PHYSICAL AND MECHANICAL CHARACTERISTICS EVALUATION OF WEAKENED ENDODONTICALLY TREATED TEETH RESTORED WITH FIBER-REINFORCED COMPOSITE: OPEN APEX AND FLARED ROOT CANALS

DAWOOD SALMAN DAWOOD ALSHETIWI

UNIVERSITI SAINS MALAYSIA

2023

PHYSICAL AND MECHANICAL CHARACTERISTICS EVALUATION OF WEAKENED ENDODONTICALLY TREATED TEETH RESTORED WITH FIBER-REINFORCED COMPOSITE: OPEN APEX AND FLARED ROOT CANALS

by

DAWOOD SALMAN DAWOOD ALSHETIWI

Thesis submitted in fulfilment of the requirements
for the degree of
Master of Science

June 2023

ACKNOWLEDGEMENT

In the name of Allah, the most gracious, the most merciful

I am extremely happy to dedicate this humble scholarly work to my homeland country Iraq, my second homeland United Arab Emirates and Malaysia, to my mother Ghaida Hussein, my father Salman Alshetiwi, my wife Amna Alfayadh and my siblings Athba, Basma, Dimah and Abdullah and to my soon to be born son Abdul Aziz. I am forever in debt to all their continuous love, support, presence, and prayers for success.

First and foremost, my sincere gratitude and appreciation to my main supervisor Dr. Nor Aidaniza Abdul Muttlib and my field supervisor Associate Prof. Dr. Hatem M. El Damanhoury for their invaluable support, advice, guidance throughout all the stages of my master degree, and giving me the opportunity to fulfil my vision of continuing post-graduate studies, without their contribution this research would not have been possible.

I am very grateful for Prof. Dato. Dr. Ab Rani Samsudin, Dr. Ali Al Qabbani for their extreme motivation, encouragement to pursue post-graduate studies, guidance, and generosity to always share their valuable knowledge and opinions. Furthermore, my gratitude is also extended to my co-supervisors, Prof. Dr. Normastura Abd Rahman, Dr Nesrine Aly Elsahn and Dr Rabihah Alawi for their detailed, in-depth reviews and advice.

I would also like to thank Dr. Soumya Sheela, Mr Wael Ibrahim Al Mousalli, Mr Emad El Sayed, and Mr Rawhi Abudaqa for their efforts and help in carrying out laboratory procedures and sharing their valuable knowledge. My appreciation is extended to the support received through the RUI grant (1001/PPSG/8012367) for funding the publication from this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF SYMBOLS

C	Celsius
Kg	Kilogram
Hz	Hertz
mm	Millimeter
µm	Micrometer
s	Second
Ø	Diameter
N	Newton
80D	Camera model
F	Force
A	Surface area
P	Push-out bond strength
MPa	Mega-pascal
π	Pi constant
r1	Radius of the post from the upper part of the specimen
r2	Radius of the post from the lower part of the specimen
h	Height of the specimen

LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
BisGMA	Bisphenol A-glycidyl methacrylate
CaOH2	Calcium hydroxide
CEJ	Cemento-enamel junction
DEJ	Dentino-enamel junction
DSLR	Digital single-lens reflex
ETT	Endodontically treated teeth
FRC	Fiber-reinforced composite
HSD	Honestly significant difference
LED	Light emitting diode
NaOCl	Sodium hypochlorite
PMMA	Polymethyl methacrylate
PVS	Polyvinyl siloxane
SD	Standard deviation
SEM	Scanning electron microscope
RIMHS	Research institute of medical and health sciences
TEGDMA	Triethylene glycol dimethacrylate
TMA	Thermomechanical aging
UDHS	University Dental Hospital Sharjah
UDMA	Urethane dimethacrylate

LIST OF APPENDICES

PENILAIAN CIRI FIZIKAL DAN MEKANIKAL GIGI YANG LEMAH DIRAWAT SECARA ENDODONTIK DAN DIPULIHKAN DENGAN KOMPOSIT BERTETULANG GENTIAN: APIKAL TERBUKA DAN KANAL AKAR YANG LEBAR

ABSTRAK

Gigi yang dirawat secara endodontik (GDSE) dengan saluran akar yang terjejas akibat kerosakan teruk yang disebabkan oleh terlalu banyak instrumentasi saluran akar dan pembentukan akar fisiologi yang tidak lengkap berisiko tinggi untuk patah. Penggunaan tiang pasang siap dalam gigi ini diikuti dengan lapisan simen resin yang tebal disebabkan oleh perbezaan saiz dan bentuk antara tiang dan saluran akar. Kajian ini dijalankan untuk menilai gabungan pelbagai bentuk komposit bertetulang gentian (KBG) yang digunakan untuk meningkatkan sifat mekanikal GDSE yang terjejas. Lapan puluh gigi premolar manusia yang dicabut telah digunakan dalam kajian ini, dan dibahagikan secara rawak kepada lima kumpulan eksperimen dengan enam belas gigi bagi setiap kumpulan (n=16). Lapan gigi dari setiap kumpulan digunakan bagi objektif 1-3. Lapan lagi (n=8) digunakan bagi objektif 4. Kumpulan dibahagikan mengikut kaedah penyediaan saluran dan pemulihan intra-radikular sama ada menggunakan tiang gentian pasang siap standard atau tiang gentian dilapis yang disesuaikan secara anatomi. Sampel kemudian diserahkan untuk penilaian penyesuaian intrakanal menggunakan bahan teraan polyvinyl siloxane (PVS) ringan dan penuaan buatan menggunakan simulator mengunyah dikawal komputer. Rintangan patah dan ujian kekuatan ikatan tolak keluar kemudiannya dijalankan menggunakan mesin ujian universal diikuti dengan kaedah analisis kegagalan melalui stereomikrosop dan mikroskop elektron pengimbasan. Penilaian penyesuaian

