TURUN YLIOPISTON JULKAISUJA
ANNALES UNIVERSITATIS TURKUENSIS

SARJA - SER. D OSA - TOM. 780

MEDICA - ODONTOLOGICA

FIBRE-REINFORCED COMPOSITES AS ROOT CANAL POSTS

by

Anna-Maria Le Bell-Rönnlöf

TURUN YLIOPISTO
Turku 2007

From the Department of Prosthetic Dentistry and Biomaterials Science,
Institute of Dentistry, University of Turku, Turku, Finland

Supervised by	Professor Pekka Vallittu Department of Prosthetic Dentistry and Biomaterials Science Institute of Dentistry University of Turku Turku, Finland
Reviewed by	Professor Kristina Arvidson Fyrberg Faculty of Odontology University of Bergen Bergen, Norway
and	Docent Leo Tjäderhane Academy of Finland Institute of Dentistry University of Helsinki Helsinki, Finland
Opponent	Professor Stig Karlsson Nordic Institute of Dental Materials, NIOM Haslum, Norway

Etching on cover: T.p.l´a 1/50 Ami Le Bell 2007

ISBN 978-951-29-3427-0 (PRINT)
ISBN 978-951-29-3428-7 (PDF)
ISSN 0355-9483
Painosalama Oy – Turku, Finland 2007

"It is not possible for two things to be fairly united without a third,
for they need a bond between them which shall join them both,
that as the first is to the middle, so is the middle to the last,
then since the middle become the first and the last,
and the last and the first both become the middle,
of necessity, all will come to be the same,
and being the same with one another,
all will be a unity."

Plato 428-348 B.C.

To my boys, Petter,
Casimir & Casper

ABSTRACT

Anna-Maria Le Bell-Rönnlöf

Fibre-reinforced composites as root canal posts

Department of Prosthetic Dentistry and Biomaterials Science, Institute of Dentistry, University of Turku, Turku, Finland.
Annales Universitatis Turkuensis. Sarja-Ser D, Medica-Odontologica
Painosalama Oy, Turku, Finland 2007.

Fibre-reinforced composite (FRC) root canal posts are suggested to have biomechanical benefits over traditional metallic posts, but they lack good adhesion to resin composites. The aim of this series of studies was to evaluate the adhesion of individually formed fibre-reinforced composite material to composite resin and dentin, as well as some mechanical properties.

Flexural properties were evaluated and compared between individually formed FRC post material and different prefabricated posts. The depth of polymerization of the individually formed FRC post material was evaluated with IR spectrophotometry and microhardness measurements, and compared to that of resin without fibres. Bonding properties of the individually formed FRC post to resin cements and dentin were tested using Pull-out- and Push-out-force tests, evaluated with scanning electron microscopy, and compared to those of prefabricated FRC and metal posts. Load-bearing capacity and microstrain were evaluated and failure mode assessment was made on incisors restored with individually formed FRC posts of different structures and prefabricated posts.

The results of these studies show that the individually polymerized and formed FRC post material had higher flexural properties compared to the commercial prefabricated FRC posts. The individually polymerized FRC material showed almost the same degree of conversion after light polymerization as monomer resin without fibres. Moreover, it was found that the individually formed FRC post material with a semi-interpenetrating polymer network (IPN) polymer matrix bonded better to composite resin luting cement, than did the prefabricated posts with a cross-linked polymer matrix. Furthermore, it was found that, contrary to the other posts, there were no adhesive failures between the individually formed FRC posts and composite resin luting cement. This suggests better interfacial adhesion of cements to these posts. Although no differences in load-bearing capacity or microstrain could be seen, the incisors restored with individually formed FRC posts with a hollow structure showed more favourable failures compared to other prefabricated posts.

These studies suggest that it is possible to use individually formed FRC material with semi-IPN polymer matrix as root canal post material. They also indicate that there are benefits especially regarding the bonding properties to composite resin and dentin with this material compared to prefabricated FRC post material with a cross-linked matrix. Furthermore, clinically more repairable failures were found with this material compared to those of prefabricated posts.

Keywords: fibre-reinforced composite root canal post, root canal post, fibre-reinforced composite, flexural properties, depth of cure, bonding, load-bearing capacity.

TIIVISTELMÄ

Anna-Maria Le Bell-Rönnlöf

Kuitulujitteiset komposiitit juurikanava-ankkuroinnissa.

Hammasprotetiikan ja biomateriaalitieteen osasto, Hammaslääketieteen laitos, Turun yliopisto, Turku, Suomi.
Annales Universitatis Turkuensis. Sarja-Ser D, Medica-Odontologica
Painosalama Oy, Turku, Finland 2007.

Kuitukomposiitti-juurikanavanastoilla on biomekaanisia etuja verrattuna perinteisiin metallinastoihin, mutta niiden sidostuvuus komposiitteihin on huono. Tämän väitöskirjatyön tavoitteena oli selvittää yksilöllisesti muotoillun kuitulujitteisen komposiittimateriaalin sidosominaisuuksia komposiittiin ja dentiiniin, sekä tutkia sen mekaanisia ominaisuuksia.

Yksilöllisesti muotoillun kuitukomposiittinastan taivutusominaisuuksia tutkittiin ja niitä vertailtiin erilaisiin tehdasvalmisteisiin nastoihin. Yksilöllisesti muotoillun kuitu-komposiittinastan polymeroitumisaste eri syvyyksissä tutkittiin IR-spektrofotometrialla ja mikrokovuusmittauksella ja polymeroitumisastetta vertailtiin resiiniin ilman kuituja. Materiaalin sidosominaisuuksia resiinisementtiin ja dentiiniin tutkittiin Pull-out- ja Push-out-testeillä, ja analysoitiin pyyhkäisyelektronimikroskoopilla. Vertailumateriaalina käytettiin tehdasvalmisteisia kuitukomposiitti- ja metallinastoja. Materiaalin kuormitus-lujuutta ja venymää tutkittiin käyttämällä eri nastoilla restauroituja inkisiivejä.

Yksilöllisesti kovetetulla ja muotoilulla, kuitulujitteesta valmistetulla nastalla todettiin olevan paremmat taivutusominaisuudet kuin tehdasvalmisteisilla kuitunastoilla. Lisäksi yksilöllisesti kovetetulla ja muotoilulla kuitunastalla todettiin olevan sama polymeroitumisaste eri syvyyksissä kun resiinillä ilman kuituja. Semi-lomittais-verkostorakenne- (IPN) polymeerimatriisin omaava yksilöllisesti muotoiltu kuitunasta sidostui paremmin resiinisementtiin kuin ristisilloitetun matriisin omaavat tehdas-valmisteiset kuitunastat. Lisäksi yksilöllisesti muotoillulla kuitunastalla ei havaittu sidoksen pettämistä nastan ja resiinisementin välillä, toisin kuin muiden nastojen kohdalla. Tulos viittaa parempaan materiaalien väliseen sidostavuuteen. Kuormitus-lujuus- ja venymämittauksissa ei havaittu tilastollisesti merkitseviä eroja eri materiaalien välillä. Tästä huolimatta todettiin onttorakenteisilla, yksilöllisesti muotoilluilla nastoilla restauroiduissa inkisiiveissä, hampaan korjaamisen kannalta edullisempia murtumia kuin muilla nastoilla restauroiduissa inkisiiveissä.

Yhteenvetona voidaan todeta, että yksilöllisesti muotoiltua semi-IPN-matriisin omaavaa kuitukomposiitti-materiaalia on mahdollista käyttää nastana juurikanava-ankkuroinnissa. Tehdyt sidoslujuustutkimukset viittaavat myös siihen, että tällä kuitumateriaalilla saadaan aikaan parempi resiinisementti- ja dentiinisidos kuin tehdasvalmisteisilla ristisilloitetun matriisin omaavilla kuitunastamateriaaleilla. Hampaiden murtumistapaa vertailtaessa todettiin yksilöllisesti muotoilluilla kuitukomposiittinastoilla enemmän kliinisesti korjauskelpoisia murtumia kuin tehdasvalmisteisilla nastoilla.

Avainsanat: kuitulujitteinen juurikanavanasta, juurikanavanasta, kuitulujitteinen muovi, taivutusominaisuus, konversioaste, sidostaminen, kuormituslujuus.

CONTENTS

ABBREVIATIONS **8**

LIST OF ORIGINAL PUBLICATIONS **9**

1. INTRODUCTION..**10**

2. REVIEW OF THE LITERATURE **11**

2.1 Root canal post anchoring systems..11
2.1.1 Biomechanical considerations and technical post failures 11
2.1.1.1 The ferrule effect 13
2.1.2 Retention factors...13
2.1.2.1 Post length 14
2.1.2.2 Post diameter and remaining dentin 14
2.1.2.3 Post design..15
2.1.2.4 Luting cements 16
2.1.3 Cast metal posts 17
2.1.4 Prefabricated metal posts and screws 19
2.1.5 Ceramic posts 20
2.1.6 Fibre-reinforced composite (FRC) posts 21
2.1.6.1 The use of FRC in dentistry...22
2.1.6.2 Material properties and structure...22
2.1.6.3 Prefabricated FRC posts 26
2.1.6.4 Individually formed FRC posts 29
2.2 Bonding of posts..30
2.2.1 Bonding of composite resin luting cements to metal posts 33
2.2.2 Bonding of composite resin luting cements to FRC posts......................34
2.2.3 Bonding of composite resin luting cements to dentin............................35
2.2.4 Bonding of core build-up composites to posts 35
2.3 Loading conditions of tooth-post-core-crown systems 36
2.4 Clinical outcome of using post systems 38

3. AIMS OF THE STUDY...**39**

4. MATERIALS AND METHODS **40**

4.1 Materials...40
4.1.1 Post material 40
4.1.1.1 Individually formed FRC posts 40
4.1.1.2 Prefabricated FRC posts 41
4.1.1.3 Prefabricated metal posts...43
4.1.2 Other studied materials...43
4.1.3 Specimen preparation 44
4.1.3.1 Preparation of posts for flexural testing (I)...............................44
4.1.3.2 Preparation of cylinders for degree of conversion and microhardness measurements (II)...44
4.1.3.3 Preparation of discs for bond strength measurements (III, IV) .45
4.1.3.4 Root-post-crown system preparation for static load testing (V) 47

4.2 Methods 49
4.2.1 Flexural testing (I) 49
4.2.2 Degree of monomer conversion and surface microhardness measurements (II) 50
4.2.3 Bond strength measurements (III, IV) 51
4.2.3.1 Pull-out test (III) 51
4.2.3.2 Push-out test (IV) 52
4.2.4 Static load test and strain measurement of tooth-post-crown system (V) ... 53
4.3 Analysis 54
4.3.1 Scanning electron microscopy (I, III, IV) 54
4.3.2 Assessment of failure mode (IV,V) 54
4.3.3 Acoustic emission analysis (V) 55
4.3.4 Statistical methods (I-V) 55

5. RESULTS 56
5.1 Flexural properties of FRC (I) 56
5.2 Degree of monomer conversion and Vicker's hardness of FRC (II) 58
5.3 Adhesion of FRC to composite resin cement and dentin (III, IV) 60
5.4 Load-bearing capacity and microstrain of FRC (V) 61
5.5 SEM analysis of posts and post restorations (I, III, IV) 63
5.6 Failure mode assessment (IV, V) 65

6. DISCUSSION 67
6.1 General discussion 67
6.2 Flexural properties 68
6.3 Degree of monomer conversion and microhardness 70
6.4 Bonding properties 71
6.5 Load-bearing capacity 74
6.6 Clinical considerations and future investigations 76

7. CONCLUSIONS AND SUMMARY 77

ACKNOWLEDGEMENTS 78

REFERENCES 81

ORIGINAL PUBLICATIONS (I-V) 91

ABBREVIATIONS

ANOVA	analysis of variance
BisGMA	bisphenol-A-diglycidyl ether dimethacrylate
CTE	coefficient of thermal expansion
DC	degree of conversion
E-glass	electrical glass
FEPA	Federation of European Producers of Abrasives
FPD	fixed partial denture
FRC	fibre-reinforced composite
FT-IR	Fourier transform infrared
GPa	gigapascal
IPN	interpenetrating polymer network
MPa	megapascal
n	number of specimen
N	newton
PMMA	polymethylmethacrylate
SEM	scanning electron microscopy
Semi-IPN	semi-interpenetrating polymer network
SD	standard deviation
TEGDMA	triethylene glycol dimethacrylate
VHN	vickers hardness number
Vol%	volume percentage
Wt%	weight percentage

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following original publications, which are referred to in the text by the Roman numerals I-V.

I Lassila LVJ, Tanner J, Le Bell A-M, Narva K, Vallittu PK. Flexural properties of fiber reinforced root canal posts. *Dent Mater* 2004;20:29-36.

II Le Bell A-M, Tanner J, Lassila LVJ, Kangasniemi I, Vallittu PK. Depth of light-initiated polymerization of glass fiber-reinforced composite in a simulated root canal. *Int J Prosthodont* 2003;16:403-408.

III Le Bell A-M, Tanner J, Lassila LVJ, Kangasniemi I, Vallittu PK. Bonding of composite resin luting cement to fiber-reinforced composite root canal posts. *J Adhes Dent* 2004;6:319-325.

IV Le Bell A-M, Lassila LVJ, Kangasniemi I, Vallittu PK. Bonding of fibre-reinforced composite post to root canal dentin. *J Dent* 2005;33:533-539.

V Le Bell-Rönnlöf A-M, Lassila LVJ, Kangasniemi I, Vallittu PK. Load-bearing capacity of human incisor restored with individually formed fibre post. *Eur J Oral Sci* 2007, submitted.

The original publications have been reproduced with the permission of the copyright holders.

1. INTRODUCTION

The restoration of an endodontically treated broken down tooth has been a challenge for dental materials research for decades. The traditional and accepted method is to restore the tooth with a post and core-restoration that may be covered with a crown. Until the mid-1980s, the cast-metal post, made indirectly by a dental technician, was considered the safest way to restore an endodontically treated tooth (Healey 1960, Shillingburg 1970). Also prefabricated metal posts in combination with different core materials under artificial crowns were used. The general opinion in the beginning was that a post reinforces the endodontically treated tooth (Baraban 1967). Later on, many studies have reported the opposite, i.e. that a post may be a predisposing factor for root fracture (Hunter et al 1989, Peroz et al 2005). A post should be used only when the remaining coronal tooth tissue can no longer provide adequate support and retention for the restoration (Assif et al 1993, Torbjörner and Fransson 2004b).

As it has become more common for dentists to carry out the post-rebuilding procedure directly in the mouth, e.g with a prefabricated metal post and a composite core, less time is consumed (Torbjörner 2000) and the patient's costs can be reduced. This matter, in combination with the facts that rigid and stiff post material induce stress inside the tooth and may be a cause of root fracture and failure, and also the higher requirements for esthetical solutions, were starting factors for new post materials research. In the 1990s, fibre-reinforced composites (FRC) were introduced as post material.

FRCs have good mechanical properties and can be tailored to specific needs, enabling preservation of tooth structure, using minimal invasive preparations and adhesive techniques (Freilich et al 1998, Meiers et al 1998, Vallittu 1998a, Vallittu and Sevelius 2000). FRCs have been successfully used in dentistry in different applications. As post material FRCs, especially glass FRC, have many benefits compared to metal posts. For example, their modulus of elasticity is closer to that of dentin, and therefore less stress is induced in the root (Schmitter et al 2007). However, the prefabricated FRC posts used today also have shortcomings. Especially their cross-linked finally polymerized polymer matrix is difficult to bond to dentin, resin cements and composite core material (Purton and Payne 1996, Torbjörner and Fransson 2004a). Furthermore, if thin FRC posts are used, adequate load-bearing capacity is not achieved. A special FRC material, consisting of glass fibres and a semi-interpenetrating polymer network (IPN)-polymer resin matrix after polymerization, has been reported to enhance adhesion between polymer-based materials (Lastumäki et al 2003). The semi-IPN FRC material has been reported to have a relatively good clinical outcome in different dental applications (Vallittu and Sevelius 2000, Sevón et al 2000), and it may also be advantageous to use it as root canal post material.

In this series of studies attempts were made to evaluate whether it would be possible to use an individually formed and *in situ* polymerized FRC material with semi-IPN polymer matrix as root canal post material. Both mechanical and bonding properties were evaluated.

2. REVIEW OF THE LITERATURE

2.1 Root canal post anchoring systems

A post (dowel) and core is often used after endodontic treatment when restoring a damaged tooth with extensive loss of coronal tooth structure (Shillingburg and Kessler 1982, Morgano 1996, Morgano and Brackett 1999). The main purpose of this treatment is to provide retention for a crown or a fixed partial denture (FPD) (Shillingburg et al 1970). Post insertion should be avoided if adequate retention can be achieved from the remaining coronal tooth structure (Hunter et al 1989, Assif et al 1993, Torbjörner and Fransson 2004b).

Prior to post preparation and insertion the quality of the endodontic therapy should be evaluated clinically and radiographically. The root filling should be a well-condensed gutta-percha filling, optimally ending 0-1 mm from the radiographic apex (Schaeffer et al 2005). However, errors in estimation of the radiographic working length occur and therefore each tooth should be individually analysed (Williams et al 2006).

2.1.1 Biomechanical considerations and technical post failures

A tooth which is endodontically treated and restored with a post system is affected by the endodontic and prosthetic procedures (Gutmann 1992). Much more important than possible changes in the structure and nature of the dentin of a pulpless tooth, is the loss of internal and external tooth structure due to the restorative procedures (Peroz et al 2005). Studies show that a post does not reinforce an endodontically treated tooth (Sorensen and Martinoff 1984a, Trope et al 1985, McDonald et al 1990, Heydecke et al 2001), although this was earlier suggested (Healey 1960, Silverstein 1964, Baraban 1967). In a study where the reinforcement effect of cast posts and pins was examined, it was found that the endodontically treated unreinforced teeth which served as control were twice as resistant to fracture as the teeth treated with posts or pin-retained cores (Lovdahl and Nicholls 1977). Although this fact has been known for many years and several current studies have confirmed it, a literature survey made in Sweden showed that a high proportion of dental practitioners still believe that a post reinforces an endodontically treated tooth (Eckerbom and Magnusson 2001).

Biomechanical failures associated with post-treated teeth are common; failure rates of 7-15% after three years have been reported (Karlsson 1986, Goodacre et al 2003, Torbjörner and Fransson 2004a). These failures usually have serious consequences for the teeth involved and may result in extensive prosthetic reconstruction. Loss of retention seems to be the most frequent type of failure in post-restored teeth (Mentink et al 1993, Goodacre et al 2003), the failure rate being 9% in the study of Torbjörner et al (1995). Root fracture (3%) is still the complication that leads to the greatest damage and usually results in extraction of the tooth (Torbjörner et al 1995). Root fractures are usually caused by fatigue, and it is tension stress, not compression, that causes fatigue fractures (Torbjörner and Fransson 2004b). By minimizing the non-axial forces, the risk of fatigue fractures may be reduced (Yang et al 2001). Post fracture (1%) is more common in prefabricated posts than in cast posts and is often regarded as a restorable failure (Torbjörner et al 1995). Root perforation is a severe type of failure that may occur during post preparation (Torbjörner et al 1995). Failures in post-retained crowns frequently occur in the maxillary anterior region, where the horizontal forces are great, and therefore this area is considered to be a high-risk area for technical failures (Bergman et al 1989, Mentink et al 1993, Naumann et al 2005a).

In order to restore an endodontically treated tooth successfully, preservation of tooth structure is extremely important (Fokkinga et al 2007). Post preparation weakens the root structure (Trabert et al 1978, Gutmann 1992, Lang et al 2006) and the strength of an endodontically treated tooth is directly related to the amount of remaining dentin structure (Trope et al 1985, Torbjörner and Fransson 2004b, Naumann et al 2006). A recent study reported significant destabilization after access root preparation to pulp chamber and post preparation (Lang et al 2006). Root canal instrumentation, even up to large file sizes (ISO 110), did not cause destabilization, if root canal geometry was preserved (Lang et al 2006).

If a horizontal load is applied to a tooth, the maximum forces and stress areas are situated on the external surfaces e.g. the buccal and palatal surfaces of the root. Consequently, the post positioned in the most central part of the root (neutral axis), does little to reinforce the root (Guzy 1979, Torbjörner 2000) (Figure 1). A more optimal place for the reinforcement, in terms of mechanics, would be at the external surfaces where the maximum stress areas are situated. Usually, whenever possible, this reinforcement is integrated into the crown in the form of a collar or a ferrule (Figure 2), which is situated in the crown margin area where the greatest forces occur.

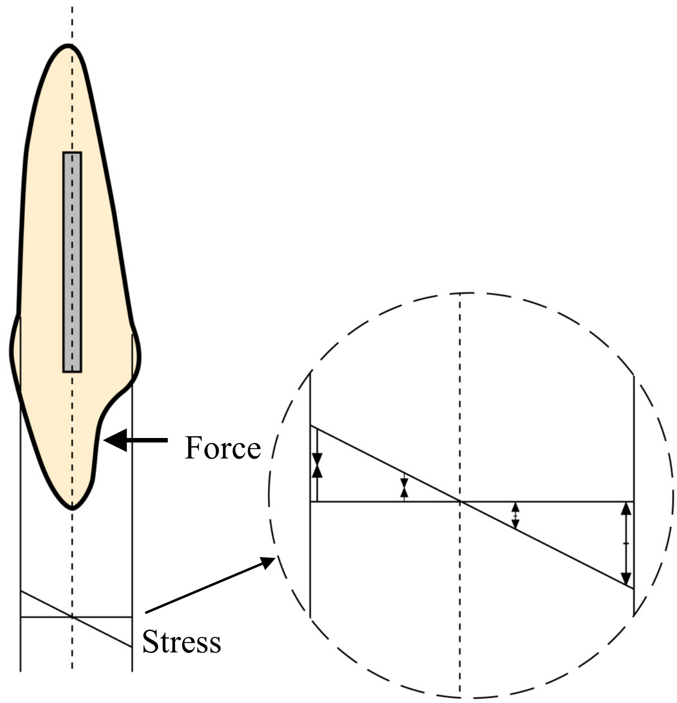


Figure 1. Stress distribution in a post-treated tooth. A post situated in the most central part of the tooth, where stresses are minimal, does not reinforce the root. The figure is modified from Guzy and Nicholls 1979 and Torbjörner 2000.

