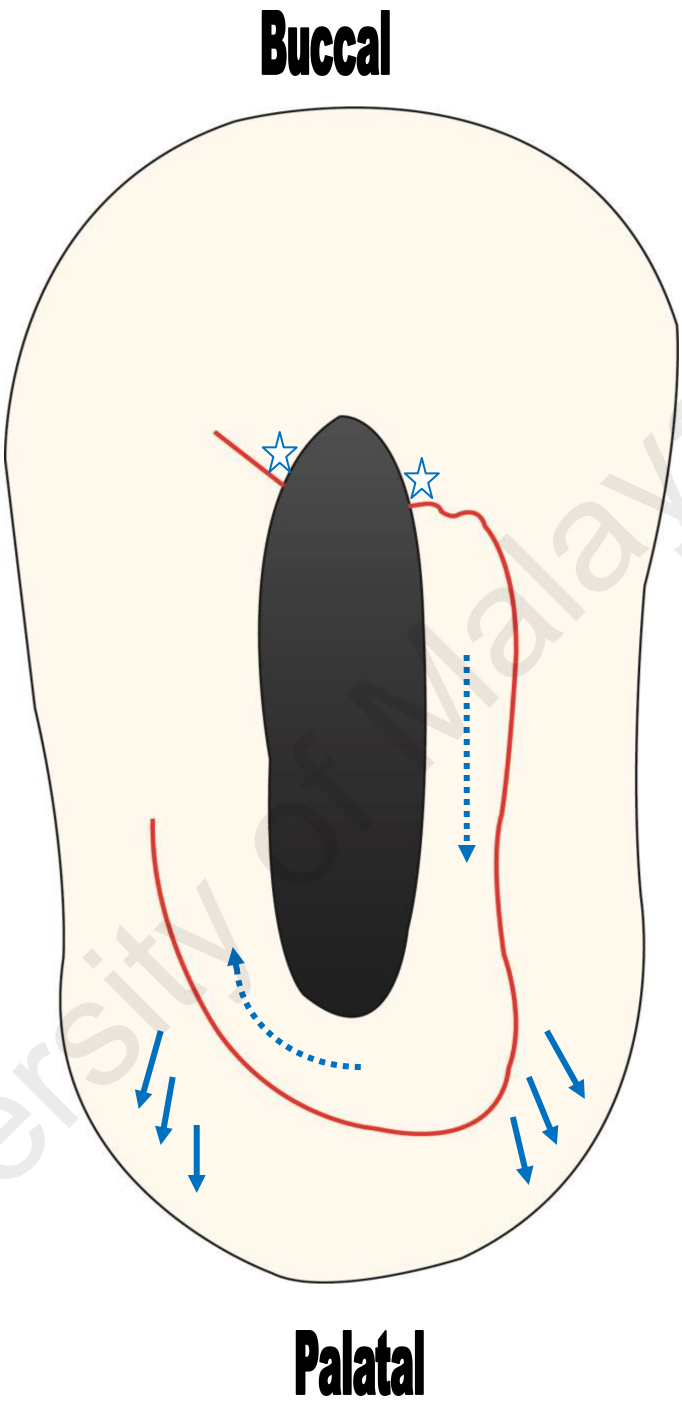

Figure 4.13: Schematic representation of fractured tooth surface in IPS e.Max group. Stars represent the crack origins. Dashed arrows indicate the direction of crack propagation. Hackle features (Solid arrows) also show crack propagation path

4.3.3 Fractography of Cercon

The major fracture pattern among Cercon group exhibited the same mode of IPS e.Max group; separating the tooth horizontally into two pieces with the ceramic crown remaining sound as shown in Figure 4.14. Fractography analysis was obtained for this group via SEM surface investigation of Cercon sample C4. In figures 4.15 (a,b), SEM image of the buccal half of the fractured surface reveals the basic fractographic features; crack origin and crack propagation path. Two similar cracks can be observed on the mesial and distal sides, initiating at the internal margins of the root and extended through the surface in two directions; palatally and proximally. One minor crack was arrested at one point on the surface close to the internal margin of the tooth. Figure 4.15 (c,d) shows hackle lines that were detected throughout the fractured surface, which indicate the final approach of crack propagation. Figure 4.16 shows a schematic diagram through which the fractographic analysis is further explained. The two stars on both sides determine the cracks origins while the dashed arrows indicate the directions of cracks propagation on both sides; mesially and distally. Likewise, the solid arrows represent the direction of the hackle lines.