intrakanal menunjukkan perbezaan yang signifikan secara statistik ($p<0.05$) dalam berat bahan PVS antara kumpulan. Kumpulan 1 (kawalan) mempunyai berat bahan PVS yang paling ringan, diikuti oleh kumpulan yang dipulihkan dengan tiang gentian disesuaikan (Kumpulan 4 dan Kumpulan 5) dan kumpulan yang dipulihkan dengan tiang gentian standard (Kumpulan 2 dan Kumpulan 3). Keputusan ujian penuaan buatan melalui perbandingan Pairwise Log-Rank menunjukkan bahawa tidak terdapat perbezaan yang signifikan secara statistik antara Kumpulan 1, Kumpulan 5 dan Kumpulan 4 ($p>0.05$). Kumpulan 2 dan Kumpulan 3 menunjukkan kadar survival yang lebih rendah secara statistik berbanding semua kumpulan lain. Keputusan ujian rintangan patah menunjukkan rintangan patah tertinggi (1796 N) berada dalam Kumpulan 5, dan ia adalah lebih tinggi secara signifikan berbanding kumpulan lain ($p<0.05$), manakala Kumpulan 2 menunjukkan rintangan patah min terendah (758 N) dan adalah jauh lebih rendah berbanding kumpulan lain. Bagi ujian kekuatan ikatan tolak keluar, Kumpulan 5 dan Kumpulan 4 menunjukkan kekuatan ikatan yang jauh lebih tinggi pada semua pertiga akar ($p <0.05$) berbanding Kumpulan 3, Kumpulan 2 dan Kumpulan 1. Kegagalan yang paling kerap diperhatikan berlaku di antara simen resin dan dentin radikular untuk semua kumpulan. Kesimpulannya, penggunaan komposit bertetulang gentian pendek (KBGP) untuk melapik tiang KBG pasang siap telah menunjukkan peningkatan penyesuaian intrakanal, kadar survival yang lebih tinggi, rintangan patah yang tinggi dengan corak kegagalan yang boleh dibaiki dan peningkatan nilai kekuatan ikatan tolak keluar berbanding dengan tiang KBG pasang siap standard.

PHYSICAL AND MECHANICAL CHARACTERISTICS EVALUATION OF WEAKENED ENDODONTICALLY TREATED TEETH RESTORED WITH FIBER-REINFORCED COMPOSITE: OPEN APEX AND FLARED ROOT CANALS

ABSTRACT

Endodontically treated teeth (ETT) with compromised root canals due to pervasive damage induced by root canal over-instrumentation and incomplete physiological root formation are at high risk of fracture. The use of intra-radicular posts in these teeth is accompanied by a large resin cement layer due to the discrepency in the size and shape between the post and root canal. This study was conducted to assess the combination of different forms of Fiber-reinforced composites (FRC) used to enhance mechanical behavior of compromised ETT. Eighty extracted human premolar teeth were used in this study. Teeth were randomly allocated to five experimental groups with sixteen teeth per group (n = 16). Eight teeth from each group (n = 8) were submitted for objectives 1-3. The remaining eight teeth (n = 8) were prepared for objective 4. Groups were divided according to canal preparation methods and intra-radicular restoration with either a standard prefabricated fiber post or anatomically customized relined fiber post. Samples were then submitted for evaluation of intracanal adaptation using polyvinyl siloxane (PVS) light body impression material and artificial aging using computer-controlled chewing simulator. Fracture resistance and push-out bond strength tests were then carried out through a universal testing machine followed by mode of failure analysis via a stereomicrosope and scanning electron microscope. Assessment of intra-canal adaptation showed a statistically significant difference ($p<0.05$) in PVS material weight between the

groups. Group 1 (control) had the lightest weight of PVS material, followed by groups restored with customized fiber posts (Group 4 and Group 5) and groups restored with standard fiber posts (Group 2 and Group 3). Artificial aging test results through Pairwise Log-Rank comparisons revealed that there was no statistically significant difference between Group 1 (control group), Group 5 and Group 4 ($p>0.05$). Group 2 and Group 3 showed a statistically significant lower survival rate compared to all other groups. Results of fracture resistance test showed the highest fracture resistance (1796 N) in Group 5, and it was significantly higher compared to other groups ($p<0.05$), while Group 2 showed the lowest mean fracture resistance (758 N) and was significantly lower compared to the other groups. In relation to push-out bond strength test, Group 5 and Group 4 demonstrated a significantly higher bond strength at all root thirds ($p<0.05$) than Group 3, Group 2, and Group 1. The most frequently observed failure occurred between the resin cement and radicular dentin for all the groups. In conclusion, the use of short fiber-reinforced composite (SFRC) to reline the prefabricated FRC post has been proven to improve intracanal adaptation and result in higher survival rate, superior fracture resistance with favorable failure patterns and increased push-out bond strength values compared to standard prefabricated FRC posts.

CHAPTER 1

INTRODUCTION

1.1 Background

The restoration of endodontically treated teeth (ETT) has been an area of extensive research to investigate the best materials, protocols, and parameters that will ultimately enhance the fracture resistance and prognosis of the tooth following root canal treatment; yet remains controversial from many perspectives.

Endodontic treatment is a dental clinical procedure to treat the inflamed or infected dental pulp tissue due to caries or trauma. In the case of infected or irreversibly inflamed pulp, a series of clinical treatments are carried out which involved the complete removal of the diseased tissues, cleaning, disinfecting, shaping the root canal space and finally filling it with an obturation material and a final restoration to restore the function of the tooth (Gopikrishna, V., Grossman, 2021).

Previous studies have proposed that following endodontic treatment, the dentin exhibited substantial changes compared to teeth with vital pulps (Huang *et al.*, 1992). Reduction of the moisture content of the calcified tissues in pulpless teeth was also confirmed by Helfer *et al*., (1972) when compared to vital teeth. The dentin was thought to become more brittle due to loss of water content and cross-linking of collagen (Schwartz and Robbins, 2004). However, another study concluded that endodontic treatment did not cause degradation of the physical properties of dentin (Rivera and Yamauchi, 1993).