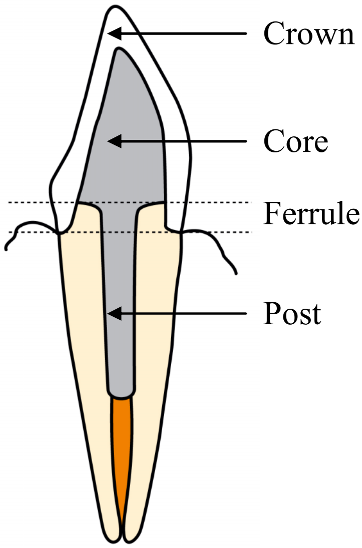


Figure 2. The ferrule effect. The preparation is extended 1.5–2 mm over the core and lie on sound tooth structure, thus forming a protecting ferrule construction. The figure is modified from Torbjörner 2000.

2.1.1.1 The ferrule effect

The crown preparation should be carried out so that the margins of the crown extend over the core material and lie on a sound tooth structure. In this way, the crown will form a collar, which surrounds the cervical parts of the root. The importance of incorporating this kind of construction, called a ferrule (Figure 2), in the crown, was very early emphasized in the literature (Rosen 1961). The ferrule, which should be at least between 1.5 and 2 mm above the crown margin area, embraces the circumference of the root, thus protecting it from fracture (Morgano 1996, Sorensen and Engelman 1990, Pereira et al 2006, Naumann et al 2007). The ferrule also increases the resistance of the post to torsional forces (Hemmings et al 1991, Stankiewicz and Wilson 2002). The ferrule effect of the crown is suggested to be of greater significance than the post and core technique (Torbjörner and Fransson 2004a, Creugers et al 2005b). The absence of a crown ferrule on an endodontically treated post-and-core restored tooth is associated with greater variations of failure load (Naumann et al 2006). It has also been shown *in vitro* that a tooth restored with a crown with a uniform 2 mm ferrule is significantly more resistant to fracture than a tooth restored with a crown with a non-uniform ferrule (Tan et al 2005).

2.1.2 Retention factors

The retention need varies depending on the type of prosthetic construction and the intermaxillary relations. There are many factors affecting the longevity and the retention of post systems (Stockton 1999, Fernandes et al 2003) .

2.1.2.1 Post length

The length of the post influences stress distribution in the root, and thereby affects its resistance to fracture. When the length of the post is increased the retentive capacity increases (Standlee et al 1978, Shillingburg et al 1987, Isidor et al 1999, Nergiz et al 2002). A longer post also helps the root to resist bending (Leary et al 1987). However, a long post preparation increases the risk of root perforation. There are many guidelines in the literature concerning the length of the post. A common recommendation has been that the length of the post should be equal to or greater than the length of the crown (Rosen 1961, Silverstein 1964, Sorensen and Martinoff 1984b, Peroz et al 2005). Other studies have suggested that the post length should be equal to a certain amount of the root, e.g. half the length of the root (Baraban 1967, Jacoby 1976), two thirds of the root length (Larato 1966) or at least half way between the apex of the root and the alveolar crest of supporting bone (Perel and Muroff 1972, Stern and Hirshfeld 1973). It has also been stated that more important than the length of the post is the ferrule height, when investigating the fracture resistance to cyclic loading of crowned teeth (Isidor et al 1999).

Other criteria consern the endodontical apical seal. Recommendations about the amount of gutta-percha which is left after post preparation vary. It has been suggested that leaving at least 4-5 mm of root-filling material is necessary to maintain the apical seal (Mattison et al 1984, Sorensen and Martinoff 1984b). Another study reported that roots with posts in which the remaining root filling was shorter than 3 mm showed significantly higher frequency of periapical radiolucencies compared to roots with longer fillings (Kvist et al 1989). Other studies tend to evaluate the remaining root filling after post space preparation, especially with respect to leakage. It seems that the more gutta-percha is left, the less leakage occurs and the better is the apical seal (Nixon et al 1991). Moreover, it has been shown that luting with composite resin cement can compensate for the loss of retention of prefabricated metal posts of reduced length (Nissan et al 2001).

2.1.2.2 Post diameter and remaining dentin

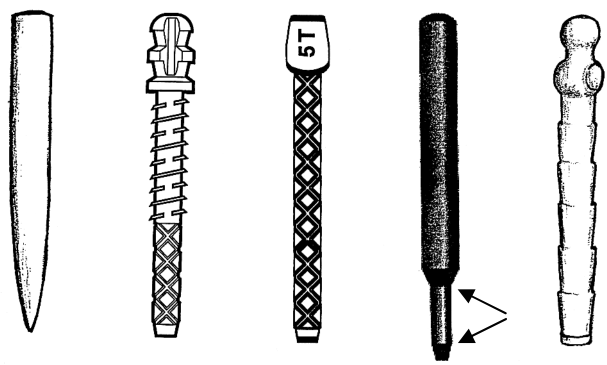
The diameter of the post and the remaining dentin also play a large part in preventing the root from fracture. Several *in vitro* studies have confirmed the importance of the remaining bulk of the tooth structure with regard to strength and resistance to root fracture (Guzy 1979, Trabert 1978, Tjan and Whang 1985, Naumann et al 2006, Lang et al 2006). In addition, a 5-year prospective clinical study emphasizes the immense importance of the remaining dentin height (Creugers et al 2005b). When the diameter of the post is increased, the surface of the post that is in contact with the tooth is increased. According to some studies, an increase in post diameter does not influence the retentive capacities significantly (Standlee et al 1978, Nergiz et al 2002). However, it can increase the stiffness of the post and therefore elevate the risk of root fracture (Trabert et al 1978). On the other hand, it has been recommended not to use a post with a diameter under 1.3 mm, because thinner posts may not provide sufficient stability (Lambjerg-Hansen and Asmussen 1997). One guideline is that the post width should not be greater than one third of the root width at its narrowest dimension, keeping in mind that preservation of the remaining dentin is very important (Stern and Hirshfeld

1973, Lloyd and Palik 1993, Goodacre and Spolnik 1995, Torbjörner and Fransson 2004b). Therefore, the mesial roots of lower molars and the buccal roots of upper molars are not very suitable for post preparation (Gutmann 1992).

2.1.2.3 Post design

The design of the post affects the retention and the success of the restoration (Figure 3). Regarding the post taper, parallel-sided posts are more retentive than tapered posts (Torbjörner et al 1995), and they distribute stress more uniformly along their length during function (Asmussen et al 2005): the greater the taper, the less the retention (Qualtrough et al 2003). Tapered posts function as wedges and initiate stress areas coronally, while parallel-sided posts create the highest stress areas apically around the post end (Johnson and Sakamura 1978, Stockton 1999, Asmussen et al 2005) .

Recent studies have focused on factors increasing the retention of a post without increasing the risk of root fracture. Such factors are the surface design of the post and the types of cement used. The surface designs can be divided into serrated, threaded and smooth surface designs (Figure 3). A serrated post significantly increases the retention of the post compared to a smooth post (Standlee et al 1978). The surface designs can further be divided into active self-threaded and passively luted posts (Cohen et al 1999). Of the surface designs, the active self-threaded posts have been reported to cause the highest stress in the root (Sorensen and Martinoff 1984b, Stockton 1999). The threads of these active self-threaded posts and screw post systems function as stress centres and can easily propagate cracks in the root, and thus may lead to root fracture (Zmener 1980). The surface of the post may also be treated using techniques such as air-particle abrasion, etching and silanization in order to increase retention. Moreover, so-called stabilisation stages at the end of the post (Figure 3d), aiming at distributing stress (Fredriksson et al 1998), as well as different post head designs (Cohen et al 2000) (Figure 3b and 3e), have been used in prefabricated posts.



a b c d e

Figure 3. Posts with different designs: **a)** tapered post with smooth surface, **b)** parallell post with threads, serrations and retentive post head, **c)** parallell post with serrations, **d)** parallell post with stabilization stages (arrows) and smooth surface, and **e)** parallell post with serrations and retentive post head.

2.1.2.4 Luting cements

Zinc phosphate, zinc polycarboxylate, glass-ionomer and resin cements are the most commonly used luting cements for posts. Zinc phosphate cement has been commonly used for decades for the most conventional fixed constructions due to its easy handling characteristics and adequate long-term clinical results (Jokstad and Mjör 1996). Zinc phosphate cement adheres by mechanical interlocking to irregularities in the dentin and the prosthetic construction. The use of resinous cements has increased, and studies have reported higher retention values and resistance to fatigue for these cements compared to brittle zinc phosphate cements (Assif and Ferber 1982, Junge et al 1998). The modulus of elasticity of resin cements approaches that of dentin, and therefore they may have the potential to clinically reinforce thin-walled roots (Mendoza et al 1997). However, resin cements are technique-sensitive because of their short working time, the number of operating steps involved, and the sensitivity to moisture, compared to zinc phosphate cements. Some of the newest self-etching resin cements may overcome the technique-sensitiviness of conventionally bonded resin cements. Also an increase in the surface roughness of the post space improves the retention of different cements (Nergiz et al 1997). The influence of the cement layer elasticity in redistributing the stresses, has been shown to be less relevant as the post flexibility is increased (Lanza et al 2005).

There are several other aspects affecting the retention and durability of a post system, such as the location of the post-treated tooth in the dental arch, the occlusal design of the prosthesis, and the post and core material used. It has been suggested that the type and design of post is of very little importance when it comes to fracture behaviour, if the tooth is covered with a complete cast crown with limited ferrule (Fokkinga et al 2006a), or a sound design having a 2 mm ferrule on a healthy tooth structure (Hoag and Dwyer 1982, Assif et al 1993). Furthermore, in a prospective 10-year clinical study, when comparing different post systems, it was concluded that if the recommended procedures are strictly followed, posts and cores can serve for a long time, irrespective of the post system (Ellner et al 2003). Moreover, a recent investigation showed that root-filled maxillary premolars restored with direct composite crowns without the use of a post, yielded similar fracture resistance compared to the use of metal or glass fibre posts (Fokkinga et al 2005). The same hypothesis, that posts are not necessarily required, was tested and supported in a prospective 5-year clinical trial, where it was found that teeth restored with post-free direct composite crowns yielded a 100% survival rate, whereas a survival rate of 96% was observed for teeth restored with posts (Creugers et al 2005a). In addition, the same conclusions were drawn in another clinical study, where 325 root-filled teeth were restored with either cast metal posts-and-cores or prefabricated titanium posts with composite cores and were compared to teeth without posts (Salvi et al 2007).

Although posts may influence the fracture resistance of a tooth, they are still necessary in several clinical situations, when rebuilding an endodontically treated severely damaged tooth. Especially in cases where the ratio of the height of the clinical crown versus the cross-sectional diameter of the root is unfavourable, the core and the crown are left without sufficient mechanical support. In addition, posts may be needed in cases when the small diameter of the root (incisors, canines and premolars) does not allow placing of large volumes of particulate filler composite material as a “box” type “endocrown” which could be sufficiently durable against biting forces.

The need for additional retention from the root canal in the form of a post must be carefully analysed every time an endodontically treated severely damaged tooth is restored. There is no ideal post system for every clinical case. Depending on the configuration of the root canal, the amount of remaining dentin and the retention need, different post systems are suitable for different situations. The root canal post anchoring systems can be divided into four groups: 1) Cast metal posts, 2) Prefabricated metal posts and screws, 3) Ceramic posts and 4) Fibre- reinforced composite (FRC) posts.

2.1.3 Cast metal posts

A post is either prefabricated (direct technique) or made by using a cast (indirect technique) in the dental laboratory. The cast metal post (custom-made cast post) has been the standard restoration for endodontically treated teeth for many decades (Shillingburg et al 1970, Morgano and Milot 1993). Already in the 1700s, a French dentist, Pierre Fauchard, also called “the father of modern dentistry”, inserted wooden dowels in the canals of teeth to aid in crown retention. The wooden dowels expanded with moisture and eventually fractured the root. Later, after introducing the so-called Richmond crown in 1878, a modification consisting of a one-piece dowel and crown became common. The development of cast posts and cores was a logical evolution from the Richmond crown (Morgano and Brackett 1999). Cast metal posts are still used today, but the procedure requires a lot of time (usually at least two dental appointments) and is expensive (because of the laboratory work and temporary restorations), which is why the prefabricated posts have gained popularity among dentists (Hew et al 2001).

Cast posts can be used throughout the mouth in a variety of clinical situations. A cast post reproduces the contours of the prepared canal, the adaptation to the canal is good and it can be designed to resist torsional forces. One distinct advantage with a cast post and core is that if a tooth is misaligned, the core may be angled in relation to the post to achieve proper alignment with the adjacent tooth. A cast post and core also may be indicated when there is minimal coronal tooth structure available for anti-rotation features or bonding. When the morphology of the canal is critical, e.g. in the case of an oval canal, it is indicated to use a cast post. In these cases, using a prefabricated post would result in minimal contact with the canal walls and would lead to loosening of the post due to the large cement layer. Moreover, if a prefabricated post is used and an extensive preparation is made to improve the adaptation of the post, it would lead to increased root fracture risk due to the weakened tooth structure.

Despite the above-mentioned features, cast posts also have disadvantages. They have low retentive abilities and the technique is both time consuming and expensive. A temporary restoration is also always required, increasing the risk of contamination of the root-canal system (Fox and Gutteridge 1997). In addition, in certain cases, the need for more esthetical solutions has launched the development of new alternative post materials.

In the indirect technique, the dentist prepares the tooth and the root canal, following accepted guidelines for tooth preparation for intact teeth (Shillingburg et al 1987), preserving as much dentin as possible. The post space should not be overly tapered because this decreases the retention (Tjan and Miller 1984). The crown preparation is made so that the crown will extend 2 mm apical of the core-tooth junction if possible, so that the very important ferrule may be incorporated in the crown (Rosen 1961, Shillingburg et al 1970). The dentist takes an impression of the prepared canal and the remaining tooth structure, and the dental laboratory technician fabricates the cast post and core using the gypsum cast made from the impression.

The indirect method requires at least two visits to the dentist which may be seen as a disadvantage, but on the other hand, the procedure saves chair time by delegating part of the work to a dental laboratory. Success of the indirect method depends, among other things, on the accuracy of the impression replicating the internal surface of the prepared root canal. Several materials have been described for fabrication of the post-core pattern. Many methods of replicating the design of the root canal using different rigid objects in the canal to strengthen the impression and minimize distortion, e.g. plastic toothpicks and paper clips, have been described in the literature (Shillingburg et al 1970, Baraban 1967). Another method was also developed, where a prefabricated plastic pattern, which corresponded to the reamer, is used. For practical reasons, the one-piece dowel and crown was further developed into a post-and-core restoration with a separate artificial crown cemented over the core (Rosen 1961). To achieve exact fitting and adaptation of both the cast post and the crown, the literature recommends this kind of two-piece restoration instead of a one-piece cast-post-crown (Shillingburg et al 1970, Shillingburg and Kessler 1982, Shillingburg et al 1987). There are many advantages of having the retention device separate from the crown. These include, for example, the fact that the adaptation of the crown is totally unrelated to the fit of the post and the crown may easily be remade or changed into a bridge retainer. When the post core is ready made it should fit passively and drop into place when tried in the canal, but should resist rotation after seating. A cast post and core is contraindicated when the root canal is very narrow and short, and traditionally, a pin-retained amalgam core has been recommended instead (Shillingburg et al 1970). A root canal post material should be biocompatible, have high flexural and tensile strength and fatigue resistance. The cast post-and-core is usually fabricated in a precious metal. Gold alloys are most commonly used, but also silver-palladium is used.

There are conflicting reports on the outcome of cast metal post systems. A 6-year retrospective study of 96 endodontically treated teeth with extensive loss of tooth structure and restoration with the use of cast post and cores showed a success rate of 90,6% (Bergman et al 1989). Significantly higher fracture thresholds were recorded for cast post and cores compared to carbon-fibre posts in another study (Martinez-Insua et al 1998). In a clinical study where 1273 endodontically treated teeth with six different intracoronal reinforcement methods were evaluated, the tapered cast post and core displayed a higher failure rate than teeth without intracoronal reinforcement (Sorensen and Martinoff 1984b). However, this study was later criticized and the data of the same patient material were re-evaluated in a retrospective (review) study where the high failure rate of the cast posts and cores was concluded to be due to the fact that almost half of the cast posts were half the desired length or less (Morgano and Milot 1993). In a study where restored teeth were intermittently loaded and the adaptation of the posts to the root was measured, it was found that the adaptation was better for teeth restored with parallel-sided prefabricated posts and composite cores than that of teeth restored with tapered individually cast posts (Isidor and Brøndum 1992).

2.1.4 Prefabricated metal posts and screws

There are over 100 different prefabricated post systems available. According to a nationwide survey of dentists in the United States, 40% of general dentists used prefabricated posts most of the time, and the most popular prefabricated post was the parallel-sided serrated post (Morgano et al 1994). Most prefabricated posts are metallic, but there are several newer nonmetallic systems available. Most typically, metallic prefabricated posts are made of stainless steel or titanium alloy. The stainless steel commonly used in prefabricated posts contains chromium (18%) and nickel (8%) (Anusavice 2003). Because of concerns about the allergenic potential of stainless steel posts, and also the risk of corrosion and the elevated root fracture risk connected to this (Silness et al 1979), titanium posts were introduced.

A great variety of prefabricated posts has been developed. The variations in post design are attempts to satisfy various root configurations and retention needs (Figure 3). The prefabricated posts may be parallel-sided or tapered. Parallel-sided posts have been reported to be more retentive than tapered posts (Standlee et al 1978, Johnson and Sakamura 1978, Qualthrough et al 2003, Sahafi et al 2004). Parallel posts induce less stress into the root because of the lower wedging effect compared to tapered posts, and are therefore less likely to cause root fractures (Martinez-Insua et al 1998). The surface designs can be divided into smooth, serrated and threaded designs (Figure 3). The prefabricated metal posts may be further divided into active and passive posts, where the active posts are threaded into the dentin (like a screw), whereas the passive posts get their retention entirely through the cement. Active threaded posts have been reported to have the greatest retention (Standlee et al 1978, Ruemping et al 1979, Cohen et al 1999). However, by inserting the threaded posts, stress may easily be induced in the root because of the threads indenting into dentin. This may lead to local fractures in the dentinal wall and might predispose the root to fracture (Standlee et al 1980, Zmener 1980, Standlee and Caputo 1992). Adaptation of threaded posts to the dentinal walls in the canal is minimal in the cervical third, and maximal in the apical third. The threaded posts should only be used in cases with severe retention problems, e.g. in very short roots, and they should be handled with great care (Standlee et al 1982, Stockton 1999). Serrated or roughened passive posts significantly increase the retention values compared to smooth surface posts, irrespective of post material (Johnson and Sakamura 1978, Nergiz et al 1997, Purton et al 2000).

Prefabricated metal posts are usually used for the direct technique where the post insertion and core build-up are performed at the same appointment by the dentist. Each prefabricated post system usually has accompanying drills with which to drill and shape the post space. Therefore, it is easy for the dentist to achieve a perfect fit for the post. Some prefabricated post types may also be used in the indirect technique, where an impression post is lifted out in an impression, the dental technician waxes the core onto the prefabricated serrated gold alloy post and a post and core is cast.

Prefabricated metal posts have several advantages. Compared to cast metal posts they may have better retentive abilities, they are time-saving (require only a single visit) and also economical (no laboratory fee). When a large amount of coronal dentin remains, a prefabricated post with a composite core may be recommended (Torbjörner 2000). However, the prefabricated posts have the disadvantage that they usually require more dentin removal than cast posts, because the natural shape of the canal is tapered. In addition, the round design of the prefabricated posts offers little resistance to rotational forces. Also, the strength of composite, nowadays commonly used as core material with prefabricated posts, is not as high as that of a cast core.

Clinical studies have indicated higher survival rates for serrated prefabricated posts than for cast posts and cores (Sorensen and Martinoff 1984b, Torbjörner et al 1995). In a prospective study where 325 single- and multirooted teeth were restored with and without posts, it was concluded that cast posts and prefabricated titanium posts yielded similarly favourable results (Salvi et al 2007).

2.1.5 Ceramic posts

With the recent advances in ceramic technology, the all-ceramic crown has become more popular. The requirement for more esthetical post solutions, especially under all-ceramic restorations, has started the development of new post materials. Metal posts may be visible through a translucent all-ceramic crown. Moreover, the marginal gingiva of a tooth restored with a metal post and an all-ceramic crown may appear dark. These concerns have led to the development of white or translucent posts made of zirconia and other ceramic materials. Stabilized zirconia ceramics (zirconium dioxide ZrO_2) have been introduced for the fabrication of posts and cores (Kwiatkowski and Geller 1989, Meyenberg et al 1995, Zalkind and Hochman 1998), because they have higher strength and fracture toughness than other ceramics. Therefore, they may be more suitable for posts.

Zirconia posts offer possible advantages with respect to esthetics and biocompatibility (Purton et al 2000), but they have several disadvantages. Zirconia posts are stiff, but at the same time very brittle, without any ductibility (Asmussen et al 1999). Therefore, it is of great importance to make a deep post preparation when using zirconia posts. Zirconia posts are not yet available in small diameters, which makes it difficult to use minimal invasive preparation on the tooth with this kind of post. In addition, if endodontic retreatment is necessary, retrieval of zirconia and ceramic posts is very difficult. One *in vitro* study recorded poor resin-bonding capabilities of the zirconia posts to radicular dentin after dynamic loading and thermocycling (Dietschi et al 1997). Also, in another study, the zirconia posts showed lower retention values compared to serrated metal posts (Purton et al 2000). In one study, zirconia posts showed poor retention to composite resin cores, and this combination was therefore not recommended for clinical use (Butz et al 2001). Instead, zirconia posts with heat-pressed ceramic cores may be used. Others again have observed good clinical success of zirconia posts with direct composite cores after a mean clinical service of 4.7 years (Paul and Werder 2004). Long-term clinical results are not yet available on this post type.