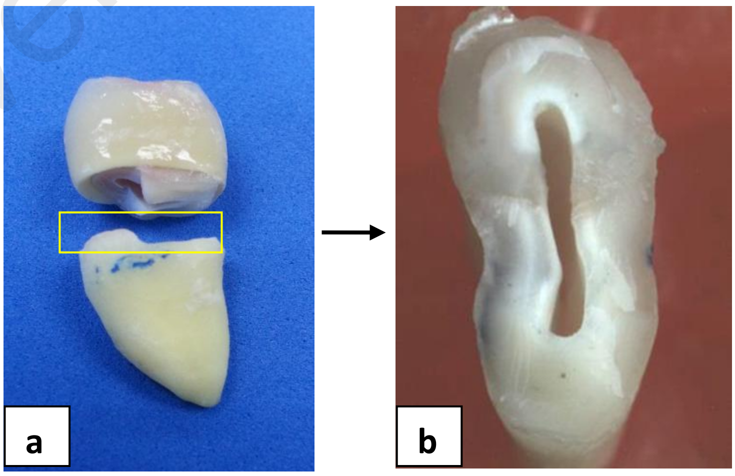

Figure 4.14: Optical images of fractured tooth in Cercon group; proximal (a) and cross-sectional (b) view

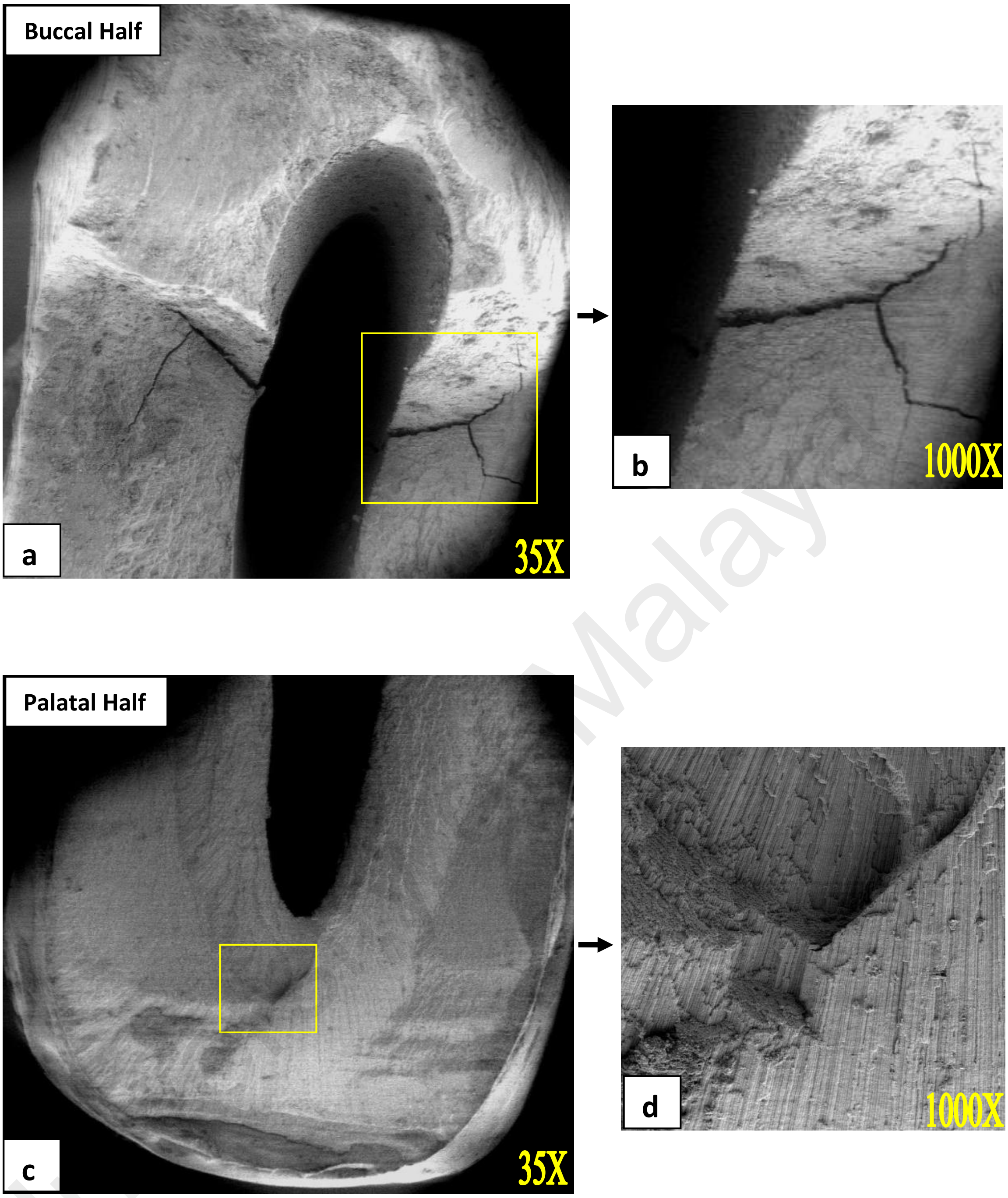

Figure 4.15: Cross-sectional SEM view of fractured tooth surface in Cercon group

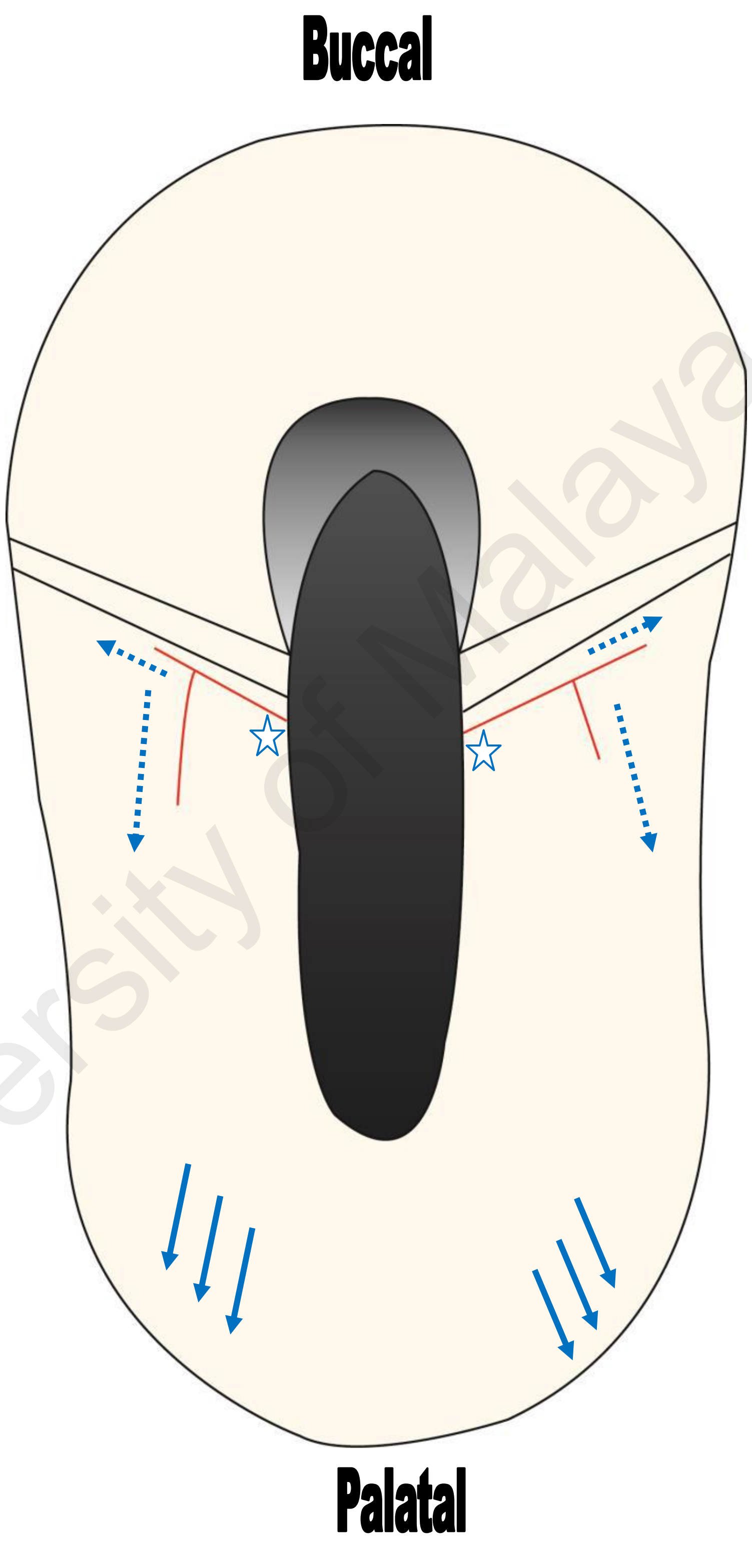

Figure 4.16: Schematic diagram of fractured tooth surface in Cercon group. Blue stars represent the crack origins. Dashed arrows indicate the direction of crack propagation. Hackle features (Solid arrows) also show crack propagation path

CHAPTER FIVE

DISCUSSION

5.1 Methodology

The main aim of this in vitro study was to evaluate and compare the failure load of CEREC Blocs, IPS e.Max Press and Cercon all-ceramic crowns. The test procedures were designed to obtain clinically applicable data, therefore, the recommendations addressed by Kelly (1999) for a clinically relevant in vitro fracture test for all-ceramic restorations were followed in this study, including using teeth as abutments, following the clinical guidelines for teeth preparation and all-ceramic crowns fabrication, and using a suitable luting cement. Moreover, the effect of lateral force, as an important clinical factor, was considered in this study (Sornsuwan et al., 2011). However, it is difficult to simulate all clinical conditions in one in vitro test (Anusavice et al., 2007).