The loss of tooth structure found in ETT appears to be the most important consideration and the significant role of the remaining tooth structure is very well documented (Sorensen & Martinoff, 1984, Tan et al., 2006, Ferrari et al., 2012). Carious lesion, access cavity, and root canal space preparation are the three factors responsible for a considerable amount of tooth structure loss. The loss of dentin elasticity was not responsible for the reducing structural integrity and fracture resistance of the tooth compared to vital teeth (Reeh *et al.*, 1989). Based on these considerations, the quantity and quality of the remaining tooth structure and a restorative solution of high quality that promotes the structural integrity directly enhance the prognosis and longevity of endodontically treated teeth.

Excessive removal of the radicular and coronal dentinal tissue during endodontic procedures such as over-flaring of canals or attaining straight-line access impacts the flexural behaviour and resistance to failure (Gomes *et al.*, 2015).

From the 1990s, cast and prefabricated metallic post systems have been replaced with carbon or glass fiber post systems. These posts have been an alternative to overcome the challenges of restoring badly broken ETT. Glass fiber post systems have been reported to have a modulus of elasticity closer to that of human dentin, thus have better stresses distribution along the root and cause less catastrophic failures than previously used metallic posts as reported in many previous studies (Plotino *et al.*, 2007; McLaren *et al.*, 2009; Chuang *et al.*, 2010; Santos-Filho *et al.*, 2014). The reliability of the fiber posts has been demonstrated in several longitudinal investigations, and their therapeutic effectiveness is well established in the literature. With the use of a fiber post, the failure mode was reported to be in the form of debonding without the incidence of catastrophic root fracture, thus the tooth was still restorable even after failure (Dietschi *et al.*, 2008).

To conserve as much of the residual root structure as possible following endodontic treatment, posts with a tapered and conical design that better fits the canal anatomy were developed (Wang et al., 2016). However, some clinical situations presented with flared and wide canal space, such as endodontic retreatment cases.

Another example is immature permanent teeth with open apex, which requires intra-radicular posts for core retention (Zhabuawala *et al.*, 2016). For such cases, the prefabricated post will not provide good fit to the canal due to the discrepency in the size and shape between the post and root canal.

A variety of direct clinical techniques have been introduced as an alternative to restore structurally compromised ETT damaged by caries, trauma or congenitally malformed such as experimental dentin posts with tapered design (Wang *et al.*, 2017) or reshaped anatomically customized posts (Grande *et al*., 2006; Grandini *et al*., 2003; Aidaniza *et al*., 2018; Bakaus *et al*., 2018; Gomes *et al*., 2016) to adapt to the walls of non-circular root canals have been proposed.

In 2003, a case report was published where a clinical technique described as "anatomic post technique" has been used to improve the fiber post adaptation and retention to the root canal space in flared canals with wide, elliptic shape such as following endodontic treatment in younger age patients, or cases of endodontic retreatment (Grandini *et al*., 2003). It involved using a fiber post covered with a layer of light-cured composite resin. This resulted in lower resin cement thickness, as evident by scanning electron microscope (SEM) evaluation study that was carried out later (Grandini *et al*., 2005).

Since the introduction of the first filled resin composite by Bowen in the early 1960s, many developments and modifications have been applied to the organic matrix and the inorganic filler particles phases. In particular, the bulkfill and fiber-reinforced dental resin composite restorative materials have provided a significant milestone and solution to overcome many of the limitations and drawbacks of the conventional resin composites, such as limited depth of cure, increased polymerization shrinkage stress, as well as offering improved fracture strength (Bowen, 1963).

Most of the currently available literatures are in the form of *in vitro* studies which mainly evaluates fracture resistance of post-endodontic restorations in the form of relined FRC posts using static loading only (Zogheib *et al.*, 2008; Abduljawad *et al.*, 2016; Kubo *et al.*, 2018; Bhaktikamala *et al.*, 2022). However, as a result of the dynamic interactions among different challenges in the oral cavity and exposure of resin composite restorations to cyclic loading during function, dynamic artificial aging and fatigue resistanc tests are suggested for enhanced clinical performance prediction (Ferracane, 2013). This study incorporated thermo-mechanical aging simultaneously, to better simulate the function of the natural dentition and investigates the effect of relining long unidirectional fiber posts with E-glass discontinuous short fiber-reinforced composite (SFRC) as an intraradicular mean to restore endodontically weakened teeth, which to the extent of our knowledge has not been tested yet.

1.2 Problem statement

Due to the discrepancy between the shape of the root canal space and the shape of the prefabricated post, the adaptation will be adversely affected. It will result in an excessively thick layer of cement between the post and the radicular dentine, hence increasing polymerization shrinkage at the different interfaces, leading to bubbles formation and debonding/adhesive failure (Grandini *et al.*, 2003). Studies still report that oval and tapered posts did not offer improved fracture resistance, nor did they have a better adaptation to canal morphology compared to older generations of cylindrical posts. It also has been proven challenging to reduce the cement film thickness in such clinical scenarios (Uzun *et al.*, 2015; Wang *et al.*, 2017)

1.3 Justification of the study

This study aimed to provide a restorative solution that enhances the intracanal adaptation and mechanical behavior of compromised ETT under conditions that closely simulate the function of natural dentition in the oral cavity, thus the prognosis of badly broken ETT, presenting with flared root canals and/or immature open apex will be improved. Patients will be able to retain their dentition and avoid extraction as a choice of treatment. The intra-canal adaptation fitment will be improved by fabricating anatomically customized fiber posts that better confirm to the anatomy and taper of the root canal, thereby limiting the resin cement thickness. Furthermore, the survival, fracture resistance, bond strength will be enhanced and failure patterns altered to a more favorable patterns by the combined use of different fiber-reinforced materials which are 1) unidrectional long continuous prefabricated fiber posts and 2) bulkfill flowable discontinuous SFRC . This is hypothesized to address major issues encountered in the restoration of ETT.