2.1.6 Fibre-reinforced composite (FRC) posts

The rigidity of traditional metal posts and novel ceramic posts is a major concern, because the rigidity may pose a risk of root fracture (Torbjörner et al 1996, Schmitter et al 2007). A stiff post transmits the occlusal forces to the surrounding dentin. Tension stress at the apical regions of the post cause microscopic fatigue fractures, which, with time, may lead to macroscopic fractures of the root. There are two ways of reducing the tension stress that causes fatigue fracture of the root. The traditional approach is prolonging the post preparation of a stiff post. This principle, which is called the moment compensation principle, is in practice, very difficult and not always possible to carry out. Another current approach, called the modulus compensation principle, is to use a post material which is biomechanically more suitable, e.g. a post material which is strong enough but also flexible so that it can behave like tooth structure inside the root under the occlusal forces. The flexibility or stiffness of a material may be described by the so-called modulus of elasticity or elastic modulus (Young's modulus, E-modulus). The E-modulus is the constant that relates the stress and the strain in the linear elastic region where elastic deformation of a material occurs (Gutmann 1992, Van Noort 2002). A group of materials which offers stiffness equal to that of dentin, as well as high durability is the group of fibre-reinforced composites (FRC) (Table 1).

Table 1. Mechanical properties of some dental and post materials.

Material	**Flexural Strength (MPa)** (Transverse strength)	**Elastic modulus (GPa)** (E-modulus)	**Reference**
Dentin	30-105*	15	O'Brien 2002
Enamel	10*	50-84	O'Brien 2002
Titanium	550-930*	117	O'Brien 2002
Stainless steel	841-924*	177-202	O'Brien 2002
Gold alloy	469–759*	77-108	O'Brien 2002
Zirconia post**	900–1200	200-210	manufacturer's information
Carbon fibre post***	1154	82	Torbjörner et al 1996
Glass fibre post****	990	29	manufacturer's information
Glass fibre post*****	1145	16	Study I

* ultimate tensile strength
** values of yttrium-oxide stabilized zirconia (Cosmopost, Ivoclar)
*** Composipost, RTD (Torbjörner et al 1996)
**** epoxy matrix (ParaPost FiberWhite, Colténe/Whaledent Inc)
***** interpenetrating polymer network (IPN) matrix (study I)

2.1.6.1 The use of FRC in dentistry

The good mechanical properties of FRCs have been used in a diverse range of industrial applications for decades, such as sport equipment, windmills and the ship and aircraft industry. Already in the 1960's, there were early reports of the use of fibre reinforcements in denture-base acrylics (Smith 1962, Schreiber 1971). However, it was not until the handling properties of fibre reinforcements improved, together with the development in manufacturing the reinforcements, that they were commonly accepted in the field of dental materials. Thus, during the 1990's, FRCs became commonly used in dental materials as well (Goldberg and Burstone 1992). FRCs were first used in reinforcing the acrylic-base material of removable dentures, and were found to be superior to the conventional methods (Vallittu 1996a, Narva et al 2001). Before that, removable dentures had been strengthened with metal reinforcements, but with only moderate clinical success (Vallittu and Lassila 1992). The combining of reinforcing fibres with dimethacrylate resins and particulate filler composites made FRCs suitable for fixed partial dentures (FPD), manufactured both indirectly (Freilich et al 1998, Vallittu 1999a, Vallittu and Sevelius 2000, Vallittu 2001a, Behr et al 2003, Vallittu 2004, Göhring and Roos 2005) and directly in the mouth (Meiers et al 1998, Ahlstrand and Finger 2002, Dyer et al 2005, Meiers and Freilich 2006a). The use of FRCs has also become common in periodontal splintings (Meiers et al 1998, Sevón et al 2000), in orthodontic treatment (Kargül et al 2005), and as implant suprastructures (Meiers and Freilich 2006b). In addition, FRCs have been suggested to function as crack stoppers, and as a reinforcing layer beneath large composite restorations (Fennis et al 2005), as well as repair material of fractured incisors (Garoushi et al 2006), although clinical long-term studies are still lacking.

In the early 1990s, prefabricated, finally polymerized FRC root canal posts were introduced to the market. One of the first prefabricated FRC posts was the C-Post (Composipost), which was a post fabricated from a carbon-fibre reinforced epoxy resin, and was developed in France (Duret et al 1990, King and Setchell 1990). Soon also glass and quartz fibres were used in root canal posts. The use of FRCs in root canal posts was justified because their elastic modulus was similar to that of dentin (Table 1). When bonded in place with resin luting cement, it has been proposed that the occlusal forces would be more evenly distributed in the root, resulting in fewer root fractures (King and Setchell 1990, Torbjörner et al 1996, Isidor et al 1996, Ferrari et al 2000a, Ferrari et al 2000b, Schmitter et al 2007) and more favourable failures compared to metal posts (Fokkinga et al 2004).

2.1.6.2 Material properties and structure

FRCs are materials that are composed of reinforcing fibres embedded in a polymer matrix. The fibre reinforcement is characterized by its length being much greater than its cross-sectional dimensions. The fibres give strength and stiffness, while the polymer matrix combines the fibres together, forming a continuous phase around the reinforcement. This phase transfers the loads to the fibres, and also protects the fibres from the moisture of the oral environment (Vallittu 1996b). In order to have a reinforcing effect, the fibres must possess a higher flexural modulus than that of the matrix polymer (Murphy 1998).

The mechanical advantages provided by FRCs are their flexural strength, fatigue strength, elastic modulus and bond strength (of fibres to veneering composites and resin luting cements). In addition, FRCs are metal-free, biocompatible and esthetical. In order to obtain a good reinforcing effect with fibre reinforcements, many important factors should be taken into account. Such factors are fibre orientation, fibre quantity, the impregnation of fibres with matrix polymer, adequate adhesion of fibres to the matrix polymer, and the type and properties of the fibres (Vallittu 1998a).

Fibre orientation

Fibre orientation (direction) influences the mechanical and thermal properties of FRCs (Dyer et al 2004, Tezvergil et al 2003, Tezvergil et al 2006). Reinforcing fibres can be continuous (long fibres) as well as discontinuous (short fibres). Continuous unidirectional fibres give strength, stiffness and anisotropic mechanical strength to the composite in the direction of the fibres, and therefore they are suitable for applications in which the direction of the highest stress is known, e.g. in pontics of FRC FPDs. The efficiency of the fibre reinforcement (Krenchel's factor, value 0 to 1) is used when theoretical estimates of the strength of FRCs are made (Krenchel 1964). The reinforcing efficiency of unidirectional fibres is theoretically 1 (100%), which means that reinforcing properties can be obtained in one direction (Murphy 1998). In FRC root canal posts, continuous reinforcing fibres are used. Continuous bidirectional (woven, weave) fibres have reinforcing fibres in two directions, thus reinforcing the polymer equally in two directions (Krenchel's factor 0.5 (50%) or 0.25 (25%)). Woven fibres add toughness to the polymer, act as crack stoppers, and are especially suitable in cases where the direction of the load is unknown or where there is no space for unidirectional fibres, e.g. in FRC crowns. The use of woven fibres gives so-called orthotropic properties in a plane. If the fibres are oriented randomly as in a fibre mat or as in chopped short FRCs, the mechanical properties are the same in all directions and are so-called isotropic three-dimensionally (Krenchel's factor 0.38 (38%) in two dimensions and 0.2 (20%) in three dimensions (Vallittu 2001b).

Fibre quantity

The fibre quantity of FRCs affects the strength and load-bearing capacity of the system. The fibre quantity is commonly reported with the unit of fibre content by weight (Wt%), but may also be converted to volume fraction (Vol%), when the densities of the polymer and the fibres are known. Because the volume fraction of the fibres in the polymer matrix influences the mechanical properties of FRCs, it is recommended to present the fibre quantity also in volume fraction (Vallittu 1998a). The volume percentage of fibres manually incorporated into the dental resins is generally in the range of 5-15% (Goldberg and Burstone 1992). With the use of a controlled manufacturing process, the volume fraction for dental FRC has been increased to up to 45-65% (Vallittu et al 1994, Vallittu 2001b, Lassila et al 2005).

Impregnation and adhesion of fibres

The fibres should be well impregnated, meaning that resin should come in contact with the surface of every fibre, in order to achieve adequate adhesion of the fibres to the polymer matrix (Beech and Brown 1972). With good impregnation, optimal reinforcement and transfer of stresses from the polymer matrix to the reinforcing fibres may be achieved. An improper degree of impregnation causes several problems with the use of FRC, such as increasing water sorption through voids, leading to reduced mechanical properties of the FRC (Miettinen and Vallittu 1997). Also discolouration of the FRC and oxygen inhibition of the radical polymerization of the resin inside the FRC may occur.

If successful impregnation is not achieved, due to high viscosity or high volumetric polymerization shrinkage of the resin, the mechanical properties of the FRC will not reach the theoretically calculated values (Vallittu 1998b). To overcome the basic problem of impregnating fibres with highly viscous dental resins, preimpregnation with linear porous polymethyl methacrylate (PMMA) has been introduced (Vallittu 1998a, Vallittu 1999b). PMMA requires further chairside or dental laboratory impregnation with either light polymerizable dimethacrylate resin, or with heat polymerizable acrylic (denture base) resin. This results in a multiphase polymer matrix between the reinforcing fibres, a so-called semi-interpenetrating polymer network (semi-IPN) matrix. In this matrix, the dimethacrylate monomers of the resin are partially diffused into the polymer structure of the linear polymer (PMMA) (Sperling 1994, Vallittu 1998a, Kallio et al 2001, Lastumäki 2003). The clinical advantage of the semi-IPN structure is the high degree of impregnation of the fibres with resin. However, further-impregnation is required.

Therefore, to improve the handling properties and to reduce the number of clinical steps, a preimpregnation combining PMMA and dimethacrylate resin in a polymer-monomer gel matrix has been introduced (Vallittu 1999b). The advantages of this structure are the improved handling properties, the high quantity of fibres (up to 70%) resulting in high strength (maximum flexural strength of up to 1250 MPa) and a semi-IPN structure of the polymer matrix, which improves the adhesional behaviour of the material (Vallittu 2001b). With well impregnated fibres, the fibre quantity is increased, resulting in a decrease in water uptake. This, in turn, results in improved flexural properties (Lassila et al 2002).

Besides the impregnation level, the adhesion at the fibre-matrix interface is dependent on the interactions between the components, which can be of mechanical or chemical type. Mechanical bonding depends on the morphology of the fibres. The chemical bond between the polymers and fibres should preferably be a of covalent nature. Silane coupling agents have been successfully used to enhance the surface wettability and to improve the adhesion between polymers and glass fibres (Clark and Plueddemann 1963, Vallittu 1997a, DiBenedetto 2001). The function of silane coupling agents is based on the formation of siloxane bridges and hydrogen bonds on the glass surfaces (Matinlinna et al 2004).

Fibre type and properties

Glass fibres (GFs) are the most commonly used reinforcing fibres in both dental and industrial applications, mostly because they offer several advantages such as high tensile strength, excellent compression and impact properties, relatively high E-modulus (Table 1) and low cost. The transparent appearance makes GFs appropriate for dental applications with high cosmetic demands, such as root canal posts in anterior teeth. Glass fibres stretch uniformly under stress to their breaking point, and on removal of the tensile load short of breaking point, the fibre will return to its original length. This property, together with their high mechanical strength, enables glass fibres to store and release large amounts of energy (Murphy 1998). Glass fibres are formed by blending and heating raw materials (sand, kaolin, limestone and colemanite) at a temperature of 1600°C. The liquid glass mass is then drawn into filaments, with a diameter of 10–24 μm, from which the actual fibre is processed. According to the chemical composition of the glass mass, the glass fibres are classified into A (alkali)-, C (chemically resistant)-, D (dielectric)-, E (electrical)-, R (resistant)- and S (high strength)- glass types. They differ in mechanical and chemical resistance properties. The most commonly used glass fibres in reinforced plastics is E-glass (99% of all glass fibres manufactured today), which has a calcium-alumino-borosilicate composition. E-glass has good tensile and compressive strength, as well as electrical properties and rather low cost, but relatively poor impact resistance. S-glass, which is also used in dentistry, has a different chemical composition, giving higher tensile strength and better wet strength retention, but is rather expensive. In dentistry, E- and S-glass fibres have become the most common reinforcing fibres used. The developments in dental FRC technology, in terms of optimizing the fibre volume fraction and the properties of the polymer matrix, have resulted in relatively high flexural strength values (up to 1150 MPa) (Lassila et al 2002, Alander et al 2004, Väkiparta et al 2004, Bouillaguet et al 2006) of unidirectional E-glass fibres, comparable to those of cast cobalt-chromium alloy (1200 MPa) (Vallittu 1997b).

Carbon fibres (CFs), or carbon/graphite fibres, have been widely used in reinforced composites since the late 1950s. Today, they are commonly used in high performance applications, e.g. sport equipments. Carbon fibres are produced by controlled oxidation, carbonisation and graphitisation at high temperatures, of carbon-rich organic fibre-form precursors, commonly polyacrylonitrile (PAN). The resulting fibre is stronger than steel, lighter than aluminium and stiffer than titanium (Murphy 1998). Mechanical properties of carbon fibres vary along with the composition, but generally carbon/graphite fibres exhibit very high strength in both tension and compression (Table 1). They also have high resistance to corrosion, creep and fatigue (DeBoer et al 1984), and a low coefficient of thermal expansion. Only the impact strength is lower than that of glass fibres. Due to the carbon content, the fibres are permeable to x-rays. Surface treatment and sizing are used to improve bonding and handling properties. The first dental application of carbon/graphite fibres, was in reinforcing PMMA in the early 1970s (Schreiber 1971), which resulted in an increase in flexural strength of almost 100%. Since then, carbon/graphite fibres have been commonly used, e.g. implant-fixed dental bridges from carbon/graphite fibre-reinforced polymethylmethacrylate have been developed (Ruyter et al 1986). The main drawbacks limiting the use of carbon/graphite fibres in dental applications, is the black colour of the fibres, as well as the difficulties in manufacturing and handling properties. However, in prefabricated root canal posts, carbon/graphite fibres are widely used (Isidor et al 1996, Purton and Payne 1996, Torbjörner et al 1996, Sidoli et al 1997, Fredriksson et al 1998).

Ultra-high molecular weight polyethylene (UHMWPE) fibres are also utilized in dental applications (Ladizesky et al 1990, Belli et al 2006). UHMWPE fibres are one of the strongest reinforcing fibres available. They are made of aligned polymer chains, have low elastic modulus and low density. They offer good impact resistance and are white in colour (Murphy 1998). Although they have several significant properties, their clinical use is limited, mainly because of the problem of bonding the fibres to the matrix polymer. A previous study reported increased retention of oral microorganisms on UHMWPE composite surfaces compared to other FRC and conventional restorative materials (Tanner et al 2003).

Aramid fibres (AFs), more commonly known as Kevlar fibres, are produced from aromatic polyamide fibres. They have relatively low density, low weight, high tensile strength and particularly high impact strength. Due to the aromatic structure, they have good thermal and chemical resistance. Aramid fibres are often used in combination with other fibre reinforcements (Murphy 1998). Aramid fibres have been shown to increase the transverse strength of PMMA (Mullarky 1985, Vallittu and Lassila 1992). However, their yellow colour and their poor polishability may limit their use in dental applications.

2.1.6.3 Prefabricated FRC posts

The mechanical properties of prefabricated FRC posts depend, among other things, on the type of fibre used, the type of matrix used, the fibre content, and the direction of the fibres (Table 1). Prefabricated FRC posts consist of a high volume percentage of continuous unidirectional reinforcing fibres in a finally polymerized polymer matrix. The fibres used in prefabricated FRC posts are carbon or glass (E-glass, S-glass, quartz/silica) fibres, and the matrix is usually an epoxy polymer or a mixture of epoxy and dimethacrylate resins with a high degree of conversion and a highly cross-linked structure (Figure 4). The fibres contribute stiffness and strength to the usually elastic matrix. The fibre quantity in prefabricated FRC posts varies from 40 to 65 vol% (Torbjörner 2004a) according to the manufacturer. Similarly to metallic prefabricated post systems, many prefabricated FRC posts have their own accompanying drills with which to make the post space. Prefabricated FRC posts are recommended to be cemented with composite resin luting cement, and composite is used as core material, thus forming a post-core construction that is as homogenous as possible.

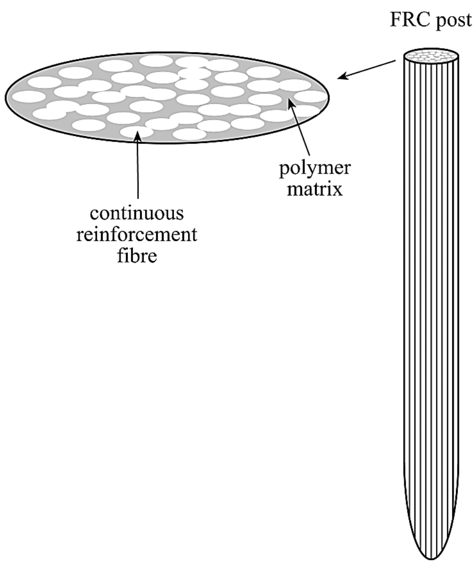


Figure 4. The prefabricated FRC post consists of continuous unidirectional reinforcing fibres in a highly cross-linked polymer matrix.

The first prefabricated FRC post (Composipost, C-Post) that was introduced to the market in the 1990s, consisted of carbon/graphite fibres with a diameter of 7-10 µm in an epoxy matrix (Duret et al 1990, King and Setchell 1990). The tensile strength of the Composipost was, according to the manufacturer, 1600 MPa, which is higher than that of some prefabricated metallic post systems. Since then, due to the higher cosmetic demands and requirements for advanced flexural behaviour, different glass and quartz fibres have also been used in the fabrication of prefabricated FRC posts (Pegoretti et al 2002, Malferrari et al 2003, Schmitter et al 2007). Glass FRC posts can be made of different types of glasses. E-glass is the most commonly used glass type, in which the amorphous phase is a mixture of SiO_2, CaO, B_2O_3, Al_2O_3 and some other oxides of alkali metals. S-glass, which is also used in posts, is also amorphous, but differs in composition. Additionally, glass FRC posts can also be made of quartz fibres. Quartz is pure silica in crystallized form. It is an inert material with a low coefficient of thermal expansion (CTE) (Murphy 1998). Different polymer matrices are also used in prefabricated FRC posts. The stability of the fibre/polymer matrix interface and the effect of a possible mismatch of physical properties, such as CTEs, between fibres and matrix polymers, must be considered when the clinical longevity of FRC posts is evaluated.

There are many suggested advantages with prefabricated FRC posts, compared to conventional metallic posts, one of the most important being the suitable elastic modulus (with glass FRC similar to that of dentin), which should result in fewer root fractures and fewer unfavourable failures (King and Setchell 1990, Isidor et al 1996, Fokkinga et al 2004, Schmitter et al 2007). The flexibility varies according to the type of fibres used. In the case of prefabricated carbon FRC posts, the elastic modulus is in fact much higher than that of dentin, and about three times as high as for glass FRC posts (Table 1), although the manufacturers claim that their stiffness is similar to that of dentin. Carbon FRC posts may thus be seen as a high stiffness material, comparable with metallic and ceramic posts. The choice of appropriate post material and whether a low modulus material will reduce the risk of root fracture or not, is, however, controversial (Torbjörner 2004a, Naumann et al 2007). Additional advantages of prefabricated FRC posts are the easiness of build up and removal *in situ*, and good esthetics, especially with the prefabricated glass FRC posts.

However, prefabricated FRC posts also have shortcomings. The low load-bearing capacity of thin FRC posts has raised arguments against FRC posts in general. By increasing the thickness of the post, or by making individually formed FRC posts, this problem may be overcome. Although prefabricated FRC posts are attached to the root using adhesives and composite resin luting cements, their highly cross-linked polymer matrix with a high degree of conversion is non-reactive, and therefore difficult to bond to resin luting cements and core material (Kallio et al 2001). The research in this area is controversial, but it seems that the bond between the epoxy-based matrix and composite resin luting cements and composite core material is mainly mechanical (Purton and Payne 1996, Torbjörner and Fransson 2004a). With another kind of multiphase polymer matrix, consisting of both linear and cross-linked polymer phases, the bonding abilities may be improved. The monomers of the adhesive resins and cements can diffuse into the linear polymer phase and, by polymerization, form interdiffusion bonding and a so called semi-IPN structure (Sperling 1994, Lastumäki et al 2003). To differentiate this from semi-IPNs of the polymer matrix of FRC materials, the semi-IPN formed by bonding the semi-IPN FRC material to composite resin cement has been defined as secondary semi-IPN (Vallittu 2006). In addition, attempts have been made to increase the retention of prefabricated FRC posts to luting cements, core material and dentin, by developing new surface designs, e.g. serrations (Love and Purton 1996, Al-harbi and Nathanson 2003), and retentive post heads (Cohen et al 2000), as well as by different surface treatments of the post (Mannocci et al 1999, Sahafi et al 2003, Kallio et al 2003). Regarding surface serrations on prefabricated FRC posts, it has not yet been clarified whether serrations offer any advantages to a post of anisotropic nature. When a serrated prefabricated FRC post is made, the continuous unidirectional fibres are cut to form serrations (Love and Purton 1996). Therefore, the rigidity of the post is determined by its smallest diameter. Due to the anisotropicity of FRC, the resistance of the post serration to shear forces along the direction of the long axis of the post is low, thus delaminating of fibres in the serrations may occur.