5.1.1 Selection of teeth

In our study, natural human teeth were used as abutments to consider the contribution of tooth, as a clinically relevant factor, in determining the total strength of such dental restorations. According to Shahrbaf et al. (2014), all parts of the crown-tooth complex, including ceramic, cement and tooth, should be considered as contributing parameters in fracture testing of the all-ceramic restorations; rather than investigating the inherent features of the ceramic crown, as an independent component. Different abutments, such as resin dies, metal dies, animal teeth and human teeth, have been used in previous fracture studies, however, human teeth are more preferable in order to get realistic strength values (Chaar et al., 2013; Shahrbaf et al., 2014; Yucel et al., 2012).

According to Salis et al. (1987), 49 % of the recorded fractures among the maxillary teeth were in premolars. Furthermore, upper premolars were reported with a higher fracture rate compared to lower premolars. The high incidence of fractures in premolars may be due to the steep incline of their cusps, which makes them more prone to be subjected to the lateral masticatory forces than molars (Chang et al., 2009). Consequently, maxillary premolars were appropriate to be selected for this study.

All maxillary premolars collected for the present study were extracted for orthodontic purposes with no caries or defects (Hou et al., 2011). The selected teeth had comparable size and length; the obtained averages were within a 10 % deviation and the measurements were taken in bucco-palatal, mesio-distal and occluso-apical directions (Kois et al., 2013).

5.1.2 Simulation of periodontal membrane

It has been reported that the rigidity of embedding acrylic resin may affect the failure mode of the specimen during fracture testing (Newman et al., 2003). Therefore, as an attempt to mimic the physiological tooth movement, a thin layer of silicon was used in the current study as an artificial periodontal membrane; as described in different studies (Chaar et al., 2013; Hou et al., 2011; Rosentritt et al., 2011). Nevertheless, the biomechanics of the real periodontal ligaments are quite difficult to be simulated because of their complicated structure that includes blood vessels, collagen fibres, fluid and nerves (Chaar et al., 2013; Yucel et al., 2012).

5.1.3 Teeth Grouping

The present study was conducted to compare the fracture resistance of three different all-ceramic crowns cemented to prepared teeth with one luting cement. Such an in vitro study does not need a control group because the systems are different and there is no golden standard (Al-Wahadni et al., 2009; Komine et al., 2004; Potiket et al., 2004).