1.4 The general objective

To evaluate the performance of FRC posts on physical and mechanical properties of ETT with flared root canals and open apex.

1.5 The specific objectives

1. To compare the intra-canal adaptation of post-dentin interface in weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC with control group restored using standard non-customized (FRC) posts.
2. To compare the survival rate by means of artificial aging, of weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC with control group restored using standard non-customized (FRC) posts.

3. To compare the fracture resistance and fracture pattern of weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC with control group restored using standard non-customized (FRC) posts.
4. To compare the push out bond strength of weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC with control group restored using standard non-customized (FRC) posts.

1.6 The research questions

1. Do customized (FRC) posts using E-glass discontinuous SFRC have better intra-canal adaptation in weakened ETT with flared root canals and immature open apex.
2. Does the use of customized (FRC) posts using E-glass discontinuous SFRC improve the survival rate of weakened ETT with flared root canals and immature open apex.
3. Does the use of customized (FRC) posts using E-glass discontinuous SFRC improve the fracture resistance and fracture pattern of weakened ETT with flared root canals and immature open apex.
4. Does the use of customized (FRC) posts using E-glass discontinuous SFRC improve the push out bond strength of weakened ETT with flared root canals and immature open apex.

1.7 The research hypothesis

In this study, the null hypotheses were:

1. There is no significant difference in intracanal adaptation between customized (FRC) posts using E-glass discontinuous SFRC and standard non-customized fiber posts used to restore weakened ETT.

2. There is no significant difference in survival rate of weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC when compared to weakened ETT restored with standard non-customized fiber posts after artificial aging.
3. There is no significant difference in the fracture resistance and fracture pattern of weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC when compared to weakened ETT restored with standard non-customized fiber posts.
4. There is no significant difference in the push out bond strength of weakened ETT restored with customized (FRC) posts using E-glass discontinuous SFRC when compared to weakened ETT restored with standard non-customized fiber posts.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The history of endodontic practice and achievements dates back to ancient times, but it would be difficult to correlate to and understand considering the endodontics specialty we practice currently. Years between 1687-1805 were described as the empirical era, where the tooth-worm theory persisted since the Babylonian time. It included the findings by Charles Allen (1687) who described the procedures for transplanting sound teeth after removing rotten teeth or stumps. Nevertheless, in 1700, Anton Von Leeuwenhoek published data that significantly refuted the tooth-worm idea and suggested that the cause of the infection of these teeth was cheese that had been contaminated with worms. The methods of pulp extirpation, which include "opening" teeth to alleviate abscesses and drain pus, as well as descriptions of pulp cavities and root canals, were all documented by Pierre Fauchard in his book "The Surgeon Dentist" in 1728. Nevertheless, root canal therapy was not discussed. The first documented description of endodontic procedures is attributed to Rober Woofendale in 1766, where he described a method for relieving pain by cauterizing the pulp with heated instrument. In the 19th century, the vitalistic era included procedures of filling the roots of teeth when it was not advisable to extract them, as attributed to Edward Hudson who practiced filling the roots with gold foil in 1809, followed by many discoveries and findings related to pulp capping and testing methods (Cruse and Bellizzi, 1980).

2.2 Effects of endodontic treatment

The presence of highly mineralized tissues will aid the tooth to function and minimize wear and fracture due to the excellent physical and mechanical properties which were determined by the internal architecture and constituents of these tissues. Alterations of the mechanical and structural properties of the tooth following endodontic treatment must be considered, as it will affect the way stresses were handled and distributed through the dental hard tissues (Gwinnett, 1992).

Enamel, which covers the outside surface of the crown is a hard yet brittle tissue, with low tensile strength and high elastic modulus (Giannini *et al.*, 2004) as it is mainly composed of 92-96% of inorganic materials, 1-2% organic material, and 3-4% water (Nanci and Cate, 2008). The results of previous studies revealed that the type and direction of stress, as well as the orientation of enamel prisms affect the mechanical properties of enamel (Urabe *et al.*, 2000; Giannini *et al.*, 2004).

Dentin is the major component of the structure of the human dentition. It can be found in both the tooth's root and crown (coronal dentin) (radicular dentin). Unlike enamel, it is composed of 70% inorganic material, 18% organic matrix, and 12% water by weight (Nanci and Cate, 2008).

It is characterized by having lower modulus of elasticity than enamel as well as the lower mineral content results in lower hardness compared to enamel (O'Brien, 1987). Many microscopic channels traverse the dentin, referred to as the dentinal tubules, where odontoblastic processes are located as they extend from the pulp, then through the dentin towards the enamel of the crown and cementum of the root. These tubules are surrounded by peritubular dentin in the form of a cuff around them, and intertubular matrix. Collectively, they form the dentin biological composite. The junction where enamel meets the dentin is referred to as the dentin-enamel junction

(DEJ). It is reported to have high fracture strength. With the presence of the underlying dentin, it supports the integrity of enamel, prevents fractures, and inhibits crack propagation (Urabe *et al.*, 2000).

Collectively, enamel and dentine are located at the coronal and radicular parts. The pulp tissues create an organ of high integrity, that works in harmony to withstand any functional stresses. According to a previous study, radicular dentin has more flexural strength than coronal dentin and can resist more severe inelastic deformation (Eltit *et al.*, 2013).