Another drawback is that the coronal part of the prefabricated FRC post-core system may not be stiff enough to resist the high stresses in the coronal and cervical areas. It has been shown in finite element method (FEM) analysis studies that the highest stress areas in teeth restored with prefabricated glass FRC posts are situated in the cervical areas (Pegoretti et al 2002, Albuquerque et al 2003). Thus, the post system should produce enough reinforcement in this area to resist the stresses, which might not be the case with the prefabricated glass FRC posts on the market today.

Additionally, like all prefabricated posts, prefabricated FRC posts are designed so that a circular post preparation is required, and therefore an unnecessary amount of dentin has to be removed (Figure 5). Moreover, the adhesive procedures when using a prefabricated FRC post with a composite core, are rather technique-sensitive compared to the method of cast posts. Some of the prefabricated FRC posts have poor radiopacity (Finger et al 2002), but this problem has partly been solved by adding radiopaque fillers to the matrix.

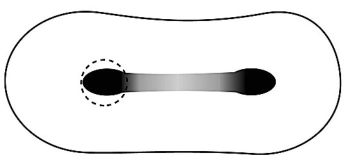


Figure 5. Cross-section of a premolar with oval canals, showing that removal of dentin is required for the circular prefabricated FRC post.

The storage conditions also affect the prefabricated FRC post systems. The flexural properties of prefabricated carbon FRC decrease after water storage and thermocycling (Torbjörner et al 1996, Lassila et al 2002, Bouillaguet et al 2006). FRCs may also be more sensitive to effects produced with time, compared to metallic restorations. Failures that may occur after a longer time are debonding of the post or the core, and leachable restorations, caused by polymerization shrinkage or thermal stresses

(Tezvergil et al 2003, Tezvergil 2006). Therefore, the importance of long-term clinical studies is emphasized in the literature (Hedlund et al 2003).

There are several reports in the literature, both *in vitro* and *in vivo*, of the carbon FRC posts. Most of the clinical studies are short term studies, but also some long-term clinical reports are gradually arriving. Teeth restored with carbon/graphite fibre posts are found to resist fracture propagation better, when intermittently loaded, than teeth restored with prefabricated titanium posts or cast metal posts (Isidor et al 1996). Teeth restored with carbon fibre posts and composite cores typically showed failure of the post/core interface before fracture of the tooth, compared to teeth restored with cast posts that commonly resulted in tooth fracture (Martinez-Insua et al 1998). Another clinical study reported a success rate of 95% for carbon FRC posts, compared to 84% for cast posts and cores, during four years of clinical service (Ferrari et al 2000a). It was concluded that carbon FRC posts can be routinely used. A similar outcome was found in another retrospective study (Ferrari et al 2000b). The survival rate of teeth restored with carbon FRC posts covered with metal ceramic crowns in a prospective study with an average follow-up period of 2.3 years, was 89.6%, and the conclusion was that the post system was one of the most predictable systems available (Glazer 2000). A retrospective study reported a success rate of 97% for carbon FRC posts in three years of clinical service (Hedlund et al 2003), a figure which is higher than the success rates mostly reported for metallic posts and cores (Torbjörner et al 1995). It must be empahisezed that the follow-up time in these studies is relatively short.

Despite these reports of good survival of carbon FRC posts, some unfavourable reports have also been made of carbon FRC posts. In a clinical retrospective study (Fredriksson et al 1998), where 236 teeth were treated with prefabricated carbon/graphite FRC posts, a success rate of 98% was reported after 2 to 3 years of clinical service. A recent retrospective clinical report (Segerström et al 2006) based on the same material as Fredriksson et al's (1998), demonstrated a success rate of only 65% after a 6.7-year follow-up. This result emphasizes the importance of long-term clinical observations. However, the lower number and drop-out of patients in this study must be taken into consideration.

As for glass FRC posts, reports of good clinical results have been published (Grandini et al 2005, Dallari et al 2006), and claims of more repairable failures and fewer root fractures have been made (Cormier et al 2001, Schmitter et al 2007). It appears that glass FRC posts, in combination with adhesive bonding, resin cement and composite core material, may have the possibility to act like a homogeneous unit, if successful bonding is achieved, but long-term clinical results are still lacking.

2.1.6.4 Individually formed FRC posts

Attempts to eliminate the disadvantages of prefabricated FRC posts have been made by developing new concepts and alternative procedures to build up a root with a direct post system. Different concepts have been used, but the main idea is to build up a post construction from a plastic formable fibre material *in situ* in the post space following the anatomical form of the root canal, using minimal invasive preparation, and to completely fill the large coronal opening of the root canal with FRC material (Figure 6). By this concept, more reinforcement fibres may be placed in the cervical parts, which should result in increased resistance. Additionally, by following the root anatomy, more dentin can be saved. Also cement thickness may be reduced, thus resulting in reduced polymerization stress. Because the dental FRC materials are typically based on light-initiated polymerization, the fundamental requirement for *in situ* polymerized FRC posts is an adequate degree of conversion of the polymer matrix in the root canal. The degree of conversion (DC) indicates the portion of double bonds that have reacted in polymerization, and therefore demonstrates how thoroughly a material has polymerized. The higher the DC, the better the strength and the wear resistance of resins (Anusavice 2003).

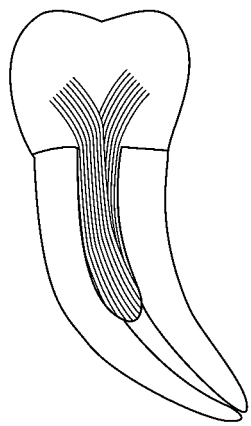


Figure 6. Schematic drawing of an individually formed FRC post.

In one report, this type of alternative post design concept, using cold-gas plasma-treated polyethylene woven fibres, is presented (Terry et al 2001). In another study, greater resistance under loading and more favourable fractures were reported with individual customized FRC posts compared to prefabricated FRC posts (Corsalini et al 2007). Moreover, some benefits may be obtained with translucent posts for building up so-called anatomical well-fitting posts directly (Grandini et al 2003). Incorporating glass fibre fabric within the composite crown in combination with a custom-made glass FRC post showed a beneficial effect on the failure mode of statically loaded maxillary premolars (Fokkinga et al 2006b). Additionally, significantly higher bond strengths and fatigue resistance have been reported with individually formed glass FRC posts with semi-IPN polymer matrix, compared to prefabricated posts (Bitter et al 2007, Al-Tayyan et al 2007, Xie and Wu 2007).

2.2 Bonding of posts

Loss of retention of root canal posts is the most frequent mode of failure (Mentink et al 1993, Torbjörner et al 1995, Goodacre et al 2003). Besides length, diameter and design of the post, the post retention is influenced by several factors related to the bonding of the post, the luting cement and the interaction between the post-core, post-cement and dentin-cement interfaces (Figure 7). The influence of different cements on the retention of posts, and on resistance to fracture of endodontically treated teeth has been investigated extensively (Standlee et al 1978, Trope et al 1985, Ferrari et al 2000a).

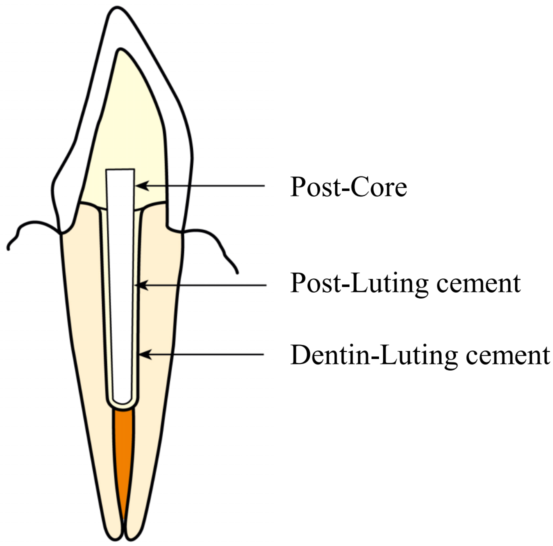


Figure 7. The different interfaces in a post-core system.

Zinc phosphate, modified glass-ionomer and resin cements are the most commonly used luting cements for posts today. Zinc phosphate cement has been the most frequently used cement in fixed prosthodontics due to its easy handling properties and satisfactory long-term clinical results (Shillingburg and Kessler 1982, Jokstad and Mjör 1996). It adheres by mechanical interlocking to irregularities in the dentin and the prosthetic construction. As disadvantages, zinc phosphate cement lacks adhesiveness to tooth structure, it irritates the pulp, and has no anticariogenic properties (Anusavice 2003). Glass-ionomer cements have also been used in luting metallic posts. Their advantages are ease of use, good bonding to tooth structure, and anticariogenic properties, but their low stiffness and brittleness make them non-competitive with resin cements. Newer resin-modified glass-ionomer cements, with improved mechanical behaviour, are increasingly being used in luting root canal posts.

The use of resin cements has increased rapidly, and studies have reported higher retention values and resistance to fatigue for these cements compared to brittle zinc phosphate cements (Assif and Ferber 1982, Trope et al 1985, Mendoza et al 1997, Junge et al 1998, Al-harbi and Nathanson 2003), although some results are conflicting (Sidoli et al 1997, Gallo et al 2002, Schmage et al 2004). Resin cements are especially recommended when luting FRC and ceramic posts, but also when luting metal posts (Peroz et al 2005). Their fracture toughness is higher than that of other cements. The composition of most modern resin-based cements is similar to that of resin-based composite filling materials (a resin matrix with silane-treated inorganic fillers). Monomers with functional groups that have been used to induce bonding to dentin are often incorporated in resin cements. Polymerization can be achieved by the conventional peroxide-amine induction system (self-cure, autopolymerizable) or by light activation (light-cure). Several systems use both mechanisms and are referred to as dual-cure systems (Giachetti et al 2004). Dual-cure cements are recommended especially with translucent fibre posts, which allow light transmission into the root canal. In this way, the degree of conversion of the cement may be increased, and the mechanical properties such as the E-modulus and hardness of the cement improved (Giachetti et al 2004). Light-cure cements generate more polymerization shrinkage stress compared to self-cure cements. Resin-based cements adhere mechanically, by means of a dentin-bonding agent, to the tooth structure (Anusavice 2003). The modulus of elasticity of resin cements approaches that of dentin, and therefore they may have the potential to clinically reinforce thin-walled roots (Mendoza et al 1997). Compensation for reduced post length in metal posts has been shown with resin cements (Nissan et al 2001). In addition, less microleakage and solubility is associated with resin cements in comparison to zinc phosphate cements (Reid et al 2003). However, resin cements are technique-sensitive (Schmage et al 2004) because of their short working time and the number of operating steps involved. Moreover, they require optimal moisture during setting for optimal adhesion and polymerization, which may cause problems when cementing a post in a deep post space, where moisture control is difficult.

In order to bond a post successfully to the tooth, some sort of adhesion mechanism between the different interfaces must be achieved (Figure 7). Adhesion means that an intimate contact at the molecular level between the adhesive and the substrate is achieved (Van Noort 2002). The most important mechanisms of adhesion regarding post cementation, include mechanical adhesion (interlocking), chemical adhesion, and interdiffusion. Mechanical adhesion is based on the interlocking of the adhesive into surface irregularities of the substrate. Chemical adhesion is based on covalent or ionic forces, which results in a strong adhesive bond. Interdiffusion bonding is based on the diffusion of the polymer molecules on one surface into the molecular network of the other surface. This requires that chains of the adhesive and substrate polymers possess enough mobility and are mutually soluble. These mechanisms, among others, or combinations of them, are used when bonding root canal posts. The importance of the mechanical homogeneity and integration of the different interfaces in a post system has been emphasized in the literature (Pest et al 2002).

When a bond failure occurs in a post system, it is important to establish the mode of failure, and at what interface the failure has occurred. The failure may be an adhesive failure between two interfaces or a cohesive failure within a material (adhesive, cement or post). Initially, the failure may occur at the dentin/cement interface. Secondly, the cement itself can fail cohesively. If the bond strength exceeds the tensile strength of the cement, a cohesive failure of the cement will occur before the bond fails. The third possible interface of concern is the cement/post interface. Attempts have been made to improve this interface in many ways, e.g. by developing the material (Giachetti et al 2004, Kalkan et al 2006), the design (Love and Purton 1996, Cohen et al 2000, Al-harbi and Nathanson 2003, Qualtrough et al 2003) and the surface treatment (air particle abrasion, etching, silanization) (Goracci et al 2005, Monticelli et al 2006, Magni et al 2007) of the post.

There are a number of potential causes of interference and failure between the bonding of the different interfaces in post systems. For example, factors relating to dentin (variation in structure, endodontic procedures, dentin surface treatments), factors relating to the adhesive and the cement (difficult access to the canal, moisture control, polymerization shrinkage, degree and depth of cure), and factors relating to the post material (bonding properties, water adsorption, thermal properties, post surface treatments), are important. In addition, the cementation technique and the thickness of the cement layer may influence the quality of the bond.

Bond strength between the post and the tooth can be measured with conventional tensile testing on external root dentin, or on the post space surface with pull-out (De Santis et al 2000) and push-out methods (Pest et al 2002, Goracci et al 2004, Bitter et al 2006). When using small-sized specimens, the microtensile method has commonly been used (Bouillaguet et al 2003, Vano et al 2006, Magni et al 2007). The push-out method has been reported to simulate the clinical situation better than the microtensile method (Goracci et al 2004, Goracci et al 2005, Bouilllaguet et al 2006). It has also been shown that the push-out method is more sensitive to the thickness of the tested disc than is the pull-out force method (Hsueh 1993). Shear bond tests are also used for measuring bond strengths of post systems (Stockton and Williams 1999, Le Bell-Rönnlöf et al 2007). Also observational studies using the scanning electron microscope (SEM) are commonly used for examination of fractured surfaces and interfaces (Mannocci et al 1999, Pest et al 2002, Monticelli et al 2004, Bitter et al 2006, Vano et al 2006, Magni et al 2007). Electrical resistance strain gauges may be used to provide evidence of preliminary failure of the cement (Junge et al 1998). Moreover, the Finite Element Method (FEM) has been used to evaluate the bonding mechanism of posts (Lanza et al 2005).

2.2.1 Bonding of composite resin luting cements to metal posts

The mechanism that commonly bonds resin cements to the surface of metal posts is called mechanical adhesion (Van Noort 2002). It is based on the interlocking of the cement into surface irregularities such as surface serrations and undercuts on the metal posts. There are different factors increasing the retention of a metal post to resin cement, such as serrations (Standlee et al 1978) and grooves (Nergiz et al 1997) on the post surface, a retentive post head (Cohen et al 2000), and different surface treatments of the post, such as grinding, etching, air-particle abrasion, silanization and treatment with metal primers (Akişli et al 2002, Sahafi et al 2003, Matinlinna and Vallittu 2007).

Superior retention values (Assif and Ferber 1982, Mendoza et al 1997) and higher resistance to fatigue (Junge et al 1998) have been obtained for teeth with metal posts luted with composite resin cements than with zinc phosphate cements, although some studies also report similar retention (Schmage et al 2004) and fatigue resistant values (Bolhuis et al 2004). Today, the use of resin cements may be recommended both for luting prefabricated metal posts, as well as for conventional cast metal posts (Bolhuis et al 2004, Peroz et al 2005).

2.2.2 Bonding of composite resin luting cements to FRC posts

Although it has been claimed that there exists a chemical bond between FRC posts and resin cements, debonding failures have been reported (Ferrari et al 2000b). Retentive failure between carbon FRC posts and resin cements occurs at the post-cement interface (Purton and Payne 1996, De Santis et al 2000). Improved retention has been shown with serrated carbon FRC posts (Love and Purton 1996). Research in this area is still rather scarce and controversial, but it seems that the bond between the epoxy-based matrix of the FRC post and composite resin luting cements is mainly mechanical.

Prefabricated FRC posts are attached to the root using adhesives and composite resin luting cements. However, their highly cross-linked polymer matrix, which is polymerized to a high degree of conversion, is difficult to bond to resin luting cements and core material (Purton and Payne 1996, Kallio et al 2001, Lastumäki 2003, Torbjörner and Fransson 2004a). This is due to the fact that the monomers of the composite resin luting cements, which are used when bonding FRC posts, cannot penetrate into the polymer matrix of a cross-linked nature (Vallittu and Ruyter 1997).

Attempts have been made to enhance the adhesion of resin cements to FRC posts by developing surface designs with serrations (Love and Purton 1996, Al-harbi and Nathanson 2003), retentive post heads (Cohen et al 2000), and by different surface treatments, both mechanical and chemical, of the post (Mannocci et al 1999, Sahafi et al 2003, Kallio et al 2003, Monticelli et al 2006, Bitter et al 2007, Magni et al 2007). The mechanical method of using air-particle abrasion, sandblasting the post surface with aluminum oxide particles, gives the post an increased surface roughness, which results in increased surface area. Air-particle abrasion, in combination with the chemical method of silanization of the post surface, has shown promising results (Sahafi et al 2003, Magni et al 2007). The effect of the particle size used in air-particle abrasion on the morphology and mechanical behaviour of FRC posts has not yet been clarified. It has been claimed that the combining of air-particle abrasion and silanization, as well as another method of post surface treatment with hydrogen peroxide (Vano et al 2006), do less damage to the post surface than the chemical treatment method of etching with hydrofluoric acid, which may damage the glass fibres and deprive them of their matrix (Vano et al 2006, Magni et al 2007).

One surface treatment method which should also be mentioned because of its promising results (Lastumäki et al 2002, Lastumäki et al 2003, Keski-Nikkola et al 2004), is the application of an intermediate resin (IMR) to form a secondary semi-IPN between composite resin cement and FRC posts with a semi-IPN matrix.

Furthermore, attempts to develop alternative polymer matrices of FRC posts have been made. With a multiphase polymer matrix, consisting of both linear and cross-linked polymer phases, the bonding abilities of a FRC post may be improved (Bitter et al 2007). The monomers of the adhesive resins and cements can diffuse into the linear polymer phase, and by polymerization, form interdiffusion bonding and a so-called secondary semi-IPN structure (Sperling 1994, Lastumäki et al 2003, Vallittu 2006).

2.2.3 Bonding of composite resin luting cements to dentin

Bonding to root canal dentin is affected, for example, by variations in dentin structure, the endodontic procedures performed prior to post cementation, and the dentin surface treatments (Gutmann 1992, Bouillaguet et al 2003). Bond strength between resin luting cements and dentin measured with the pull-out method is reported to be somewhat lower (11-21 MPa) than that of resin luting cements and FRC posts (26-30 MPa) (Pest et al 2002).

When luting FRC posts with resin cement to root canal dentin, commonly used adhesive procedures are used (Mannocci et al 1999). Due to acid etching of the root canal, the dentin tubules in the root dentin are widened and the collagen fibres are exposed. The infiltration of this network with resin is the best method to obtain a strong and reliable bond of resin cements to dentin. The higher the tubule density, and the more the tubules are widened by the etchant, the greater is the possibility of obtaining a reliable bond. It has been hypothesized that acid etching may enhance the bond strength by increasing the dentin surface area available for bonding, although different areas in the same root canal and also different teeth do not respond equally to acid etching (Ferrari et al 2000c). Tubular density was reported to be higher in the pulpal coronal dentin than in more apical parts of the root canal. The findings suggest that the bond is weaker in the apical parts of the root canal (Ferrari et al 2000c), which is supported by a push-out study of different glass fibre posts (Kalkan et al 2006). On the other hand, in one study, the apical region of the root canal revealed significantly higher bond strengths compared to the middle and coronal region (Bitter et al 2006). The action of different chemicals during endodontic treatment, such as sodium hypochlorite (NaOCl) and ethylenediaminetetraacetic acid (EDTA), may also influence the quality of bonding to dentin (Morris et al 2001).

Moreover, the polymerization stress of resin cement in a root canal with an unfavourable cavity configuration factor (C-factor) may reduce the bond strength to dentin. The C-factor is defined as the ratio of the bonded to the unbonded surface areas of the cavity (Feilzer et al 1987, Anusavice 2003). In the case of a very high C-factor, as in the root canal, the polymerization stress is very high so the risk of the resin cement detaching from the root canal dentin wall is increased, and thus interfacial gaps may be formed (Pest et al 2002). Results of higher bond strengths with dual-cure cements compared to self-cure cements have been reported (Bitter et al 2006). The bonding to root canal dentin may also be affected by the lack of direct viewing and difficulties in moisture control. Ongoing research is evaluating whether self-etching adhesives, which do not require rinsing of the etchant, would bring any benefit to the bonding of FRC posts. In addition, enzymatic activities in root dentin may have some effect on the bonding properties (Tay et al 2006).

2.2.4 Bonding of core build-up composites to posts

The different components of a post system should ideally act like a homogenous unit in order to function similarly to the natural tooth (Pest et al 2002). When an endodontically treated tooth is built up with a glass FRC post, adhesively luted with a resin cement, and the core is made of composite, this is almost achieved. Composites have been increasingly used and accepted for core reconstruction, along with the increased popularity of prefabricated posts. A large variety of composite resin materials, from packable to microhybrid to flowable composites, both light-cure and self-cure, are available for the core build-up procedure. They differ from each other in terms of strength, stiffness and elasticity (Monticelli et al 2004). The stiffer self-curing core composites provide a stable support for the crown, whereas the more elastic flowable light-curing core materials result in fewer voids, better integration with the post surface, and easier handling properties (Monticelli et al 2006). The technique of directly building up the core with composite has several advantages such as a simplified, fast and economical chairside procedure and an esthetic appearance under the tooth-coloured final restoration. As regards mechanical properties, cores directly built-up with composite resin have shown a fracture resistance comparable to that of cast gold cores (Möllersten et al 2002). Moreover, failures under compressive load have been reported to be more favourable for the remaining tooth structure for carbon FRC posts with composite cores than for cast gold alloy posts and cores (Sidoli et al 1997, Pilo et al 2002). It has been suggested that if a sufficient ferrule can be created, the type of core build-up in a post system does not play a significant role (Bolhuis et al 2001).