5.1.4 Preparation of teeth

The teeth preparation procedure conducted in this study followed the general guidelines recommended by manufacturers for all-ceramic crowns; an anatomical occlusal preparation was done to reproduce the geometry of the occlusal surface and the axial walls were prepared with a convergence angle of 12˚ to obtain an adequate taper degree. The protocol conducted for teeth preparation in the current study was similar to the protocol of previous study conducted by Al-Makramani et al. (2010). Shoulder design of finishing line was produced in this study; according to Aboushelib (2012), the design of the finish line does not influence the fracture resistance of the crown. However, some studies found that the design of the finish line has a significant effect on the fracture resistance (Reich et al., 2008; Vult et al., 2000)

5.1.5 Configuration of all-ceramic crowns

The test ceramic crowns in the present study were fabricated according to manufacturer's instructions. Crowns were produced with comparable morphological features to those of natural teeth in order to involve the effect of the stress distribution on the failure patterns as in the clinical situations (Shahrbaf et al., 2014). It was strongly recommended to consider the role of the occlusal geometrical shape of the crowns during ceramic fracture testing, as it appears that the stress distribution within the whole crown-tooth complex is affected by the anatomical features of the crown; namely cusp height and cusp angle (Altamimi et al., 2014; Sornsuwan et al., 2011).

To reduce variability amongst crowns, the crowns fabrication procedure in this study was handled by one certified dental technician (H.H, University of Malaya) with eight years of experience as a dental ceramist. He was instructed to standardize the anatomy and the dimensions for all ceramic crowns as much as possible (Schmitter et al., 2013; Zahran et al., 2008).

5.1.6 Cementation of crowns

All test crowns in the current study were cemented to their corresponding teeth using one dual-cured adhesive cement. The crack propagation within the ceramic crown is influenced by the underlying substructure; the cement layer and the dentine (Borges et al., 2009). The adhesive properties of resin-based cements have the action of wrapping the internal surfaces of the ceramic microcracks; the propagation of these microcracks are thus inhibited and blunted (Shahrbaf et al., 2014). Moreover, the higher mechanical features of such resin materials can enhance the fracture resistance of the dental restoration (Shahrbaf et al., 2007). In this way, it was frequently suggested that resin cements can increase the fracture strength of the ceramic crown and the tooth structure as well (Al-Makramani et al., 2008; Yucel et al., 2012).

5.1.7 Thermocycling

All specimens in the present study were thermocycled, according to (ISO/TS 11405/2003), to reproduce comparable thermal stresses to those in clinical cases (D'Amario et al., 2010; Shahrbaf et al., 2007). Shahrbaf et al. (2007) stated that thermocycling can induce stresses that weaken the adhesive bonding of the tooth and, consequently, reduce the fracture resistance of the tooth.

5.1.8 Loading conditions

A static loading until failure was used in the current study. Static loading has been frequently used in many in vitro mechanical tests for assessment the fracture resistance of dental crowns and, moreover, it is less complicated procedure than cyclic testing (Shahrbaf et al., 2007; Shahrbaf et al., 2014).

In the present study, all specimens were fixed in a custom designed jig to receive an oblique loading at 45˚ angle to the occlusal plane of the crowns. According to different recent studies, this angle was suggested to reproduce the average transverse contact between upper and lower premolars during mastication (Abduljabbar et al., 2012; Kalburge et al., 2013; Nam et al., 2010). Furthermore, some studies have used an oblique loading at 30˚ angle for the same purpose (Hou et al., 2011; Schmitter et al., 2013; Sonza et al., 2014).

During mastication, teeth receive a mixture of vertical and lateral forces. Thus, it was strongly recommended to involve the effect of the lateral forces during fracture testing as one of the clinical relevant factors (Nam et al., 2010; Shahrbaf et al., 2007). Literature evidence suggests that the application of angulated compressive load could induce the off-axis loading that observed in posterior teeth during function (Sonza et al., 2014).