2.3 Predisposition to fracture

Fracture of the ETT is a common issue faced in the clinical practice (Dietschi *et al.*, 2007). Naturally, teeth were constantly exposed to forces during chewing cycles, which lead to deformation (strain), followed by generation of stresses. Nevertheless, structural failure happens when these loads are greater than the tooth's strength. (da Silva *et al.*, 2011). The endodontic treatment involved many mechanical and chemical procedures associated with removal of the pulp and carious dentin, which ultimately result in altering the mechanical properties of the tooth which increased risk of fracture by altering the tooth's native stress-strain distribution (Soares *et al.*, 2007)

The first important factor that contributes to fracture is the change in the dentinal structure. As dentinal collagen significantly dictates the mechanical properties of the dentin, brittleness of the pulpless teeth is caused by alterations in the cross-links of these collagen fibrils. (Soares *et al.*, 2007). Endodontic treatment will lead to a reduction in the water and moisture content. This alteration will produce stresses that initiate cracks which finally result in tooth fracture (Lee et al., 2004; Soares et al., 2007). Other studies reported reduction in shear strength and tooth stiffness recorded in the ETT (Carter et al., 1983; E. S. Reeh et al., 1989). Many studies have investigated the association between access cavity preparation and the risk of facture. Saberi *et al*., (2020) reported a conservative access cavity design reduced the risk of fracture Saberi *et al*., (2020), while other studies reported no difference in fracture strength between traditional and conservative access cavity designs. Root canal treatment procedures also resulted in increased risk of fracture by lowering the integrity of the radicular dentin and creating intracanal defects that act as stress concentration niches (Adorno *et al*., 2009; Kim *et al.*, 2010).

Existing carious lesions and the overpreparation of the root canal will lead to wide flared canals which gave rise to a thin radicular dentinal walls, thus leads to the inability of such teeth to withstand and resist functional stresses which later become more prone to fracture (Coelho *et al.*, 2009; da Silva *et al.*, 2011). Therefore, a more advanced restorative techniques will be required to obtain a more biomimetic homogenous response to external loads applied to the tooth.

The chemical agents used in conjunction with mechanical preparation of the root canals such as irrigants, intracanal medications and root canal filling materials will affect the collagen structure, this significantly affects the dentin's mechanical characteristics (Renovato *et al.*, 2013). In a study which assessed the effect of sodium hypochlorite (NaOCl) as an irrigant used in endodontic treatment, it was found that there was a reduction in both flexural strength and modulus of elasticity of the dentin. Whilst, the use of both 3% and 5% concentrations and saturated Calcium Hydroxide ($Ca(OH)_2$) was also reported to reduce the flexural strength (Grigoratos *et al.*, 2001).

In cases of root canal re-treatment, the exposure of radicular dentin to chemical solvents used to remove previous obturation materials will adversely affect the chemical composition of the dentin. In a study by Guedes *et al*., (2014), it was reported that the use of xylene and orange oil showed no significant differences in bond strength of fiber posts to root canal dentin, while eucalyptol lowered bond strength to fiber posts (Guedes *et al.*, 2014).

Teeth exhibiting extensive loss of coronal structure will require a post system to retain the core and aid in a more homogenous distribution of functional stresses. Removing obturation material and preparing the post-space are additional steps involved in inserting a post which were associated with mechanical and thermal modification to the ETT. Such events were also accompanied by strain deformation that contributed to vertical root fractures (Amade et al., 2013). Other consequences including tooth ankylosis, bone resorption, or necrosis have also been reported (Eriksson & Albrektsson, 1983). Periodontal supporting tissues including the alveolar bone and periodontal ligament can be damaged when high-temperature levels were generated. Increased temperature could occur during mechanical drilling for post space preparation. Temperature above 47° Celsius for alveolar bone and 43° Celsius for periodontal ligament was reported to cause damage to these tissues. The heat generation can be minimized during post preparation with frequent irrigation, clinician's force, condition, and type of the post drills (old vs. new) to ensure that the tooth structure is protected from further damage (Saunders & Saunders, 1989).

2.4 Restorative options for ETT

Choosing the right restoration and material for ETT is still a challenge for the clinician, and many objectives have to be accomplished by the final restoration such as: 1) preventing microbial leakage into the root canal 2) restoration of form, function, occlusal stability and proximal contact with neighboring teeth 3) protection of remaining tooth structure against further fracture 4) achieving optimal aesthetics 5) maintenance of periodontal health (Bhuva *et al.*, 2021). Multiple factors should be considered when restoring ETT, mainly the presence or absence or a ferrule, as well as the number of remaining walls and percentage of remaining walls (Juloski *et al.*, 2012; Cagidiaco *et al.*, 2008). Restorative techniques of ETT broadly include direct and indirect options. Direct restorative materials traditionally used include amalgam in the form of a core material (Nayyar core) or amalgam overlay, and resin composite which can be used as a direct final restoration of anterior and posterior ETT, or as a core material beneath indirect restorations. Options for indirect restorations are available in different materials: cast gold, metal, metal-ceramic, all ceramic, resin composite fabricated in different forms including full coverage crowns, inlays, onlays. Intra-radicular posts have been used as means to retain the core build up material in ETT, as well as strengthening teeth with wide root canals or traumatized anterior teeth with controversial results regarding the survival rate of the teeth restored with posts against the teeth without posts (Bhuva *et al.*, 2021). They are made of different materials such as gold, cobalt-chromium based, titanium, stainless steel, zirconia as well as flexible materials such as carbon, glass, or quartz fiber. Finally, endocrowns can be an alternative choice to post placement for the restoration of ETT, which are bonded adhesive restorations that utilize the pulp chamber for additional retention, and provide a full coverage restoration (Bhuva *et al.*, 2021).

2.5 Fiber-reinforced dental materials

Fiber-reinforced composites (FRC) are lightweight, aesthetic tooth-colored materials, cost effective and compatible with adhesive restorative dentistry. It is widely used and are a suitable choice for restoration of ETT due its modulus of elasticity that is closely resembling that of the natural dentin (Lippo V J Lassila *et al.*, 2004; Goracci

& Ferrari, 2011a; Novais *et al.*, 2009). Newly introduced FRCs were based on dimethacrylate resins and glass fibers in their composition. The presence of fibers provides strength and the matrix polymer forms the continuous phase that binds them together (Perdigão, 2016)

The final mechanical, optical, and bonding qualities are affected by factors such as the fibers' position, orientation, quantity, and adhesion to the matrix polymer (Perdigão, 2016). The fibers composing an FRC can be classified as unidirectional, multidirectional, short discontinuous or long continuous fibers.