Failures between carbon FRC posts and core build-up composites have been reported (Purton and Payne 1996, Sidoli et al 1997), and it has been suggested that the retention of the composite core material to FRC posts is based more on mechanical interlocking than on chemical bonding (Love and Purton 1996, Al-harbi and Nathanson 2003). Similar attempts, as for the retention of resin cements, have been made to increase the retention of the composite core material to the post surface using different post head designs (Cohen et al 2000) and post serrations (Love and Purton 1996, Al-harbi and Nathanson 2003). In addition, different surface treatments of the posts, including etching, silanization and air-particle abrasion, have been used to enhance the retention to both resin cements and composite cores. An alternative polymer matrix of the FRC post, consisting of both linear and cross-linked phases, could result in improved bonding to the composite core after polymerization through the interdiffusion mechanism (Bitter et al 2007). In addition to retention problems, microleakage, which may lead to bacterial contamination at the interface between composite and dentin, and further to secondary caries, is a problem associated with resin composite cores (Jung et al 2007).

2.3 Loading conditions of tooth-post-core-crown systems

There are many *in vitro* investigations focusing mainly on post-material behaviour under loading. The most commonly used method is the loading test. In practice, it is not possible to simulate the whole complexity of the oral cavity and occlusion. Instead only a few variables are simulated and tested with laboratory tests. The testing designs of post-core-crown systems are not yet standardized. There are differences regarding the kind of teeth (incisors, premolars, molars, upper and lower teeth), the loading components (post, core, crown), the kind of loading (static, dynamic), the loading position (incisal, palatal, facial), the load angulation, the end of loading (load until failure, nondestructive), and the maximum force applied. Therefore, a comparison of different *in vitro* studies is often almost impossible, if the same study design is not used. Attempts have been made to find a correlation between different types of loading (Naumann et al 2005b).

The three-point bending test provides a basis for comparison of flexural properties between posts made of different materials (Seefeld et al 2007). It is a simple method where the load is applied perpendicular (90º) to the long axis of the post, usually until failure occurs. The static (linear compressive) load until failure, is the most frequently used method to obtain basic knowledge regarding the fracture behaviour and load capacity of a post-restored tooth. It is a rather simple, fast and economical method of simulating the clinical loading (Naumann et al 2005b). However, it has been found that clinical failures most often result from fatigue (Torbjörner et al 2004a), and therefore dynamic (cyclic) loading has been recommended (Naumann et al 2005b, Dietschi et al 2006). Different modes of dynamic loading with different cycle counts, with or without thermocycling, and with or without additional static loading until failure occurs, have been described (Isidor and Brøndum 1992, Isidor et al 1996, Butz et al 2001, Heydecke et al 2001).

Various ageing-simulating methods have been tested, among them a gradual cycling test and a chewing simulation set-up. The problem of these ageing test methods, however, is that they are rather time-consuming. Another disadvantage is that if no failure occurs during the cycling, a comparison with studies using a load-to-failure method is not feasible (Naumann et al 2006).

The load applied at various angles to the tested post-restored tooth in loading tests usually aims to mimic an average angle of tooth contact (Lovdahl and Nicholls 1977). Usually, load angles vary between 30º and 60º to the long axis of the tooth (alternatively 120º and 150º). A load angle commonly used for anterior teeth is 45º, where the load is applied perpendicular to the occluding surface of the crown (Isidor et al 1996, Dietschi et al 2006, Pereira et al 2006). A 90º angle to the long axis of the tooth has also been used to simulate the worst case scenario (trauma towards a maxillary incisor) (Cormier et al 2001).

To further complicate the conclusions drawn from the *in vitro* studies, the load and direction of forces applied to teeth during masticatory function are complex. In a natural dentition, maximal occlusal biting forces can increase to 900 N in the molar region, but chewing forces are significantly lower, usually between 100 N and 300 N. In the molar region, the direction of forces is mainly axial, but in the anterior region great horizontal forces occur. Maximal occlusal forces may be applied to teeth 3000 times per day. Therefore, although dynamic loading may be a closer simulation of the clinical conditions, none of the test methods used today is completely able to simulate all the different movements of occlusion, including bruxism (Vallittu and Könönen 2000).

With respect to other load-testing conditions, factors that may influence the results include storage methods (water, dry, other solution) and thermocycling. Thermocycling has been found to have a negative influence on flexural properties of FRC posts (Drummond 2000).

2.4 Clinical outcome of using post systems

Well-designed randomized controlled clinical trials (RCTs) are considered to give the highest level of evidence. Among post studies, the number of RCTs is still very low. Long-term clinical survival of teeth restored with metal post systems vary from 68% to 99% with a follow-up period of 5 to 10 years, whereas that of teeth restored with FRC post systems varies from 65% to 98% with a follow-up period of 2 to 7 years (Fokkinga 2007). Most studies are retrospective, but there are some prospective clinical trials. The advantage of prospective studies is that the baseline conditions can be better standardized. However, prospective RCTs are difficult to carry out and are very time-consuming.

There is no consensus in the literature on whether new FRC posts should be recommended instead of traditional metal posts. Furthermore, agreement on when post treatment is needed and when it is not advisable has not yet been achieved, although new assessment methods have been proposed (Bandlish et al 2006). Both fracture resistance and failure mode are important when analyzing post systems. If only fracture resistance is considered, cast metal posts should be preferred over prefabricated FRC posts (Fokkinga et al 2004). Still, it should be emphasized that a more favourable failure mode could be more valuable clinically than a high fracture resistance. If a FRC post with a low E-modulus is applied, early, but hopefully repairable failure may occur, compared to that of a metal post of high stiffness which may serve for a longer time, but will more often end up in irrepairable failure (Torbjörner and Fransson 2004a). On the other hand, further development of FRC posts is needed to achieve a post system with more optimal characteristics.

3. AIMS OF THE STUDY

The purpose of the present study was to evaluate fibre reinforcement, consisting of silanated E-glass fibres and multiphase unpolymerized matrix, used as individually formed and *in situ* polymerized root canal posts. The hypothesis of the study was that the fibre-reinforced composite (FRC) material can be polymerized by light in a simulated root canal, and that the individually constructed post, following the shape of the root canal, is biomechanically more optimal when compared to prefabricated metallic or FRC posts.

The specific aims were:

1. To investigate the flexural properties of different types of prefabricated FRC root canal posts and to compare those values to a novel FRC material for dental applications (I).

2. To evaluate the possibility of polymerizing glass FRC material into the root canal by determining the depth of light-initiated polymerization of FRC (II).

3. To compare bonding of composite resin luting cement to a FRC root canal post with either a cross-linked (prefabricated post) or a semi-interpenetrating polymer network (individually formed post) polymer matrix (III).

4. To determine the bonding properties of two types of FRC root canal posts to root canal dentin and to compare them to those of prefabricated metal posts (IV).

5. To evaluate the load-bearing capacity of incisors restored with four different post systems with composite cores and crowns, and to compare them with intact teeth (V).

4. MATERIALS AND METHODS

This series of studies is based on laboratory *in vitro* studies. Studies I and II aimed to evaluate the properties of FRC post materials with the focus on flexural properties (I) and depth of polymerization (II). Studies III and IV evaluated the bonding properties of FRC posts, to composite resin luting cement (III, IV) and dentin (IV). In study V, load-bearing capacity and microstrain were evaluated on incisors restored with different posts. The testing methods used in the different studies are summarized in Table 2.

Table 2. Summary of the testing methods and analysis used in the different studies.

Study	**I**	**II**	**III**	**IV**	**V**
Flexural testing	x				
Degree of monomer conversion measurements		x			
Surface microhardness testing		x			
Bond strength measurements			x	x	
Static load testing					x
Strain measurements					x
Acoustic analysis					x
Scanning electron microscopy	x		x	x	
Failure mode assessment				x	x

4.1 Materials

The materials used in the current studies are listed in Table 3.

4.1.1 Post material

4.1.1.1 Individually formed FRC posts

The individually formed FRC posts in these studies, were made from silanized preimpregnated continuous unidirectional E-glass fibre reinforcement. They consisted of two different types of a so-called semi-interpenetrating polymer network (IPN) polymer matrix after light polymerization. A semi-IPN matrix consists of both linear and cross-linked phases, which enables semi-IPN formation through light polymerization. In these studies, both semi-IPN matrices contained polymethyl-methacrylate (PMMA) as their main linear polymer component. The semi-IPN polymer matrix may be compared to a cross-linked polymer matrix in a prefabricated FRC post, which consists of highly cross-linked phases only (Figure 8).

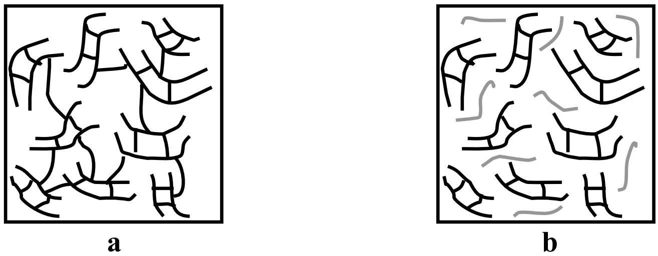


Figure 8. Schematic drawing of **a)** a cross-linked polymer matrix with only cross-linked phases (prefabricated FRC post) and **b)** a semi-IPN polymer matrix with both linear and cross-linked phases (individually formed FRC post).

In the two different types of semi-IPN matrices used in these studies, the fibre reinforcement was either a) impregnated with a polymer-monomer gel (everStick) or b) further-impregnated by immersion in light-polymerizable dimethacrylate monomer resin (Stick + Stick Resin) (Figure 9) (Table 3). The composition of the light-curing resin (Stick Resin) used to further-impregnate Stick fibre reinforcements consisted of BisGMA and TEGDMA (Table 4). As photoinitiators in the resin, the camphorquinone-amine system was used. The same resin was also used as control material in study II. For light polymerization of the individually formed FRC posts, a halogen lamp was used in studies II-V and a light-curing oven in study I. The diameters of the individually formed FRC posts ranged from 1.55 mm to 3.6 mm (I, II, III, IV) and even larger (V). In study II, a large diameter of 3.6 mm was chosen to ensure longitudinal orientation of the fibres in the simulated root canal cylinder. In study V, the post diameter varied because two types of experimental individually formed FRC posts with semi-IPN matrix were used, one with the post space full of fibres, the other made as a “hollow” post construction.

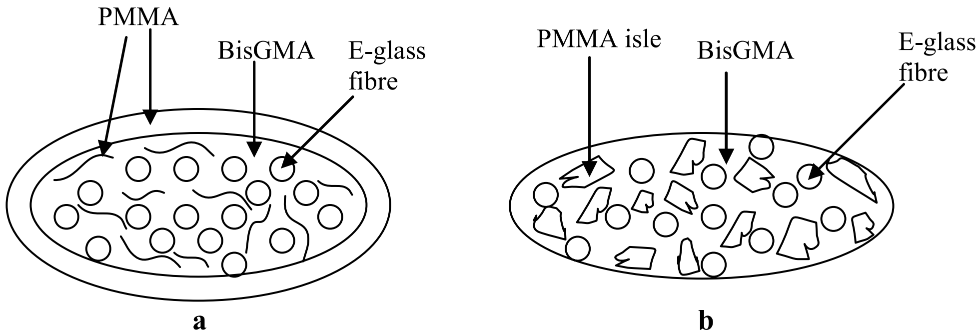


Figure 9. Schematic drawing of cross-sections of fibre reinforcements with two different semi-IPN matrices used for individually formed FRC posts: **a)** impregnated with a polymer-monomer gel with linear PMMA phases and a PMMA layer on the surface (everstick) and **b)** with PMMA islands in a cross-linked matrix (Stick).

4.1.1.2 Prefabricated FRC posts

The prefabricated FRC posts were made of either glass or carbon fibres, and were either unidirectional or organized as a braided plait. The polymer matrix in the prefabricated FRC posts was an epoxy or a mixture of epoxy and dimethacrylate resin with a high degree of conversion and a highly cross-linked structure (Figure 8a). The glass FRC posts consisted of E-glass fibres or silica-zirconium fibres. The fibre content in the studied FRC posts varied between 42% and 60%. The surfaces of the prefabricated FRC posts were either smooth or serrated. The mean post diameters are given in Table 3.

Table 3. The studied post material.

Brand	Manufacturer	Type of post	Fibre	Polymer matrix	Surface	Mean post diameter (mm) (Study)
Stick	Stick Tech Ltd Turku, Finland	individually formed	glass	IPN*	smooth	3.60 (II) 1.67 (III)
everStick	Stick Tech Ltd Turku, Finland	individually formed	glass	IPN**	smooth	1.55 (I, IV) 1.56 (III) varies (V) #
Snowpost	Carbotech Ganges, France	prefabricated	glass	cross-linked***	smooth	1.20 (I) 1.40 (I, III) 1.60 (I)
ParaPost FibreWhite	Coltène/Whaledent Inc. Mahwah, USA	prefabricated	glass	cross-linked***	serrated	1.20 (I) 1.35 (I) 1.39 (III) 1.50 (I)
Glassix	Harald Nordin sa Monreaux, Switzerland	prefabricated	glass (braided)	cross-linked***	smooth	1.35 (I)
C-Post	Bisco, Inc. Schaumburg, USA	prefabricated	carbon	cross-linked***	smooth	1.40 (I, IV, V) 1.41 (III) 1.80 (I) 2.10 (I)
C-Post serrated	Bisco, Inc. Schaumburg, USA	prefabricated	carbon	cross-linked***	serrated	1.40 (III) 1.80 (I) 2.10 (I)
Carbopost	Carbotech, Ganges, France	prefabricated	carbon	cross-linked***	smooth	1.00 (I) 1.20 (I) 1.40 (I) 1.60 (I)
Carbonite	Harald Nordin sa Montreaux, Switzerland	prefabricated	carbon (braided)	cross-linked***	smooth	1.35 (I)
Parapost XT	Coltène/Whaledent Inc. Mahwah, USA	prefabricated titanium post	-	-	serrated + threaded	1.50 (III)
Parapost XP	Coltène/Whaledent Inc. Mahwah, USA	prefabricated titanium post	-	-	serrated	1.50 (IV, V)

* Semi-interpenetrating polymer network of PMMA (Polymethylmethacrylate, Mw 220.000), BisGMA (2.2-bis [4-(2-hydroxy-3 methacrylyloxypropoxy)phenyl] propane) and TEGDMA (Triethyleneglycol dimethacrylate)

** Semi-interpenetrating polymer network of PMMA (Mw 220.000) and BisGMA

*** Epoxy resin matrix

Two types of experimental individually formed FRC posts; canal space full of fibres or "hollow" post construction

4.1.1.3 Prefabricated metal posts

The prefabricated metal posts used in studies III, IV and V were made of titanium alloy. Two types of titanium posts were used; one type had surface serrations (Parapost XP, studies IV and V), the other type had surface serrations and threads (Parapost XT, study III). The diameter of all prefabricated titanium posts used in the studies was 1.50 mm.

4.1.2 Other studied materials

Other materials used in the studies were etchants, adhesive resins, composite resin luting cements and composite core materials, all of which are commercially available materials (Table 4). In studies II and III, light-curing resin (Stick Resin), which consisted of BisGMA and TEGDMA, was used to further-impregnate Stick fibre reinforcements. The same resin was also used as control material in study II, for surface treatment as intermediate resin of all posts in study IV, and for the individually formed FRC posts in study V. In study V, the other studied posts were treated according to the manufacturer's recommendations with UniFil Core self-etching bond.

Table 4. Other studied materials.

Brand	Manufacturer	Type of material	Study	Area of usage
Ultra-Etch	Ultradent, South Jordan	35% phosphoric acid	IV	Etching of root canal
EBS MULTI primer	ESPE, Seefeld Germany	Primer	IV	Treatment of root canal
EBS MULTI bond	ESPE, Seefeld Germany	Adhesive	IV	Treatment of root canal
UniFil Core SE-bond	GC, Tokyo Japan	Self-etching bond	V	Etching and treatment of root canal, treatment of prefabricated posts (intermediate resin)
Stick Resin	Stick Tech Ltd Turku, Finland	Light-curing resin*	II, III II IV V	Further-impregnation of Stick fibres control material Treatment of all post types (intermediate resin) Treatment of individually formed FRC posts (indermediate resin)
Parapost cement	Coltène/Whaledent Konstanz,Germany	Self-cure composite resin luting cement	III	Luting of posts into composite discs
Compolute Aplicap cement	ESPE, Seefeld Germany	Dual-cure composite resin luting cement	IV	Luting of posts into dentin discs
UniFil Core	GC, Tokyo Japan	Dual-cure composite resin	V	Luting of posts into root canals
Bis-Core	Bisco, Schaumburg, USA	Composite core material	III	Manufacturing of test discs
C&B Luting Cement	Bisco, Schaumburg, USA	Self-cure composite resin luting cement	II	Cementing of specimen to a metal frame
Gradia Direct Anterior	GC, Tokyo Japan	Composite	V	Manufacturing of composite crowns

* ca 50 wt% BisGMA, ca 20 wt% TEGDMA and ca 30 wt% monomethacrylates (photoiniator of camphorquinone-amine system).

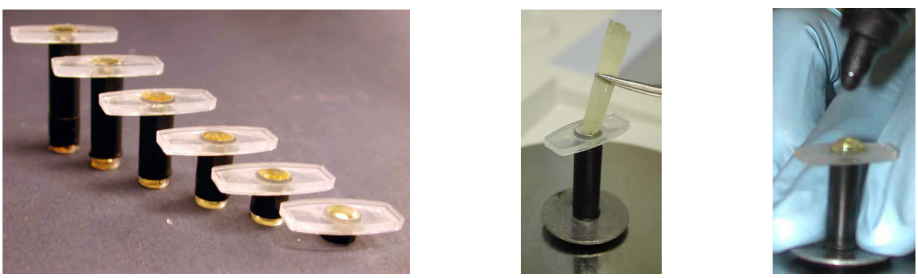
4.1.3 Specimen preparation

4.1.3.1 Preparation of posts for flexural testing (I)

In study I, 17 different prefabricated FRC posts of various brands and diameters, and continuous unidirectional silanated E-glass FRC, consisting of a semi-IPN polymer matrix (everStick), individually formed into the shape of a post, were tested. The individually formed posts were polymerized in a light-curing oven (LicuLite, Dentsply DeTrey GmbH, Dreieich, Germany) for 40 min. The materials are listed in Table 3. Five posts of each type were tested dry (stored in room humidity) and five after thermocycling in water (12,000 x, 5ºC / 55ºC, dwelling time of 30 s). Subsequent to thermocycling, the posts were stored in water for two weeks before mechanical testing. In addition, two posts from each group were embedded in PMMA and wet-ground (grit 4000 FEPA [Federation of European Producers of Abrasives]). After that, specimens were sputtered (SCD 050, BAL-TEC AG, Balzers, Liechtenstein) with gold, and transversal sections were cut for scanning electron microscopy (SEM) evaluation (JSM 5500, JEOL Ltd, Tokyo, Japan).

4.1.3.2 Preparation of cylinders for degree of conversion and microhardness measurements (II)

The fibre reinforcements used were PMMA preimpregnated continuous unidirectional silanated E-glass fibres consisting of a semi-IPN polymer matrix (Stick) (Figure 8b and 9b, Table 3). The fibre reinforcements were cut into six different lengths; 4, 8, 12, 16, 20 and 24 mm. Light-protected cylinders of the same lengths, with an inner diameter of 3.6 mm, were prepared (Figure 10a). The large diameter was chosen to ensure longitudinal orientation of the fibres in the cylinder. The reinforcements were further-impregnated with light-polymerizable dimethacrylate monomer resin (Stick Resin) (Table 4) for 20 to 28 hours in darkness. Three of the further impregnated fibre reinforcements of the same length were then manually placed into each cylinder with the help of pliers (Figure 10b). The highly viscous resin matrix of the FRC hindered fraying of the fibres and made the incorporation of the fibres into the cylinder easier. This resulted in the maximum amount of fibres that could be incorporated into the cylinder by hand. The number of glass fibres with a diameter of approximately 15 µm in each fibre reinforcement was 4000, resulting in a total of 12.000 fibres in each cylinder. Cross-sectional area fraction of fibres/resin was 21% (Figure 10a-c).



a b c

Figure 10. a) The cylinders of different lengths used in the degree of monomer conversion measurements (study II). The tested materials: **b)** further-impregnated fibre reinforcement, and **c)** resin without fibres, placed into the light-protected cylinders.

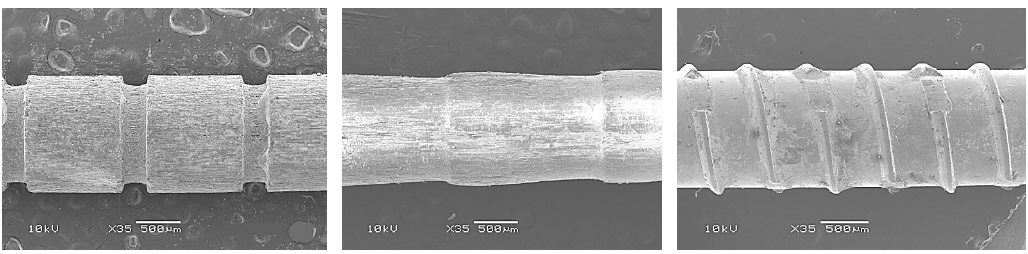
The cylinder simulated the root canal of a tooth, and the fibres were oriented in the direction of the long axis of the cylinder. There were six specimens of each cylinder length. The cylinder was then placed on the sample tray of a Fourier transform infrared (FT-IR) spectrometer, which measured the degree of monomer conversion. The cylinder was placed so that it covered the measuring area (diameter 2.2 mm) of the spectrometer (Spectrum One, Perkin Elmer, Beaconsfield Bucks, England). As control material the same resin (Stick Resin) which was used for further impregnation of the fibre reinforcements, was used, but without fibres (Figure 10c). A light-curing device (EliparHighlight, 3M-Espe, Seefeld, Germany) with a halogen lamp radiating blue light, with a wavelength of 400 to 520 nm and an intensity of 400 mW/cm^2 (measured with Optilux 501, Kerr, Danbury, USA) was used to polymerize the resin matrix of the FRC and the control resin for 40 s from one end of the cylinder. The distance from the tip of the curing device to the cylinder end was 1.5 mm, since contact of the light tip with FRC or resin could have caused misalignment of the fibres. After the degree of monomer conversion measurements, the specimens were stored in the freezer (-24°C) for further analysis.