5.2 Results

5.2.1 Fracture Values

The findings of the present study revealed that Cercon group had the highest failure load followed by IPS e.Max Press group with the lowest load in CEREC Bloc group; the fracture load of Cercon, IPS e.Max Press and CEREC Bloc were 540 ± 171 N, 452 ± 86 N and 387 ± 60 N, respectively. However, significant difference amongst groups was only detected between Cercon and CEREC groups ($p < 0.05$). So far, this is the first in vitro study in which the fracture load of these all-ceramic systems were evaluated and compared in one test.

The mean fracture value for CEREC Bloc (387 ± 60 N) in the present study is in agreement with another study conducted by Schmitter et al. (2013), in which CEREC Bloc was used as a veneer layer over zirconia cores; the established failure load of CEREC Bloc veneer was 395 ± 96 N. There were some differences in test parameters of the two studies such as restoration design, loading condition and abutment type; Schmitter et al. (2013) cemented the bilayered crowns to implants abutments and subjected them to an artificial aging, while in the current study, one layered CEREC Bloc crowns were cemented to natural premolars and tested under static loading. However, Schmitter et al. (2013) tested the specimens until failure at 30˚ angle, which is considered close to the angulated loading applied at 45˚ angle during the present study. Hence, the agreement in the findings of the two studies could be attributed to the similarity in stress distribution patterns as a result of the angulated loading applied in both studies. This indicates the important role of the loading direction in fracture testing rather than the other variables. On the other hand, our study is in disagreement with study conducted by Yang et al. (2014) in which the fracture resistance of CEREC Blocs all-ceramic crowns after mechanical and thermal cycling was investigated; the mean fracture values for CEREC Blocs before and after thermocycling and mechanical fatigue were 2281 ± 75 N and 1226 ± 77 N, respectively. In comparison, CEREC Blocs in the current study had lower fracture load (387 ± 60 N). This big variance could be referred to the different load direction and different abutment tooth used by Yang et al.; vertical load has been applied and third molars have been used as abutments. According to Hou et al. (2011), teeth structure can stand greater force in a vertical loading than the inclined loading. Moreover, reports have shown that molar teeth are less prone to fracture than premolars due to their complex occlusal anatomy and their big size which indicate favorable stress distribution and, thus increases the fracture resistance (Sornsuwan et al., 2011).

The fracture load for IPS e.Max Press in the present study (452 ± 86 N) is in disagreement with the results established in two pervious in vitro studies conducted by Zhao et al. (2012) and Altamimi et al. (2014). Zhao et al. (2012) evaluated the fracture loads for IPS e.Max Press crowns with and without veneering using static vertical load; the obtained fracture data of bilayered crowns and full crowns 1431 ± 404 N and 2665 ± 759 N, respectively. Altamimi et al. (2014) evaluated the fracture strength of monolithic IPS e.Max Press crown; the mean failure load of IPS e.Max Press was 1360 N. In comparison to our data, all values established in those two studies of Altamimi et al. and Zhao et al. are much greater than the failure load recorded in the present study for IPS e.Max Press crowns. This disagreement may be because of the different test methods used; Altamimi et al. (2014) subjected the specimens to fatigue cycling before testing and Zhao et al. (2012) used static load until failure in vertical direction, while the crowns in the present study were only subjected to static load at angulated direction. According to Shahrbaf et al. (2014), fracture resistance as well as fracture mode of ceramic crowns can be affected by many factors accompanying the fatigue cycling and , thus fracture values in fatigue test could be different from those obtained in static fracture test for the same ceramic material (Yang et al., 2014). Furthermore, the ceramic crown can show less fracture resistance against the lateral forces in which a combination of shear and compressive stresses could be simulated (Hou et al., 2011). In addition, Zhao et al. and Altamimi et al. used molar teeth as abutments which have a higher fracture resistance than premolar teeth (Sornsuwan et al. (2011).