The first application of FRC in the dental field dated back to 1960s, when it was incorporated as a reinforcement for denture base acrylics (Smith 1962; Schwickerath 1965). As a result of the improvement in handling properties, FRCs have been incorporated on a larger scale in dentistry. In the 1990s fixed prosthodontics, implant suprastructures, periodontics and orthodontic appliances started to incorporate FRC material as part of treatment modalities. Further applications of FRCs in restorative dentistry include the restoration of porcelain veneers, root canal fiber posts, and reinforced restorative composites (Fennis *et al.*, 2005; Garoushi, Säilynoja, *et al.*, 2013).

2.5.1 Structure and Properties

The structure of a fiber-reinforced composite was determined based on fibers incorporated in a polymer matrix. The filler fibers feature high aspect ratio, with lengths greater than cross-sectional dimensions. The filler fibers were responsible for provision of strength, and the polymer matrix acts as a continuous phase for binding of these fibers, as well as a separator from the surrounding oral environment and protects from moisture. The impregnation of the fibers in the resin polymer, in addition to other factors such as fiber volume fraction (fiber concentration), fiber elongation and interfacial adhesion have a very significant role in determining the reinforcing effect of the fibers (Vallittu, 1998).

Many parameters dictate the mechanical properties of the fiber-reinforced composite including the orientation, the type and position of the fibers. Fibers come in two varieties: multidirectional, which has two or more orientations, and unidirectional, which runs parallel to each other. In reference to "fiber volume fraction" and fiber concentration, the higher the fiber concentration, the greater the material's tensile strength. However, another concept of partial fiber reinforcement which involves lower fiber content is also applicable, which emphasizes positioning the fibers on the composite structure's tension side (Vallittu, 1997).

2.5.2 Fiber Length and Orientation

The orientation of the fibers in relation to the direction of stress played extremely significant role. The strongest reinforcing characteristics were achieved when fibers were orientated in the direction of the stress and were weakest when the stress was perpendicular to them. Anisotropy is the term used to describe these mechanical characteristics of FRCs that depend on the direction of the longitudinal axis of the fibers. Krenchel’s factor (Figure 2.1) described fiber-reinforcement efficiency is related to their length and orientation. This allowed for appropriate designs of FRCs to yield highest strength against applied stresses (Tanner and Le Bell-Rönnlöf, 2016). Moreover, the orientation of the FRCs affected their polymerization contraction, surface physical properties and optical characteristics (Bell *et al.*, 2005).

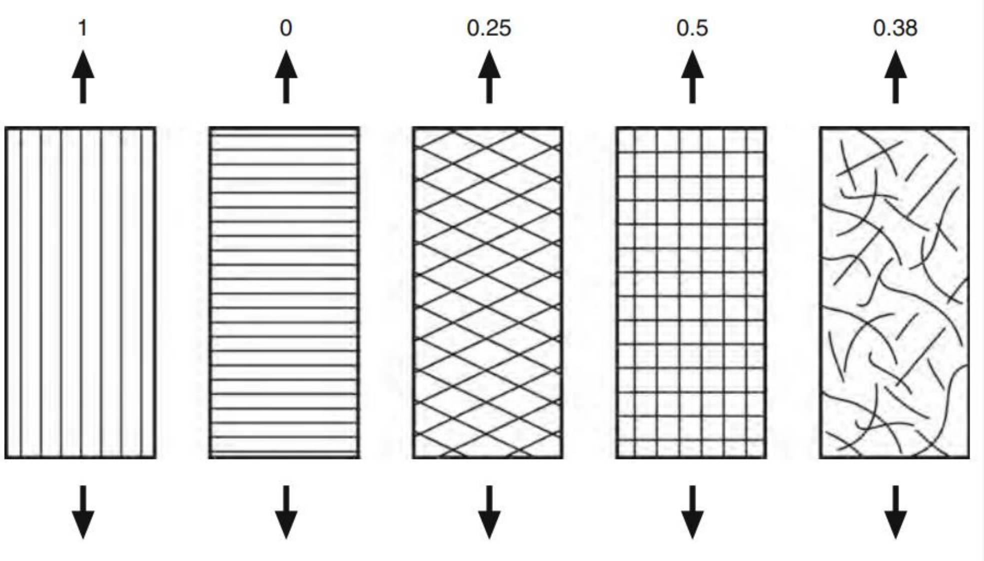

Figure 2.1 Reinforcing efficiency (Krenchel's factor) of fibers according to their orientation (Tanner and Le Bell-Rönnlöf, 2016).

In terms of fibers length, FRCs can either be a short discontinuous FRCs, or a long continuous one. An FRC post is an example of long continuous type of FRC. Dental restorative composites on the other hand have received the reinforcing effect by incorporating short discontinuous fibers in their composition. The two types of FRC differ in their failure types, due to differences in tensile strength which was dependent on fiber length, aspect ratio and interfacial adhesion. A long continuous unidirectional fibers are characterized by higher tensile strength compared with the short discontinuous multidirectional fibers (Perdigão, 2016). Short discontinuous fibers commonly experienced debonding and fracture of fibers, as well as cracking of the polymer matrix. Long continuous fibers experienced axial, transverse tensile failures, shear failures (Garoushi *et al.*, 2018).

2.5.3 Fiber types

Many types of fibers including glass, carbon fiber and polyethylene have proved their reinforcing effect in dental polymers. The fibers' flexural modulus must be greater than the matrix polymer's for them to have a strong reinforcing effect. At present, glass fibers are the most widely used in clinical dentistry. This is unquestionably attributed to their surface chemistry which allowed it to adhesively bond to other dental polymers. In addition, many other positive features of these fibers such as high tensile strength, low cost and the ability to address aesthetic demands have been reported (Schwartz and Robbins, 2004).