After thawing one 24 mm specimen of both materials for one hour at a temperature of +18°C, the light-protected cylinders were removed from the material. The specimens were cemented with an autopolymerizing cement (C&B Luting cement) to a metal frame. This was done to simplify the grinding and polishing of the specimen (grit up to 4000 FEPA). The specimens were then ready for the surface microhardness measurements.

4.1.3.3 Preparation of discs for bond strength measurements (III, IV)

Test specimens for pull-out test (III)

Posts of seven different brands (Table 3) with diameters ranging from 1.39 mm to 1.67 mm (average of 1.6 mm) were tested. Two of the tested prefabricated posts had surface serrations (Figure 11a and 11b), as did the reference titanium post, which in addition to serrations, also had threads (screw-like serrations) (Figure 11c). Two types of posts with semi-IPN polymer matrix were individually formed into cylindrical post shape from preimpregnated continuous unidirectional E-glass fibre reinforcement, 1) either impregnated with a polymer-monomer gel (everStick) or 2) further-impregnated by immersing in light-polymerizable dimethacrylate monomer resin (Stick + Stick Resin) (Table 4) for approximately one hour at room temperature and protected from light.



a **b** **c**

Figure 11. SEM photomicrographs of **a)** C-Post and **b)** ParaPost FibreWhite with surface serrations and **c)** ParaPost XT with both surface serrations and threads (original magnification x 35, bar = 500 µm) (study III).

Immediately after further-impregnation, the individually formed posts were light-polymerized for 40 s (on two different sides of the post) before cementation. A light-curing device (Elipar Highlight, 3M-Espe, Seefeld, Germany) with a halogen lamp radiating blue light (wavelength ranging between 500 and 700 nm), with an intensity of 740 mW/cm^2 (measured with Optilux 501, Kerr, Danbury, USA) was used. The light-tip was in close contact with the post. Discs made of a composite core material (Bis-Core), with a thickness of 2.2 mm ± 0.1 mm, were cemented into the metallic moulds. Holes with a diameter of 2.0 mm, simulating a post space in a root canal, were drilled into the discs. The posts were cemented with a self-cure composite resin luting cement (ParaPostCement) into the 2 mm holes of the composite discs. The post was placed with its middle part situated in the cemented area. In the case of the serrated titanium post, the area of threads was situated in the cemented area (Figure 12a and 12b).

When cementing the post, the excess of luting cement was removed with a dental probe. The use of luting cement followed the manufacturer's instructions, and therefore no treatment of the posts with an intermediate adhesive resin was done before cementation. The post-cement-disc specimens were stored at room temperature for 15-20 hours. After that, the apical ends of the post were wet-ground (Stuers LabPol-21, Stuers A/S, Copenhagen, Denmark) with silicon carbide abrasive paper (grit 180 FEPA). Eight posts of each type were tested dry, and eight after thermocycling in water (6000 x, 5°C/ 55°C, dwelling time of 30 s). After testing, the specimens were sputtered (Sputter Coater SCD 050, BAL-TEC AG, Balzers, Liechtenstein) with gold and observed under the scanning electron microscopy (SEM) (JSM 5500, JEOL Ltd, Tokyo, Japan).

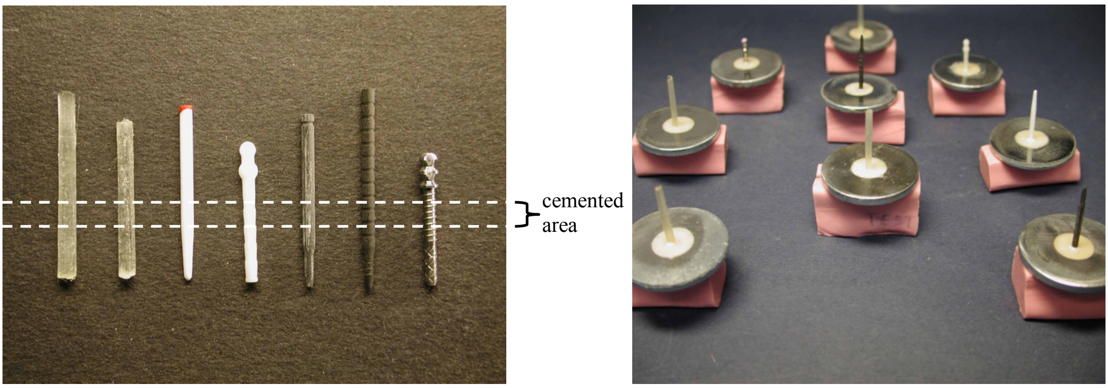


Figure 12. The posts used in the Pull-out test (study III) **a)** before and **b)** after cementation.

Test specimens for push-out test (IV)

Human third molars were extracted and stored for one week in chloramine (0.5%), and then in 0.9% NaCl w/v in a refrigerator at +8ºC for 3–6 months until preparation. Teeth selected for the study were intact. The crowns of the teeth were removed at the cemento-enamel junction by grinding (grit 180 FEPA) and post-space preparation was carried out with Parapost drills (diameter 1.5 mm) to the thickest root of the tooth. The post space was etched for 15 s with 35% phosphoric acid (Ultra-Etch), washed thoroughly and lightly air-dried. The post-space was painted and scrubbed for 20 s with EBS Multi Primer. After lightly air-drying, the post space was painted with EBS Multi Bond for 20 s, air-dried and light-cured (axially towards the end of the root) for 20 s, according to the manufacturer's instructions. A light-curing device (Optilux 501, Kerr, Danbury, USA) with a halogen lamp radiating blue light (wavelength ranging between 500 and 700 nm) and with an intensity of 780 mW/cm^2 (measured with Optilux 501, Kerr, Danbury, USA) was used.

Prefabricated carbon/graphite FRC posts with cross-linked polymer matrix and individually formed glass FRC posts with semi-IPN polymer matrix (everStick) were compared. Serrated titanium posts served as reference (Table 3). The individual FRC posts were formed by hand into a cylindrical post shape. The posts were treated with an intermediate resin, which was a light-polymerizable dimethacrylate monomer resin consisting of BisGMA and TEGDMA (Stick Resin) (Table 4) for 3 min protected from light. After gently air-drying, the posts were light-cured for 40 s on two sides of the posts. The posts were cemented with a dual-curing composite resin cement (Compolute Caps Cement) (Table 4) into the prepared post spaces of the roots. The cement was light-cured (in 45° angle, close to the orifice of the canal) for 40 s. After leaving the samples for further polymerization for 30 min, they were stored in water (37°C). After 26 days, the samples were thermocycled in water (6000 x, 5°C/ 55°C, dwelling time of 30 s).

Prior to testing, the samples were wet-ground (grit 180 FEPA) into discs of different thicknesses: 1 mm, 2 mm and 4 mm (± 0.15 mm) (n = 12 for each disc thickness and each post type) and stored in water (37°C) for 3-5 days. Only one disc was made from each tooth (Figure 13).

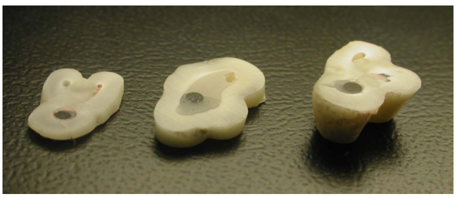


Figure 13. The discs of thicknesses 1, 2 and 4 mm made for the Push-out test (study IV).

4.1.3.4 Root-post-crown system preparation for static load testing (V)

Fifty extracted caries-free human incisors were stored in chloramine (0.5%) for one month. The crowns of the incisors were cut (ground) at the cemento-enamel junction (grit 180 FEPA), and some of the incisors were left intact for the reference group. The buccal and palatal sides of the roots were marked, the root thicknesses were measured at the cemento-enamel junction from two sides (the thinnest and the thickest), and the mean root diameter was calculated (6.17 ± 0.28 mm). The mean root diameter value did not differ between the groups ($p > 0.05$). Post preparation of up to 9 mm was carried out with Parapost drills (diameter 1.5 mm), and the coronal opening (canal entrance) was standardized with two different drills under water cooling. The canal entrance was 3 mm in diameter with a conical form towards the apical end. The preparation simulated a relatively damaged tooth. The remaining dentin was measured from two sides (the thinnest and thickest) and a mean value of remaining dentin was calculated (1.80 ± 0.14 mm). The root thicknesses of the intact roots used as reference were measured in the same way as in the other groups, and the remaining dentin thicknesses of that group were measured after testing the specimens. The roots were divided into groups according to the type of post used (Table 3): 1) prefabricated serrated titanium posts (Parapost XP) (n= 9), 2) prefabricated carbon/graphite FRC posts (C-Post) (n = 9), 3) individually formed glass FRC posts with a semi-IPN polymer matrix (everStick Post) ("everStick Post A") (n = 10) with the hole post space filled up with fibres (Figure 14a), and 4) individually formed glass FRC posts with a semi-IPN polymer matrix (everStick Post) ("everStick Post B") (n = 9) with the fibres formed into a hollow tube (Figure 14b). The remaining intact roots, which were not restored with posts, served as reference (n = 7). The individually formed FRC posts in groups 3 and 4 were formed by hand following the manufacturer's instructions. In group 3 (everStick Post A), the individually formed post was formed from one fibre bundle with a diameter of 1.5 mm and two fibre bundles with a diameter of 1.2 mm. First, the 1.5 mm bundle was fitted into the canal, both ends were cut for a perfect fit (the apical end diagonally and the coronal end leaving 4 mm of fibre bundle above the coronal opening) and then light-polymerized (Optilux 501; Danbury, USA) with a halogen lamp radiating blue light (wavelength ranging between 500 and 700 nm) with an intensity of 780 mW/cm^2 (measured with Optilux 501, Kerr, Danbury, USA) *in situ* for 20 s. After that, it was removed from the canal and further light-cured for 40 s outside the canal. Then, the 1.2 mm bundle was treated in the same way, fitted next to and attached to the individually formed 1.5 mm bundle, followed by the second 1.2 mm bundle. Finally, the individually formed fibre post, consisting of three bundles of fibres attached together, was treated with light-polymerizable dimethacrylate monomer resin consisting of BisGMA and TEGDMA (Stick Resin) for 5 min, dried, light-cured for 10 s, and then cemented (Figure 14a). In group 4 (everStick Post B), the "hollow" individually formed post was formed from one fibre bundle with a diameter of 1.5 mm and one fibre bundle with a diameter of 1.2 mm. The procedure was the same as in group 3, but the two fibre bundles were placed and pressed against the palatal (1.5 mm) and buccal (1.2 mm) surfaces while light-polymerizing, thus forming a "hollow" structure (Figure 14b).

a b

Figure 14. The individually formed FRC posts (study V): **a)** "everStick Post A" with the canal full of fibres and **b)** "everStick Post B" with the fibres formed into a "hollow" tube.

The posts were cemented with a dual-curing composite resin luting cement (Unifil Core). In group 4, the cement also filled up the "hollowness" in the individually formed FRC post. Composite crowns (Gradia Direct Anterior) (Table 4) were made with a prefabricated transparent crown mold (Pella crown, size no 21 or 22, Products Dentaires S.A., Vevey, Switzerland). The composite was applied into the molds, which were then placed on the root-post-construction and light-polymerized twice for 40 s around the crown. There was approximately 4 mm of composite on top of the post head. Possible air-bubbles were filled up with composite by hand afterwards. The crowns were polished and finished with diamond burrs under water cooling. All roots were embedded in the middle of an acrylic resin cylinder (Palapress; Heraeus Kulzer GmbH & co.Hg, Hanau, Germany) (cylinder diameter 20 mm, height approximately 14 mm) at a level of 3 mm below the lowest point of the cemento-enamel junction, simulating the bone level. A small cupformed cavity was made on the palatal side (3 mm apically of the incisal edge) of each composite crown to mark the placement of the head of the testing jig (round ball, diameter 6 mm). The test specimens were stored in water at room temperature for six days.

4.2 Methods

4.2.1 Flexural testing (I)

The three-point bending test according to the ISO 10477 standard (span 10.0 mm, crosshead speed 1.0 mm/min, cross-sectional diameter of loading tip 2 mm) was used to measure the flexural strength and modulus of FRC post specimens. All posts were tested with a material-testing machine (model LRX, Lloyd Instruments, Fareham, England) at room temperature (22 ± 1 °C), and the load-deflection curves were recorded with a PC software (Nexygen, Lloyd Instruments Ltd., Fareham, England) (Figure 15).

The fracture loads of post specimens were measured. Flexural strength (δ_f) and flexural modulus (E_f) were calculated from the formula (Torbjörner et al 1996):

$$\delta_f = 8 F_{max} l / \pi d^3 \qquad (1)$$

$$E_f = S\ 4\ l^3 / (3 \pi d^4) \qquad (2)$$

where F_{max} is the applied load (N) at the highest point of the load-deflection curve, l is the span length (10.0 mm), d is the diameter of the specimens. S = F/D, the stiffness (N/m) and D is the deflection corresponding to load F at a point in the straight-line portion of the trace. In order to eliminate the influence of the conical end of some of the posts, a short span length was used to get support for the post within the cylindrical part of the post. The parallel-sided cylindrical part of the post was considered to be the specimen.

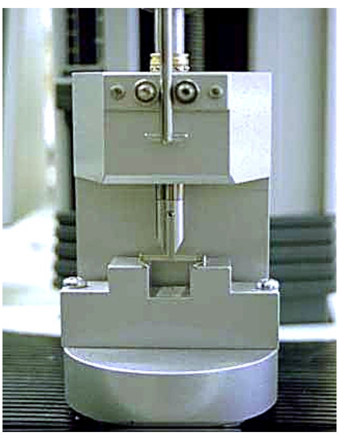


Figure 15. The flexural properties of the posts were evaluated with a three-point bending test (study I).

4.2.2 Degree of monomer conversion and surface microhardness measurements (II)

FT-IR spectroscopy was used to measure the degree of conversion of FRC material and resin in the different lengths of light-protected cylinders. The polymerization of the FRC material and resin in the cylinders was carried out on the FT-IR spectrometer sample tray (Figure 16), and the IR spectra were analysed by four scans at 40 s (0.66 min), 1.5 min, 3 min, 5 min, 10 min and 15 min from the beginning of the polymerization with attenuation total reflectance (ATR). Six specimens were analysed for each cylinder length.

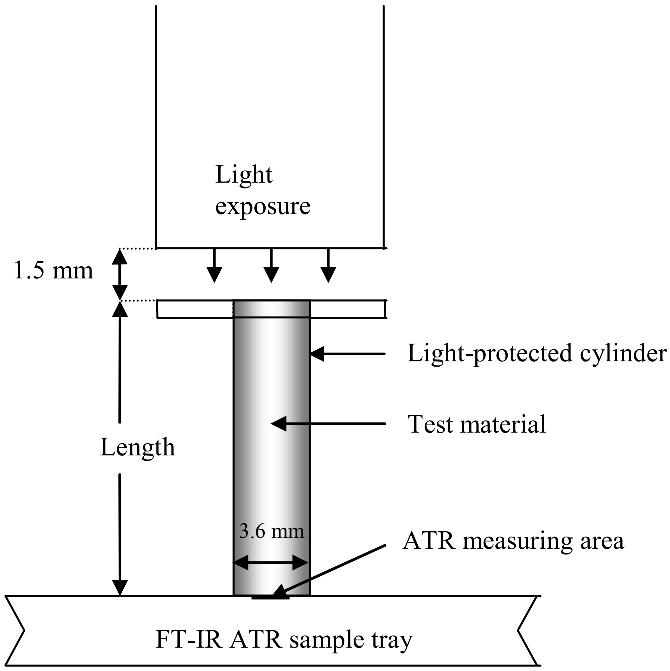


Figure 16. The test setup for determining the degree of monomer conversion of the tested materials in the light-protected cylinders (study II).

FT-IR spectroscopy measured the degree of conversion directly from the intensity ratio of the aliphatic to aromatic stretching vibrations. The degree of conversion was measured from unreacted double bonds, which defined how thoroughly a sample had cured. To determine the percentage of remaining unreacted double bonds (% C = C), i.e. the degree of conversion, the ratio of the absorbance intensity of the aliphatic C=C absorbance peak at 1648–1618 cm^{-1} to the aromatic reference peak at 1618–1590 cm^{-1} was compared before and after polymerization. The maximum height of the peaks was compared with the aliphatic and the reference peak. The specimens were stored in the freezer (-24°C) for further analysis.

To ensure continual change in material properties by increasing the length of the material, a surface microhardness measurement with a Vickers indenter was carried out on the material. The microhardness test is based on the ability of the surface of a material to resist penetration at a point under a specified load. In the Vickers hardness test, a diamond in the shape of a square-based pyramid is pressed under a specified load into the polished surface of a material. For a given load, the smaller the indentation, the larger the Vickers hardness number (VHN or HV), and the harder the material is (Anusavice 2003).

The microhardness of one 24 mm long specimen of both FRC material and resin, was measured using a microhardness measuring device (Duramin -1, Struers A/S, D-2610 Rødovre, Denmark) at HV 0.025/20 (0.254 N, duration 20 s) to determine the VHN. Because of the viscoelasticity of the materials, the time delay from applying the indenter to the determination of VHN was standardized to 10 s. Measurements were made for the FRC and resin specimens approximately 0.4 mm from the light-exposure surface, defined to be the 0-mm measuring point, and at points of 4, 8, 12, 14 and 16 mm from the 0-mm measuring point (10 measurements for each length) (Figure 17).

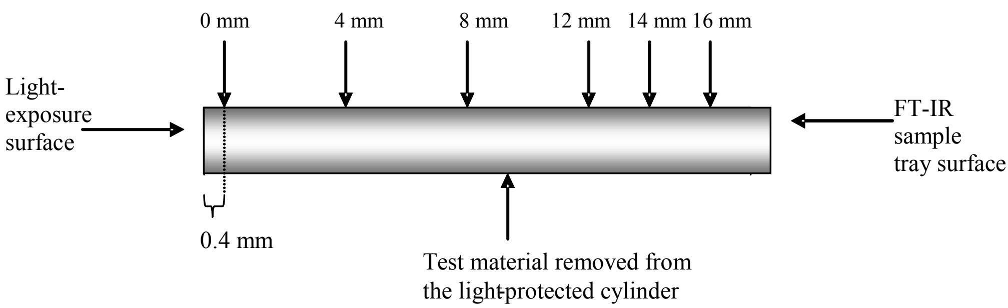


Figure 17. Microhardness measurement points (study I).

4.2.3 Bond strength measurements (III, IV)

4.2.3.1 Pull-out test (III)

The pull-out force of different posts cemented with composite resin luting cement to composite discs, was measured by pulling the post from one end using a universal testing machine (Lloyd LRX, Lloyd Instruments Ltd, Fareham, UK). A custom-made jig was used and the cross-head speed was 1.0 mm/min. The fixing of the jig to the head of the post was done using light-curing Triad Gel (Dentsply International Inc., York, USA). The area of fixation by Triad Gel was larger than the cemented area in the 2 mm thick metallic mold (Figure 18).

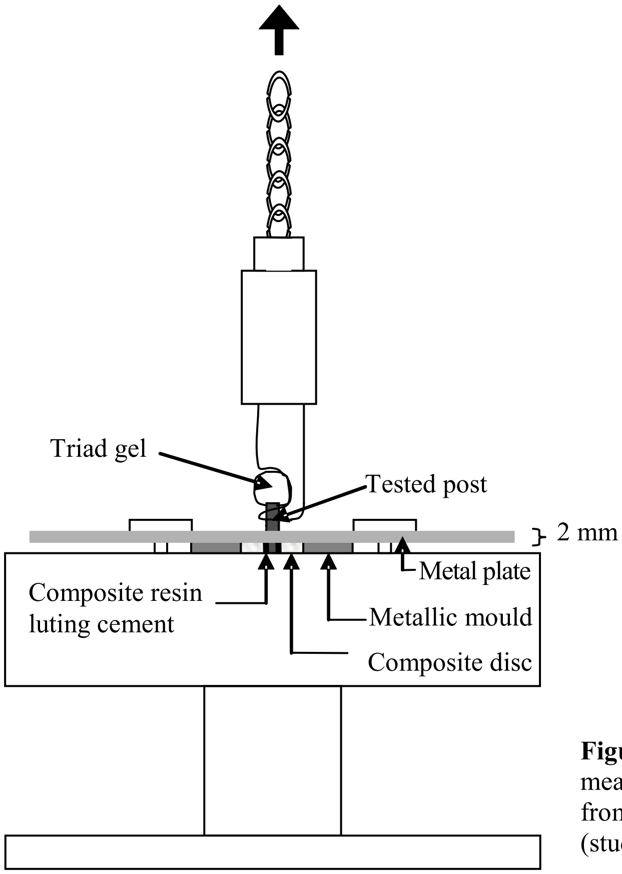


Figure 18. The custom-made jig for measuring the pull-out force of the posts from the composite resin luting cements (study III).

The force at the point of final interfacial failure between the post and the cement was observed from the loading curve. The force (Newton) required to debond the post from the cement (the final failure load) was registered for all posts. Because of the variation in post surface design (serrated versus smooth), the shear stress (Mega Pascal) between the post and canal was calculated only for the smooth surface posts. The formula for the shear bond strength calculations (σ) was:

$$\sigma = F / h \pi d$$

where F is the force (Newton) required to debond the post (the final failure load), h is the height (mm) of the disc, and d is the diameter (mm) of the post.

4.2.3.2 Push-out test (IV)

The push-out force of different posts cemented with a composite resin luting cement to dentin was measured by pushing the post in the dentin disc from one end using a universal testing machine (Lloyd LRX, Lloyd Instruments Ltd, Fareham, UK) with a custom-made jig and a cross-head speed of 1.0 mm/min (Figure 19). The force at the point of interfacial failure between the post, cement and dentin was observed from the loading curve. The force (Newton) required to debond the post from the dentin disc was registered for all posts.