The fracture load for Cercon in our study (540 ± 171 N) is in agreement with in vitro study done by Abduljabbar et al. (2012) in which the fracture resistance of bilayered Cercon crowns was investigated with different post systems in static flexural test; the obtained fracture values of Cercon used with glass fiber post and metal post were 561 ± 37 N and 541 ± 36 N, respectively. Unlike the current study in which natural teeth were used as abutments, Abduljabbar et al. used fiber glass and cast metal posts underneath Cercon crowns. However, they applied an angulated load at an angle of 45˚ which is the same angle used in our study; this may explain the findings agreement between the two studies and confirms the significant influence of the loading direction on the fracture resistance of all-ceramics crown. The fracture data of Cercon in the current study differ from those established in previous studies; 1140 ± 121 N (Yilmaz et al., 2007) and 1284 ± 124 N (Aboushelib et al., 2007). This noticeable variance could be explained due to the different test designs utilized in these two studies compared to our study; Yilmaz et al. used disc-shaped Cercon specimens in standardized biaxial flexural strength test and Aboushelib et al. used crown-shaped design with epoxy resin abutments to be loaded in vertical direction, while the method conducted in the current study depended on tooth-shaped Cercon specimens to be cemented to natural teeth and then loaded obliquely in a clinically relevant designed test. Unlike the method followed in our study, Yilmaz et al. conducted biaxial flexural test in which the ceramic material was tested and isolated to be the only variable without considering the influence of the other factors, such as crown design and substructure layers of dentine and cement, that exist in clinical situations, hence it is expected to get different fracture values for the same material when it is evaluated in clinical relevant test (Anusavice et al., 2007; Kelly, 1999).

5.2.2 Modes of Failure

In terms of fracture modes, all test crowns demonstrated two main types of failure modes; catastrophic fracture of the ceramic crown and severe tooth fracture mode. The percentage of the ceramic catastrophic failure mode among test groups are as follows; 80 % for CEREC group and 20 % for Cercon group, whereas IPS e.Max Press group did not show any ceramic fracture mode. It has been reported that ceramic bulk fractures could initiate from occlusal contact damage during static loading (Scherrer et al., 2005) or as a result of cone cracks formation beneath the occlusal contact surface (Øilo et al., 2014). Furthermore, fractures can start as a result of radial cracks that initiate at the inner surface of the ceramic crown; this failure mode has been shown both in laboratory failures (Kelly et al., 2010) and clinical failures (Kelly et al., 1989; Scherrer et al., 2005; Thompson et al., 1994). The other type of fracture mode exhibited in this study was characterized by severe horizontal tooth fracture while the ceramic crown remained contact. Amongst test groups, this type of failure mode involved 100 %, 80 % and 20 % of IPS e.Max Press, Cercon and CEREC specimens, respectively. This type of failure has been previously reported (Campos et al., 2011; Rammelsberg et al., 2000) where more occlusal stresses could be transferred through the ceramic crown to the underlying cement layer and dentine, resulting in critical deformation of these structures (Lee & Wilson, 2000). This may be explained by the differences in modulus of elasticity between ceramic and dentine; dentine has a lower elastic modulus than ceramic (Scherrer & De Rijk, 1992; Yucel et al., 2012). Cercon crowns are the only bilayered crowns in this study. Some studies have reported the delaminating of veneer layer as a common failure type of Cercon crowns (Aboushelib et al., 2007; Sornsuwan et al., 2011). However, there was no sign of any veneer delamination of Cercon crowns in the present study. This could be attributed to the good adhesion between veneer and core accomplished by using manual layering technique. According to Beuer et al. (2009) and Chaar et al. (2013), the adhesion achieved between porcelain veneer and zirconia core via manual veneer layering technique is better than those achieved either via press-on or CAD/CAM veneering techniques and, thus, the fracture resistance could be maximized.

5.2.3 Fractography

Fractography is a supplementary method through which the history of a crack could be illustrated (Campos et al., 2011). Several studies have used fractographic analysis on their fractured specimens in order to understand how cracks originated and propagated within ceramic restorations and their underlying substructures as well (Campos et al., 2011; Kim et al., 2006; Sornsuwan et al., 2011; Zhao et al., 2014). In the present study, fractography was performed on one specimen for each crown type using SEM. The crack origins were observed and the fracture features, such as hackle lines and arrested lines, were detected as indicators for the crack propagation path. for CEREC fractured specimen, micrographs revealed that a radial crack initiated at the ceramic-cement interface and propagated proximally to the outer surface of the ceramic crown; this confirms the findings that has been previously reported in some clinical and laboratory failures (Kelly et al., 1989; Kelly et al., 2010; Scherrer et al., 2005; Thompson et al., 1994) in which radial cracks were observed originating at the cement-ceramic interface and extended to the outer surface of the restoration and some were arrested within the ceramic layer. According to Aboushelib et al. (2007) and Quinn et al. (2005), radial crack is considered as the most common mechanism in clinical failures. The SEM pictures of Cercon and IPS e.Max Press groups showed that radial cracks originated at the internal surface of the root and propagated in palatal direction. Moreover, the fracture markings were detected; they indicated the crack propagation in bucco-palatal direction. This could be explained by the loading direction as the angulated load was applied on the palatal side of the crown.