Glass fibers can be divided into A (alkali), C (chemically resistant), D (dielectric), E (electrical), R (resistant), and S (high strength) glass fibers based on the chemical structure of the glass mass (Vallittu, 1998). E-glass fibers present the most commonly used type of glass fibers (99% of glass fibers manufactured). They are based on a calcium-alumino-borosilicate particulate mass (Vallittu, 1998).

In dental FRCs, research and development have improved the fiber volume fraction and attributes of the continuous phase polymer matrix to achieve high flexural strength (Lassila *et al.*, 2004). Carbon fibers have been used commonly as well in reinforcing composites with high mechanical demands, as they displayed high compressive and tensile strength. A study reported that when carbon/graphite was used to reinforce PMMA for the first time in 1970s, there was an increase in flexural strength by 100%. Their main limitation for dental application was due to the dark black color, as well as difficulties in manufacturing processes (Schreiber, 1971).

Ultra-high molecular weight (UHMW) polyethylene fibers were also among another type of strong reinforcing fibers, composing aligned polymer strands that are shown to have strong impact characteristics and a low elastic modulus. Their application was limited in dentistry due to the poor adhesive properties with the dental resins. High interaction with oral proteins and microbes that were able to adhere to the polyethylene fibers was another drawback (Tanner *et al.*, 2003).

2.5.3(a) Unidirectional FRCs

The prefabricated FRC posts are a typical example of unidirectional FRCs. Its framework was made of an epoxy polymer matrix or a mixture of epoxy and dimethacrylate resins. The fibers were either from carbon or glass (E-glass, S-glass, quartz/silica). The fiber portion ranged between 40-65% (Zicari *et al.,* 2013) depending on each manufacturer. Fiber posts are now preferred over metallic posts, due to the closer elastic modulus to that of natural dentin, which have been shown to result in favorable fractures and reduced incident of root fractures, as well as excellent aesthetics and adhesive compatibility (Goracci and Ferrari, 2011).

The disadvantages of this post include discrepancy between the shape of the root canal system and the prefabricated post, which leaves areas mostly filled by resin cement, as well as weak coronal portion of prefabricated FRC post (Pegoretti *et al.*, 2002). In addition to that, when a ferrule effect is absent, these FRC posts were liable to have adhesive failure and ultimately secondary caries at the site of tension (Creugers *et al.*, 2005). Initial shortcoming related to adhesion such as poor adhesive properties was due to highly crosslinked polymers and have been solved by means of air abrasion and silanization (Sahafi *et al.*, 2003).

To overcome the drawbacks of prefabricated FRC posts made of various materials, individually constructed FRC posts have been created. Polyethylene woven fibers subjected to cold-gas plasma treatment was one of the example. It improved resistance to fractures, has superior adaptation to the root canal anatomy with anatomic post technique together with favorable fractures were reported in studies evaluating this concept (Grandini *et al.*, 2003; Corsalini *et al.*, 2007). Further reinforcing fibers might be added, especially in cervical sections of the canal where prefabricated posts had performed poorly, increasing bond strength and fracture resistance. The taper of such restorative technique also save the dentinal structure in a weakened and compromised teeth (Lippo V J Lassila et al., 2004; Bell et al., 2005). Better bonding properties were also reported in individually formed FRC posts, due to the presence of semi-IPN network and oxygen inhibited layer which serves as a promoter for adhesion to resin cements. A better adaptation to root canal anatomy was reported as well, which minimizes the cement layer thickness and ultimately decreases polymerization stresses (Bell *et al.*, 2005). A higher degree of conversion, fracture load and decreased microleakage were also found in a study by Hatta *et al.*, (2011).

2.5.3(b) Short Discontinuous FRCs

Fibers have also been used to strengthen restorative composites. However previous attempts were failed due to poor polishability and inadequate fiber length. Short and discontinuous fibers have been used for such purpose, and a critical fiber length range was reported to be between 750-900 μm (Vallittu, 1998). Fiber-reinforced restorative composites were used as a separate base and covered by conventional composite which has better polishability, while the base FRC was found to improve fracture toughness, strength, prevention of crack propagation (Garoushi *et al.*, 2006). Another study reported a significant improvement in mechanical properties when using short-fiber reinforced composite as a core material for ETT. An increase in depth of polymerization was also seen in short-fiber reinforced composite due to the enhanced light transmission through the fibers (Lammi *et al.*, 2011).

2.5.4 Adhesive Properties

Fibers, various inorganic fillers, and a resin matrix act as bonding substrates in an FRC. The fibers' adhesive qualities will contribute to the resin cement and composites' adhesion if they are exposed to the surface. By using a silane coupling agent, the fibers in the FRC can be joined. This agent increases adhesion by generating covalent connections with the methacrylate end of dental resins and hydrogen bonds with the glass end (Matinlinna *et al.*, 2004).

Adhesion to the FRC was also related to the type of resin system in the polymer matrix. FRCs can contain either epoxy-resin or dimethacrylate resin matrix. For usage in dental applications, FRCs were coupled with resin matrices comprised of triethylene glycol dimethacrylate (TEGDMA), urethane dimethacrylate (UDMA) and bisphenol A glycidyl dimethacrylate (bis-GMA), and because these thermosetting resins form highly crosslinked polymers, Bis-GMA, TEGDMA, UDMA-based resins are considered poor adhesive substrates in the FRC, and manufacturers have utilized mechanical features such as serrations in an FRC post to improve retention (Perdigão, 2016). A different strategy to improve bonding involved changing the FRC's resin matrix by adding a phase with less cross-linking, or a semi-interpenetrating polymer network. This method uses a multiphasic polymer matrix with both thermosetting and thermoplastic systems (Sperling, 1994). Furthermore, addition of linear polymers of polymethylmethacrylate (PMMA) has also been shown to improve adhesive polymers (Lassila *et al.*, 2004).