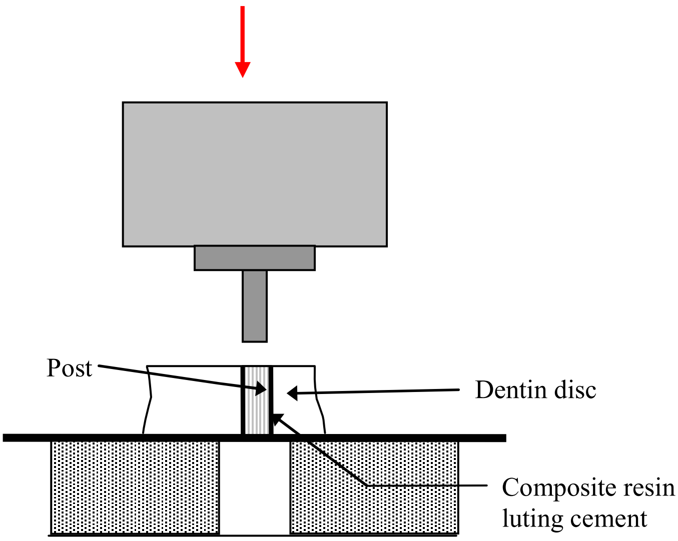


Figure 19. The custom-made jig for measuring the push-out force of the posts cemented with composite resin luting cement to dentin discs of different thicknesses (study IV).

4.2.4 Static load test and strain measurement of tooth-post-crown system (V)

Static load until failure under a loading angle of 45 degrees was applied on the incisors restored with different posts and composite crowns, using a universal testing machine (crosshead speed of 5 mm/min) (Figure 20). The initial fracture load was defined individually as an approximately 10% drop in the maximum load on the deflection curve.

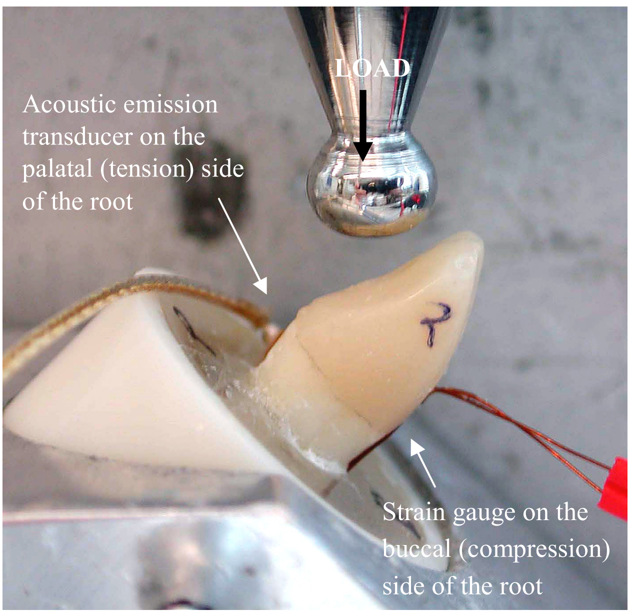


Figure 20. The test set-up for measuring the fracture load, microstrain and acoustic emission of incisors restored with different posts and a composite crown (study V).

Crown stiffness was measured on half of the test specimens by strain gauges which were fixed to the cervical root surface (just under the root-crown margin) on the buccal (compression) side of the tooth (Figure 20). According to a pilot study, where strain gauges were placed on both the tension and compression sides of the root, the strain behaviour was symmetrical on both surfaces. The compression side was chosen because the strain gauges more often remained intact on this surface and, furthermore, there was more room for the gauge to be placed correctly. The strain gauges were connected to a computer to measure and record the changes in strain data. Strain was analysed at the point of 50 N, before the initial failure occurred.

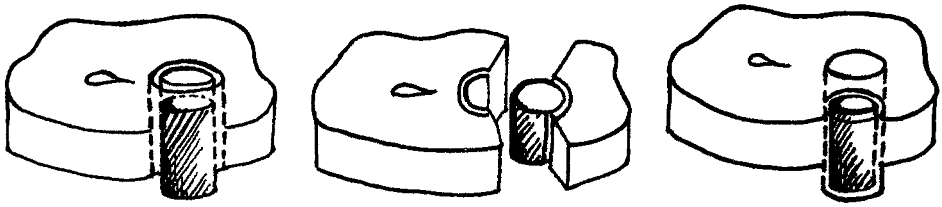
4.3 Analysis

4.3.1 Scanning electron microscopy (I, III, IV)

A scanning electron microscope (SEM) (JSM 5500, Jeol Ltd, Tokyo, Japan) was used for visual microscopic examination of the fracture surfaces in the different post systems after loading, in studies I, III and IV. After the flexural testing (study I), two posts from each group were gold-sputtered (SCD 050, BAL-TEC AG, Balzers, Liechtenstein), and transverse sections of the posts were examined with SEM to determine the differences in the posts tested. After the pull-out test (study III), all the cemented posts that had been pulled out from the composite discs were sputtered with gold and examined with SEM photomicrographs to analyse the surfaces and the attachment of the composite resin luting cement to the post surfaces. After the push-out test (study IV), 2-3 representative specimens from each post group were gold-sputtered and examined with SEM from several different angles to analyse the failures between or within the different interfaces of the post, the cement and the dentin, after testing.

4.3.2 Assessment of failure mode (IV,V)

After the push-out test (study IV), assessment of the failure mode was made by two independent operators under a stereomicroscope (Wild M3B, Heerbrugg, Swizerland), and the specimens were divided into groups according to the failure mode: 1 = adhesive failure between post and cement, 2 = cohesive failure of post-system, 3= adhesive failure between cement and dentin (Figure 21).



1 2 3

Figure 21. A schematic drawing of the three failure modes in the push-out test (study IV): **1=** adhesive failure between post and cement, **2=** cohesive failure of post system and **3=** adhesive failure between cement and dentin.

Assessment of failure mode was also carried out after the static loading test (study V), and the specimens were divided into groups according to the failure mode: 1) favourable failures which were defined as repairable failures, including fractures of the composite crown, fractures above and at the margin of the simulated bone level, and 2) unfavourable failures which were defined as nonrepairable failures, including vertical and horizontal root fractures below the simulated bone level (Fokkinga et al 2004).

4.3.3 Acoustic emission analysis (V)

Acoustic emission was measured on the incisors restored with posts in the static load test (study V) (Figure 20). The microphone was fixed with resin (Triad gel, Dentsply, York, PA, USA) on the palatal (tension) side of the root surface and connected to an acoustic emission analyser (Mistras, PAC, UK). The initial fracture load on the deflection curve in the static load test (study V) was confirmed by the acoustic emission signal.

4.3.4 Statistical methods (I-V)

Statistical analyses were performed with SPSS (SPSS Inc., Chicago, USA) software for Windows (studies I, III, IV and V) using analysis of variance (ANOVA). Subsequent comparisons between post groups were performed with either Tukey's Post Hoc analysis or Dunnett T3 Post Hoc Tests. In study II, statistical analyses were performed using SAS for Windows (Rel 8.2, SAS Institute Inc., Cary, NC, USA), using the repeated measures analysis of variance (RM ANOVA). In addition, in study II, comparisons between the groups and certain measurement points were performed with a t-test. The level of statistical significance was set at 0.05.

5. RESULTS

5.1 Flexural properties of FRC (I)

In study I, flexural strength (Figure 22), flexural modulus and maximum fracture load (Figure 23) of the tested specimens were evaluated. Thermocycling, brand of material and diameter of specimen had a significant effect on the fracture load and flexural strength (ANOVA, $P < 0.001$). The highest flexural strength was obtained with the control material everStick (Figure 22). In general, thermocycling decreased the flexural modulus of the tested specimens by approximately 10%. Strength and fracture load decreased by approximately 18% as a result of thermocycling. However, the brand SnowPost showed a greater decrease (approximately 40%) in mechanical properties after thermocycling than the other brands tested. The average reduction percentage in fracture load after thermocycling of the tested post specimens is presented in Figure 24. The fracture load values correlated to the diameters of the posts (Figure 25).

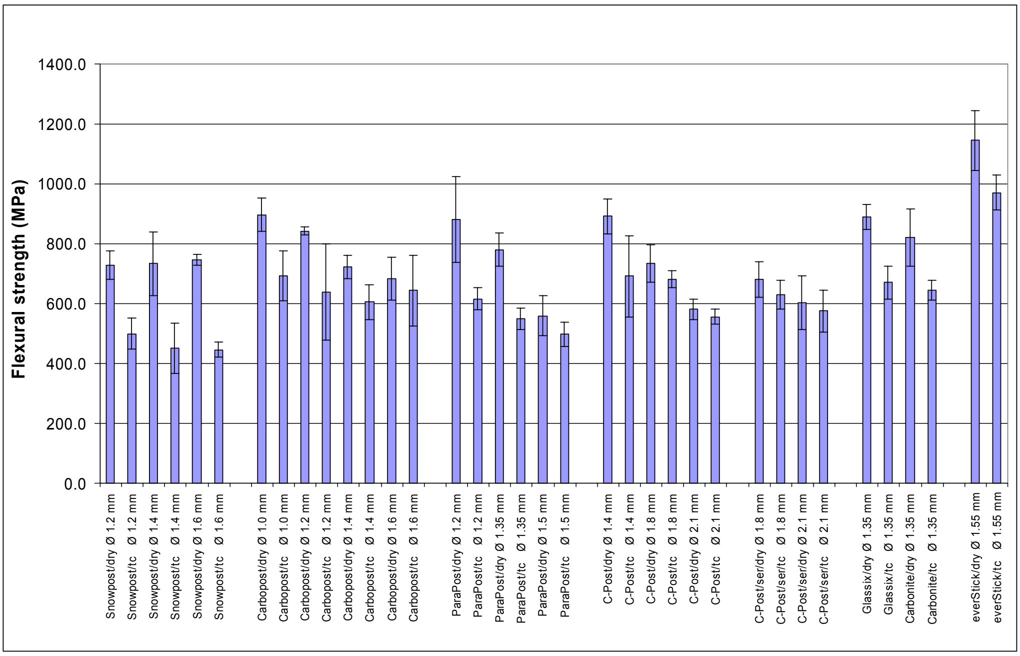


Figure 22. Flexural strength of the dry and thermocycled (tc) FRC post specimens (study I). The bars represent the mean value in MPa (SD) of five specimens.

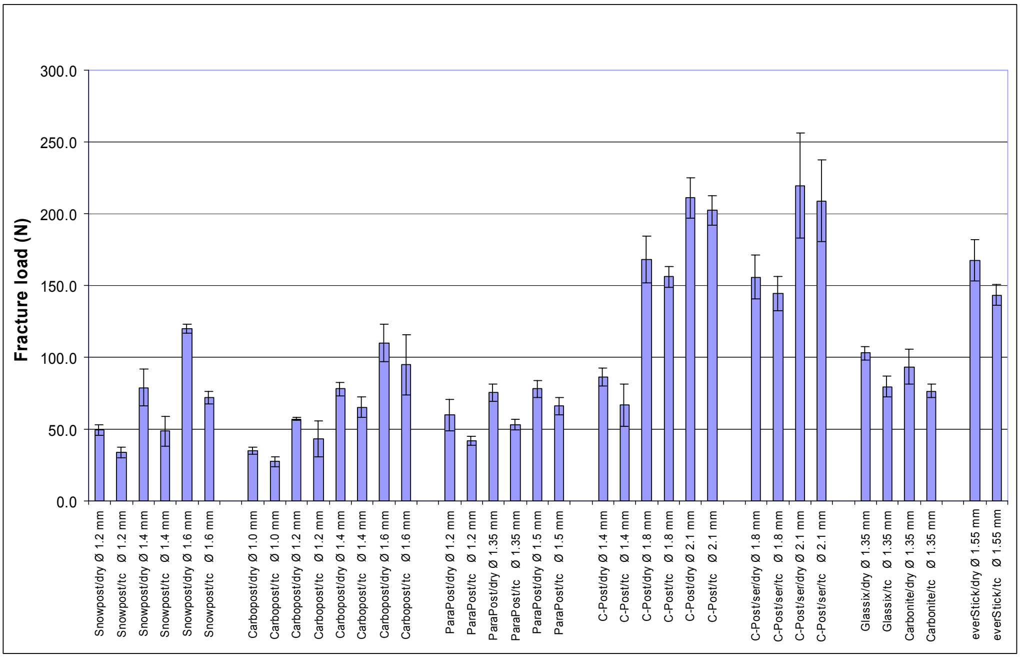


Figure 23. Maximum fracture load of the studied FRC post specimens (study I). The bars represent the mean value in N (SD) of five specimens.

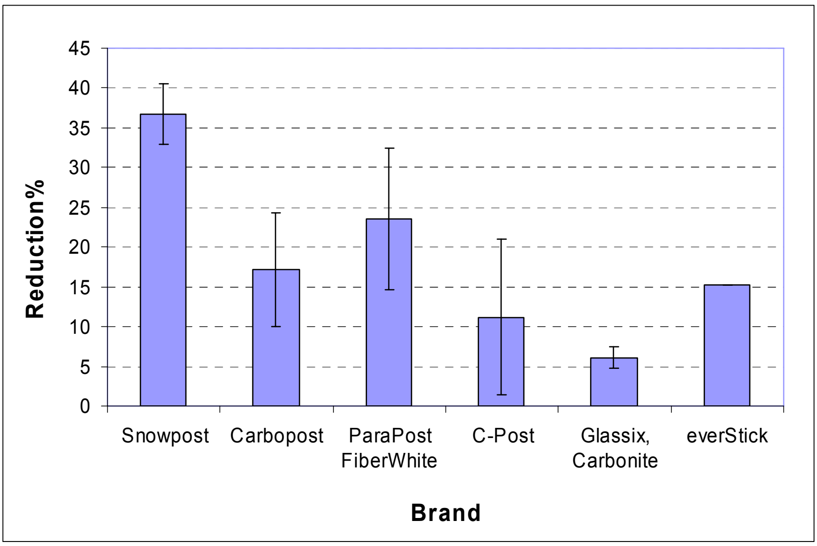


Figure 24. Reduction in fracture load of FRC post specimens after thermocycling (study I). The bars represent the mean reduction percentage (SD) of each post brand tested.

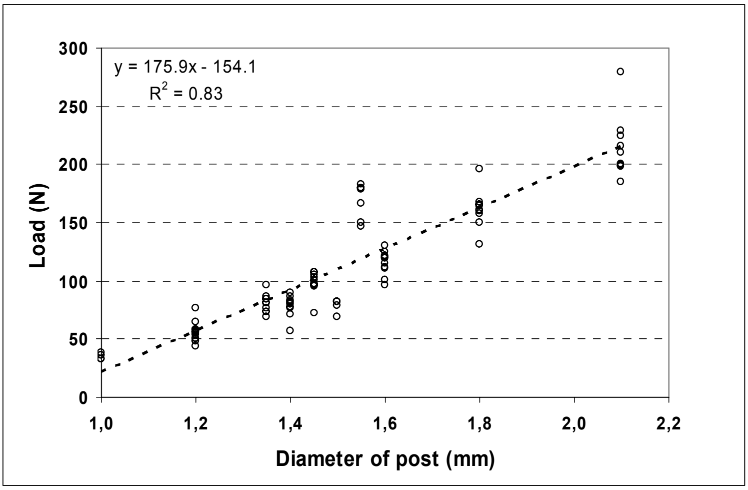


Figure 25. Linear regression curve of the effect of post diameter on fracture load of FRC post specimens (dry storage) (study I).

5.2 Degree of monomer conversion and Vicker's hardness of FRC (II)

The mean degree of conversion after polymerization increased with time in all six cylinder lengths in both the FRC and the control groups. Fifteen min from the beginning of polymerization, the degree of conversion in the shortest cylinder (4 mm) of the FRC group was 70%, and in the longest cylinder (24 mm) 33%. The values of the plain resin group were 72% in the shortest, and 15% in the longest cylinder.

When the cylinder length was increased, the degree of conversion decreased (Figure 26). The FRC group showed a slightly higher degree of conversion in the longest cylinders (24 mm) compared to that of the plain resin group (Figure 26) (t-test, $P = .018$). Both the cylinder length and material significantly influenced the degree of conversion (RM ANOVA, $P < .001$).

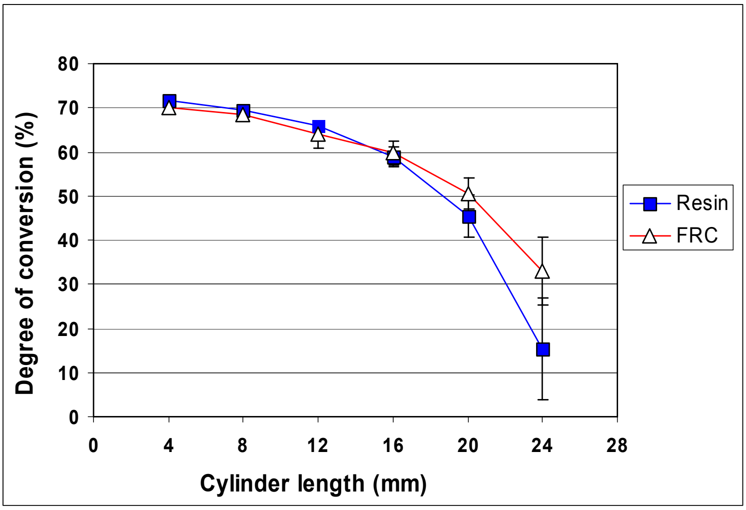


Figure 26. The mean degree of conversion (%) of six different lengths of cylinders with FRC material and control resin 15 min after the start of polymerization (study II). Vertical line represents one standard deviation.

The microhardness measurement demonstrated that the Vickers hardness number (VHN or HV) decreased when the distance from the light-exposure surface increased in both the FRC and the control specimens (Figure 27) (RM ANOVA, $P < .001$). Overall, the VHN was higher for the resin group compared to the FRC group (RM ANOVA, $P < .001$). In the FRC group, a minor but statistically significant (t-test, $P = .026$) increase in VHN values was noted from the 0-mm measuring point to the 4-mm measuring point (Figure 27).

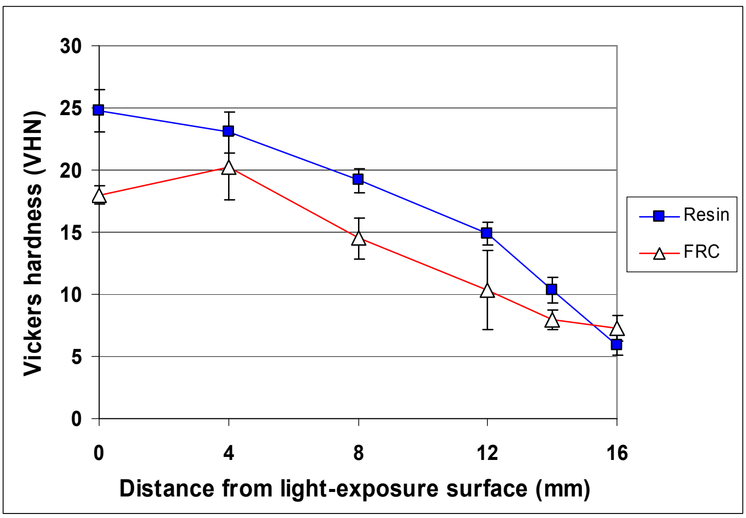


Figure 27. The mean surface microhardness (VHN) of FRC material and control resin at different distances from the light-exposure surface (study II). Vertical line represents one standard deviation.

5.3 Adhesion of FRC to composite resin cement and dentin (III, IV)

Pull-out test (III)

Both the type of post and thermocycling had a significant effect on the force needed to break the bond between the post and the cement (ANOVA, $P < 0.001$ and $P < 0.007$, respectively). One of the FRC posts with semi-IPN polymer matrix (Stick) performed superiorly to the other FRC posts (Figure 28 and 29), when comparing the thermocycled specimens. In dry conditions, the difference between Stick and everstick post did not differ significantly. The highest pull-out force was obtained with serrated titanium posts (Parapost XT), although the difference from the Stick post was not statistically significant. Post hoc analysis revealed that both types of FRC posts with semi-IPN polymer matrix (Stick and everStick) yielded significantly higher pull-out force values than the prefabricated FRC posts with smooth surface and cross-linked polymer matrix (Dunnett T3 Post Hoc, $P < 0.004$) (Figure 29).

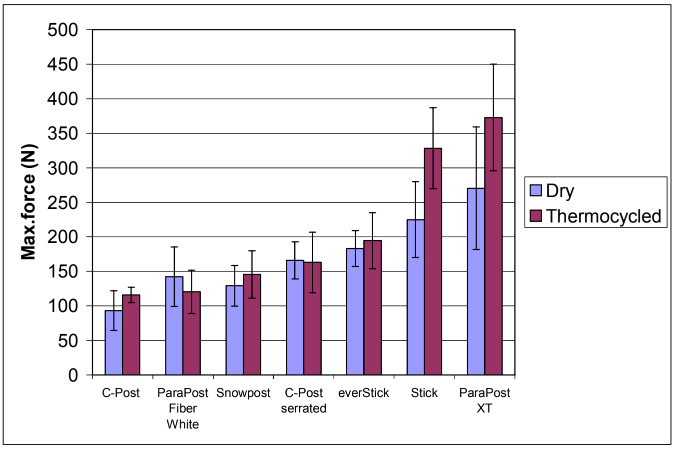


Figure 28. Mean pull-out forces in Newton (N) and standard deviations (vertical lines) (study III).