5.2.4 Clinical Significance of the study

To address the clinical significance of the data obtained in our study, we compared it to the normal forces reported during mastication. Clinically, the maximum biting force in premolar area has been reported to be between 181 N and 608 N, while it has been reported in molar are to be between 597 N and 847 N (Waltimo & Könönen, 1993; Zahran et al., 2008). However, the normal masticatory forces in humans have been reported to be in the range of 37 % to 40 % of the maximum force (up to 300 N in premolar region and 350 N in molar area) (Al-Makramani et al., 2010; Julien et al., 1996; Lundgren & Laurell, 1986; Widmalm & Ericsson, 1982). Accordingly, the mean fracture strength values of all three crown systems used in the current study exceeded the normal biting forces generated inside the mouth during function. Many previous in vitro studies have compared the fracture values of different dental ceramic restorations to the normal biting forces in order to show the clinical significance of their tested restorations and draw predictions on their performance in the oral cavity (Chaar et al., 2013; Chang et al., 2009; Shahrbaf et al., 2014; Yilmaz et al., 2007).

The findings of this study provide information through which clinicians can select with confidence the appropriate all-ceramic restoration that would offer superior strength in the posterior area. The fracture values are higher than what is expected in the mouth.

CEREC crowns exhibited lower strength values but had a favourable failure mode within the ceramic. IPS e Max and Cercon crowns had higher strength values but fractured in an unfavourable manner through tooth structure. However, clinical trials are required to validate these findings and to determine the performance of such restorations in the physiologic environment of the oral cavity.

5.3 Limitation of the study

In the current study, specimens were loaded in a single cycle until fracture using static load in a dry environment, even though clinical failures can be induced by blunt contact loading or cyclic fatigue loading in an aqueous environment. Therefore, physical fracture tests do not guarantee a clinically relevant mode of failure (Kelly, 1999). Many clinically relevant factors were applied in this study, such as specimen geometry, cementation process and off-axial loading. Therefore, such in vitro study is becoming more reliable indicators of the clinical performance of these all-ceramic restorations. Regardless of these improvements, extrapolating the obtained data to clinical cases should be carried out with caution.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Within the limitations of this study, the following conclusions can be drawn:

1. Cercon crowns experienced the highest fracture loads (540.81 ± 171.06 N), followed by IPS e.Max Press (452.25 ± 86.76 N), while CEREC crowns showed the lowest records (387.24 ± 60.20 N).
2. Among all three test groups, there was only significant difference in the mean fracture resistance between Cercon and CEREC crowns, $p < 0.05$.
3. It was suggested that all crown systems used in this study are clinically applicable as they exceeded the normal masticatory forces generated inside the mouth at the posterior area.
4. The fracture pattern of CEREC crowns showed catastrophic fracture within the ceramic crown which is more preferable than the failure modes of Cercon and IPS e.Max Press groups which exhibited severe tooth fracture with the ceramic remained intact.

6.2 Recommendations for further studies

1. The specimens in the current study were load in single static cycle. However, dental ceramic restorations may fail clinically due to the formation of slow crack growth caused by fatigue cycling. Therefore, further study is needed to include the fatigue cyclic loading to get more clinically applicable data about the performance and longevity of these prostheses.
2. The present study was designed to closely reproduce the clinical situations, considering that in vitro experimental tests do not replicate the entire clinical situations. Nevertheless, in vivo trials are needed to determine the effects of the physiological factors found in oral cavity such as cyclic loading and saliva.
3. Another study is required to evaluate the fracture resistance of CEREC, IPS e.Max Press and Cercon crowns in term of vertical loading and compare the results to those obtained in the current study, in which an angulated loading was applied, in order to give more information about the effect of the loading direction on the flexural strength of such restorations.

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