2.5.5 Stability of FRCs

The oral cavity was considered as an aggressive environment to all dental materials including FRCs with all its constituents, the polymer matrix, the fibers and the interface between them (Vallittu, 2000). A study reported a decrease by 15% in strength and modulus of elasticity following 30-day water storage (Vallittu, 2000). Other properties such as flexural strength was tested in multiple studies and was reported that short term water storage (1 month) produced reversible reduction in flexural strength, whereas longer-aging followed a different pattern, as most of the reduction took place during the first months, and then a slow and steady reduction was seen. This ultimately resulted in 20-25% decrease of the overall flexural strength (Vallittu, 2000).

When exposed to acids, bases, or water, the degree of polymerization of an FRC has an impact on how much degradation can occur, where higher degree of polymerization was found to have less degradation with such deleterious factors (LV J Lassila et al., 2002).The presence of void spaces in prefabricated FRC posts enhanced water absorption thus affecting final strength. This was due to the presence of oxygen which inhibits complete polymerization in the polymer (Lassila *et al.*, 2004).

2.5.6 Fiber-reinforced composite posts

Active or passive methods were used to insert intra-radicular posts into the root canal. Whereas passive posts used luting or adhesive chemicals for retention and did not engage the root dentin walls upon insertion, active posts did. A passive and tapered post has been recommended as it was associated with less stress formation and root fractures (Schwartz and Robbins, 2004)

The post length, width, modulus of elasticity, ferrule effect, residual tooth substance and the cementation technique were among the factors that contribute to the longevity of the ETT (Ferrari *et al.*, 2012). Increased stresses at the dentin-post interface were linked to rigid posts with high modulus of elasticity, which increases the risk of fracture. Several investigations have discovered that fiber posts' elasticity modulus is comparable to that of natural dentin (Asmussen *et al.*, 1999).

2.5.6(a) Post Length

The mechanical retention and a sufficient apical seal were dictated by the length of the post space preparation. A previous study concluded that a 3mm apical root canal filling seal was reported to have unpredictable outcome and that a 4-5mm of apical seal was recommended (Abramovitz *et al.*, 2001). A previous review article recommended a post length to be equal to three quarters the root length if possible, or at least equal to crown length (Goodacre and Spolnik, 1994). A 97% success rate was recorded in a retrospective research when the post length was identical to the crown height (Sorensen and Martinoff, 1984).

2.5.6(b) Post Thickness

It was recommended that the post diameter to be between 0.7mm for mandibular incisors to 1.7mm for maxillary central incisors (Shillingburg *et al.*, 1982). Post diameter has direct association with stress generated in the root canal, where a wider post has been associated with higher stresses. Increasing the diameter of the fiber post was found to be associated with increased fracture load, but flexural strength and modulus decreased (Zicari *et al*., 2013).

2.5.7 Intracanal adaptation of post-dentin

Adaptation of FRC posts to the root canal morphology influences their retention and bond strength (Gomes, de Rezende, *et al.*, 2014). Lack of appropriate adaptation was associated with an excessively thick resin cement layer and higher polymerization shrinkage stresses. Defects in the form of voids, gaps also accumulate in this zone thereby increasing chances of FRC post displacement and debonding (Bakaus *et al.*, 2018; Bhaktikamala *et al.*, 2022). On the contrary, satisfactory adaptation of the FRC post minimizes movement of the post and core complex and result in better stress distribution with higher fracture resistance (Xiong *et al.*, 2015; Bhaktikamala *et al.*, 2022).

2.5.8 Artificial aging

Artificial aging in the form of mechanical loading, thermal cycling or simultaneous thermomechanical loading using contemporary computer controlled mastication simulators, has been employed in multiple previous *in vitro* studies (Gomes, Gomes, *et al.*, 2014; Irmak *et al.*, 2018; Frankenberger *et al.*, 2020). Failures of restorative dental materials commonly occurs due to accumulation of stresses generated through repetitive cyclic loading rather than single impactive overloading (Lima *et al.*, 2022). Previous studies by Irmak *et al.*, (2018) and Scherer *et al.*, (2022) concluded that artificial aging caused a significant reduction in flexural strength and fracture resistance of dental materials investigated *in vitro*. Therefore, artificial aging is recommended in the design of *in vitro* studies to simulate the oral environment and the associated dynamic interactions of multiple challenges to evaluate fatigue and wear properties of dental materials, which helps in predicting their clinical performance (Lima *et al.*, 2022).

2.5.9 Fracture resistance test

Age, occlusal contacts, tooth position in the dental arch, crown placement, apical status, collagen degradation, intermolecular cross-linking of the root dentin, and the amount of remaining hard tissue affect the fracture resistance of ETT (Naumann *et al.*, 2009). Although the natural and restored teeth are subjected intraorally to cyclic and repetitive loads, static load to failure tests provide valuable fundamental information on the fracture behavior and properties as well as load bearing capacity of dental materials and post restored teeth (Garoushi *et al.*, 2007).

Weakened ETT with compromised root canals are at higher risk of fracture. Restoring the tooth with biomimetic dental materials gave promising results of enhanced mechanical behavior. The relining technique of prefabricated FRC posts have solved many of the encountered challenges such as the uneven, thick resin cement layer and poor adaptation when using prefabricated FRC posts. However, the available evidence was scarce in terms of fatigue resistance data after thermomechanical aging of ETT restored with relined FRC posts. In addition, even the previously published studies proposed many materials to perform the relining technique, their properties do not precisely overcome the challenging environment of the root canal space. Furthermore, the techniques such as root reinforcement with conventional particulate-filled composite, indirect anatomic posts and bulkfill composite placement in increments were clinically prone to operator errors due to multiple materials placement and steps. This study employed the use of a biomimetic bulkfill flowable short fiber reinforced composite to reline prefabricated FRC post in a direct technique as a dentin replacement material. A dynamic thermomechanical aging protocol was carried out using a contemporary computer-controlled chewing simulator to provide unaccelerated continuous cyclic loading of 500,000 cycles to evaluate the fatigue properties of the weakened ETT restored with the customized FRC posts.