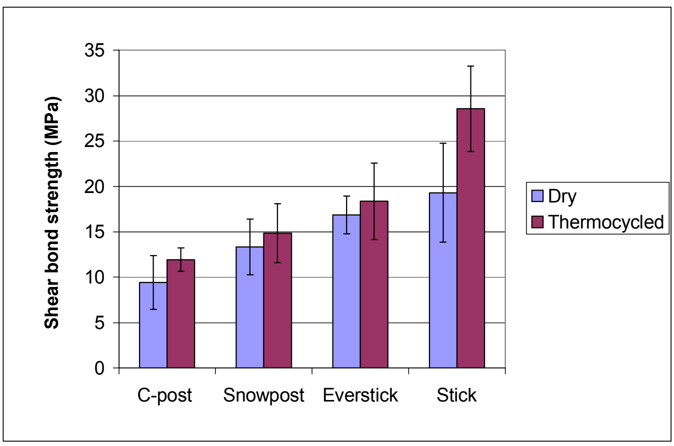


Figure 29. Mean shear bond strengths (MPa) and standard deviations (vertical lines) for the smooth surface posts (study III).

Push-out test (IV)

Both the type of post and the height of the dentin disc had a significant effect on the push-out force (ANOVA, P = 0.030 and P < 0.001, respectively). The push-out force increased with increased height of the dentin disc in all groups (Figure 30). The individually formed glass FRC posts showed highest push-out force (393.6 N) in the 4 mm thick dentin discs and the difference from that of the titanium posts was statistically significant (Tukey post hoc, P< 0.001). The differences between the other posts were not statistically significant.

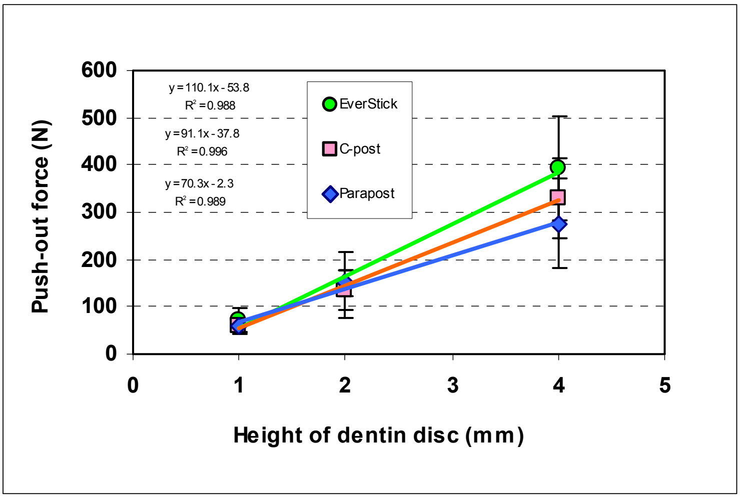


Figure 30. Mean push-out forces in Newton (N) with regression lines and standard deviations (vertical lines) for studied posts (study IV).

5.4 Load-bearing capacity and microstrain of FRC (V)

The highest mean initial fracture load was obtained in the reference group with intact teeth, although the difference was not statistically significant for everStick Post B and Parapost XP. The results of the initial fracture load and significant differences are shown in Figure 31. Microstrain values at 50 N load were highest for the intact group, which differed significantly from the other groups (Tukey Post hoc, P < 0.05). The accoustic emission data confirmed the fracture load peaks (Figure 32a-c).

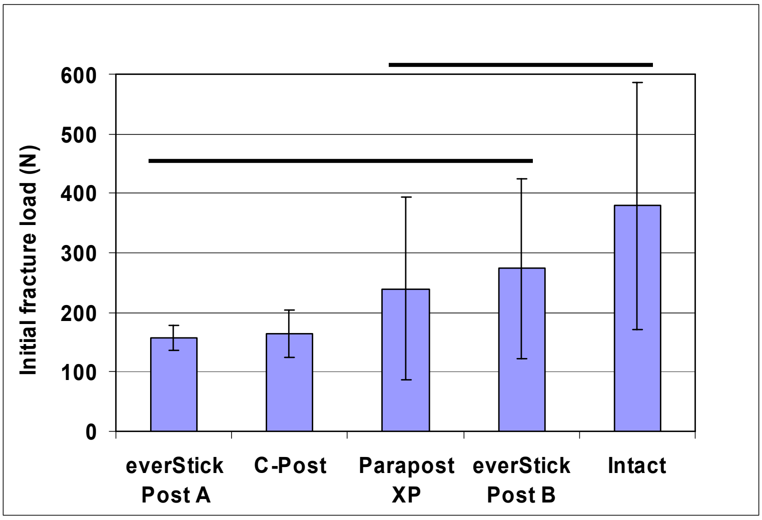


Figure 31. Mean initial fracture load (N) and standard deviations (vertical lines) of the tested groups (study V). The fracture load of everStick Post A and C-Post differed significantly from the Intact group ($P < 0.05$). Horizontal lines above the bars indicate which groups did not significantly differ from each other.

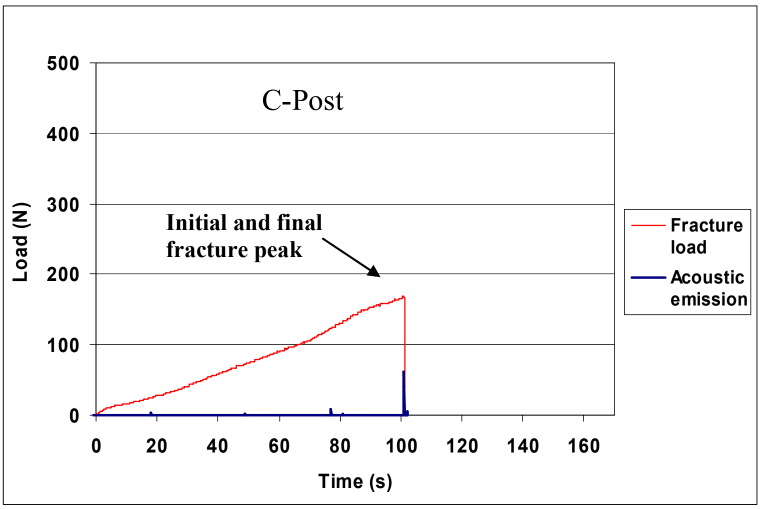


Figure 32. a) Typical shape of fracture load curve and acoustic emission peaks of the prefabricated carbon FRC post (C-Post) (study V).

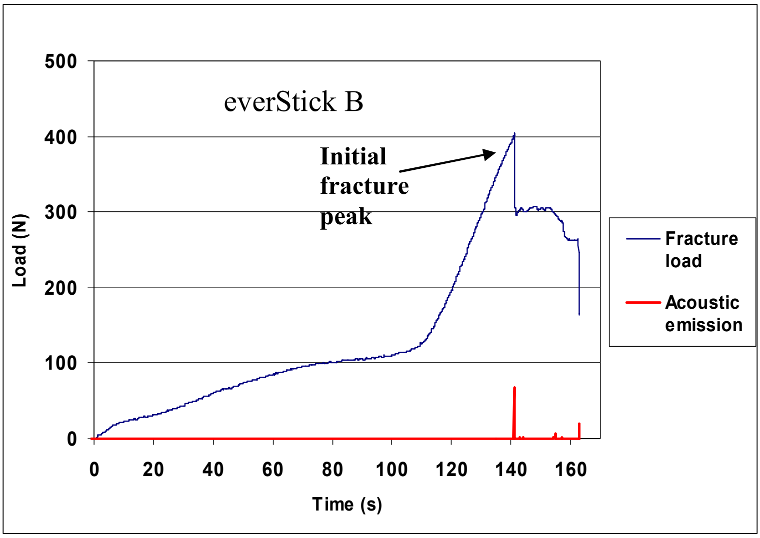


Figure 32. b) Typical shape of fracture load curve and acoustic emission peaks of the individually formed glass FRC post ("hollow" structure) (everStick B) (study V).

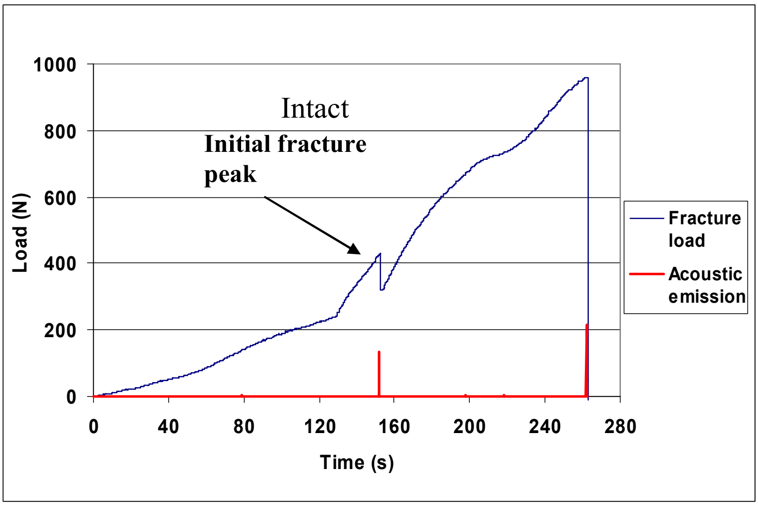


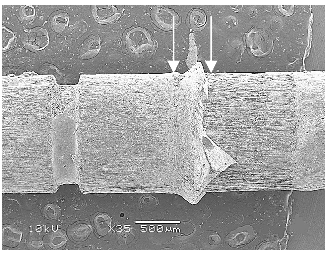
Figure 32. c) Typical shape of fracture load curve and acoustic emission peaks of the intact group (study V).

5.5 SEM analysis of posts and post restorations (I, III, IV)

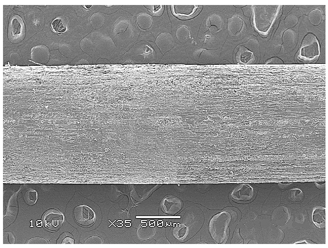
In study I, visual analysis of SEM micrographs revealed that a certain amount of porosity exists in the majority of the FRC posts. Porosity in the Snowpost was easily recognized, whereas everStick had a tight solid matrix without porosity.

In study III SEM photomicrographs showed that the composite resin luting cement attached well to the surface serrations and threads of the titanium post (Figure 33g).

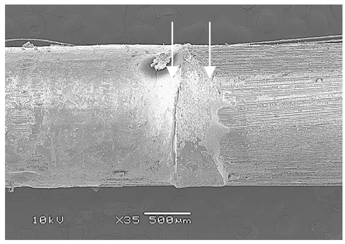
The tested serrated FRC posts showed that the fibres were cut to form the serration. The fracture line on these posts was situated on the edge of a surface serration (Figures 33a and 33d). In the smooth prefabricated FRC posts, the composite resin luting cement did not attach to the post surface (Figures 33b and 33e). In the individually made FRC posts with semi-IPN-matrix (everStick and Stick), the cement was attached to the post surface (Figure 33c and 33f), especially obviously in Stick posts (Figure 33f). Typical examples of failures and post surfaces after testing are shown in the SEM images.



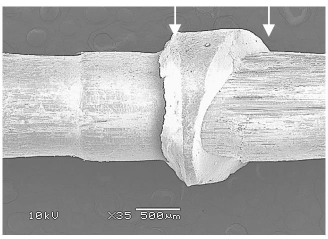
a



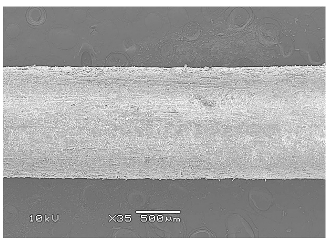
b



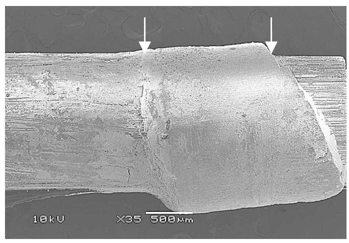
c



d

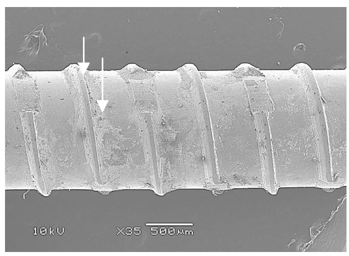


e



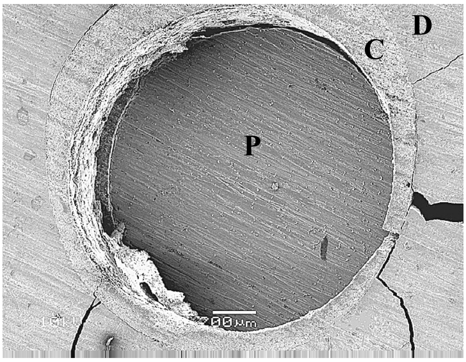
f

Figure 33. SEM photomicrographs of the fracture surfaces of the posts after the loading test (original magnification x 35, bar = 500µm) (study III): **a)** C-post serrated, **b)** C-Post, **c)** everStick, **d)** ParaPost FibreWhite, **e)** Snowpost, **f)** Stick and **g)** ParaPost XT. The arrows indicate the attached cement on the post surface after the loading test.

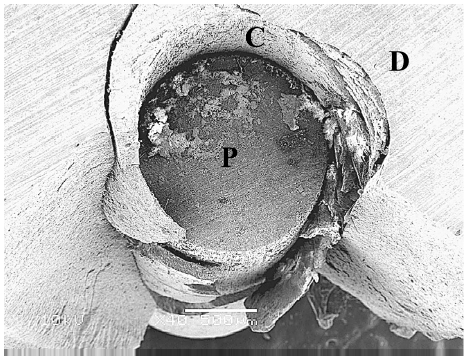


g

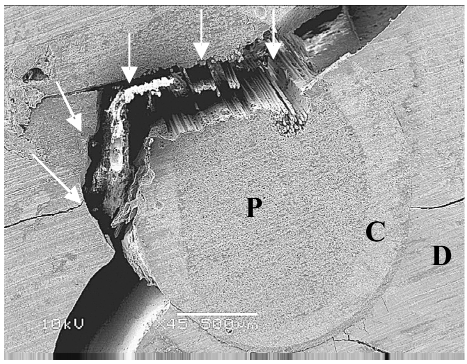
In study IV, SEM analysis demonstrated typical failure modes between the resin cement and tested posts (Figure 34). Typically, the individually formed glass FRC posts failed cohesively (Figure 34c), whereas the prefabricated carbon/graphite FRC and titanium posts showed either complete or partial adhesive failure between the post and the cement (Figure 34a and 34b). The SEM analysis confirmed the results from the assessment of failure mode.



a



b



c

Figure 34. SEM photomicrographs of typical failure modes of the cemented posts after the push-out test (study IV) **a)** adhesive failure between titanium post (Parapost XP) and cement (failure mode=1), **b)** partly adhesive failure between carbon FRC post (C-Post) and cement, partly cohesive failure (failure modes= 1, 2) and **c)** cohesive failure (failure mode 2) within the individually formed glass FRC post (everStick) The exposure of fibres aligned along the long axis of the post (arrows) demonstrates the cohesive failure in the post. In the pictures, P= post, C= cement and D= dentin. Original magnification x55 (a), x40 (b) and x45 (c), bar= 200 (a), 500 (b) and 500 μm (c).

5.6 Failure mode assessment (IV, V)

The failure mode assessment with a stereomicroscope in study IV demonstrated that none of the individually formed glass FRC posts showed adhesive failures between the post and the cement, whereas 55% of the prefabricated carbon/graphite FRC posts and 70% of the titanium posts showed either complete or partial adhesive failure between the post and the cement (Table 6). The individually formed FRC posts failed mostly cohesively (56%) and adhesively between the cement-dentin interface (30%) or in a mixture of these two modes (14%). In the 4 mm thick dentin discs neither the titanium nor the prefabricated carbon/graphite FRC posts showed any cohesive failures, unlike the individually formed glass FRC post.

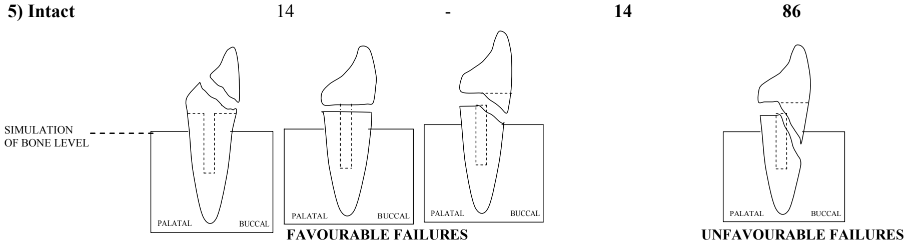
The assessment of failure mode in study V revealed that the incisors restored with FRC posts showed higher percentage of favourable failures compared to the group restored with titanium posts. The group with individually formed glass FRC posts with a "hollow" structure (everStick Post B) showed the highest percentage of favourable failures (56%). The results of the failure mode assessment and typical fracture modes are shown in Table 7.

Table 6. The results of failure mode assessment (study IV).

	Adhesive failure between post – cement interface (%) (failure mode = 1)	Other failure mode (%) (failure mode = 2, 3 or mixed)
Titanium post (ParaPost XP)	70	30
Carbon FRC post (C-Post)	55	45
Individually formed glass FRC post (everStick)	-	100

Table 7. The results of failure mode assessment (study V).

	Favourable failures (%)			**Unfavourable failures (%)**
Group	Fractures of composite crown / fractures above simulated bone level	Fractures stopped at simulated bone level	Total percentage of favourable failures	Fractures below simulated bone level, vertical and horizontal root fractures
1) ParaPost XP (titanium post)	-	11	**11**	**89**
2) C-Post (graphite FRC post)	22	22	**44**	**56**
3) everStick Post A (individ. glass FRC post, canal full of fibres)	30	20	**50**	**50**
4) everStick Post B (individ. glass FRC post, "hollow" post structure)	22	34	**56**	**44**
5) Intact	14	-	**14**	**86**



6. DISCUSSION

6.1 General discussion

This series of *in vitro* studies aimed to evaluate whether the use of an individually formed and *in situ* polymerized glass FRC material with a semi-IPN polymer matrix would offer benefits as root canal post material. Although cast metal posts are used as the gold standard, there is still no consensus on what would be the optimal way of restoring an endodontically treated tooth. Many studies have suggested that prefabricated FRC posts, especially glass FRC posts, may possess benefits over prefabricated metal posts due to their modulus of elasticity being closer to that of dentin (Asmussen et al 2005, Salameh et al 2006, Schmitter et al 2007). However, there are also disadvantages of prefabricated FRC posts, particularly their lack of good adhesion to composite resins and dentin.

The flexural properties of a post material play an important role in the stress distribution and survival of a post-restored tooth. Therefore, when preliminarily evaluating the possible use of a novel FRC material as post material, the flexural properties were evaluated and compared to prefabricated FRC posts in study I. Additionally, it is vital that a FRC post material that is polymerized *in situ* in a root canal will reach a sufficient degree of conversion. Consequently, in study II, the depth of light-initiated polymerization and the microhardness at different depths in a simulated root canal of the experimental FRC material were evaluated and compared to those of resin without fibres. Furthermore, when evaluating the clinical usability and longevity of dental materials, such as a FRC post system, the bonding properties are important. Good adhesion will help to preserve tooth structure, optimize retention and prevent microleakage (Anusavice 2003). There are reports of poor bonding properties of prefabricated FRC posts, mainly due to the highly cross-linked polymer matrix, which seems to be difficult to bond to composite resins (Purton and Payne 1996, Kallio et al 2001, Torbjörner and Fransson 2004a). Thus, it was hypothesized and evaluated in studies III and IV that an individually formed FRC post with a semi-IPN polymer matrix could offer some advantages over prefabricated FRC posts with a cross-linked polymer matrix, concerning the bonding to composite resin luting cements and dentin. Furthermore, fracture behaviour of post-core systems has been evaluated in the literature, and is of importance when evaluating and comparing different post systems (Salameh et al 2006). Fracture behaviour has been explained as the relationship between the load-bearing capacity (fracture resistance) and the failure mode of a post-core system (Fokkinga 2007). Therefore, the load-bearing capacity and microstrain of post-restored teeth were evaluated in study V. Besides the evaluation of load-bearing capacity of a post-restored tooth, it is of interest to evaluate the mode of failure. It has been emphasized that a favourable failure mode of a post system could be more valuable than a high fracture resistance (Torbjörner and Fransson 2004a, Fokkinga 2007). Assessment of the failure mode of post systems was done in order to obtain more information about failures of teeth restored with different posts systems in studies IV and V.

Quality aspects and declaration

The biomaterials laboratory where the current studies were carried out belongs to a quality assurance system and the mechanical testing machine used (study I, III, IV and V) is quality- controlled and calibrated by the Finnish Accreditation Service (Finas, certificate no: YTT-S-01519-07). The cross-head speeds used for the mechanical testing machine (1.0 mm/min in studies I, III and IV, and 5.0 mm/min in study V) were within the range of 0.5 mm/min (Bolhuis et al 2001) to 5.0 cm/min (King and Setchell 1990) reported in the literature.

The specimen preparations and the testing in studies II-V were carried out by the same operator, with the assistance of two other operators, in order to standardize the methods and minimize possible researcher-related variability. In the failure mode assessment in study IV, two independent and calibrated operators were used in order to categorize the failure modes objectively. Also in study V, only one main operator performed specimen preparation and testing, and therefore, the large standard deviations in this study are possibly due to other factors such as the variations in natural teeth. In study IV, an effort was made to use the most homogenous area and also a clinically comparable area of the root for the dentin discs, since it has been reported that different areas in the same root canal may respond differently to surface treatment and have different dentin bonding ability (Ferrari et al 2000c).

The numbers of specimen (n) in each experiment were selected according to repeatability and in order to be able to use certain reliable statistical methods. As regards the choice of reference material, in study I, the novel FRC material (everStick), the flexural properties of which had already been evaluated and were well known from previous studies, was chosen to serve as reference for the prefabricated FRC posts. In study II, it was the obvious choice to use dimethacrylate resin without fibres as reference for the resin–impregnated FRC material. Commonly used titanium posts with surface serrations (Hew et al 2001) providing mechanical interlocking to composite resin luting cement, served as reference in studies III and IV. In study V, intact incisors were used as reference, although root-filled teeth also could have been an alternative. However, with root-fillled teeth, larger deviations in the results could have been expected.

6.2 Flexural properties

The three-point bending test is a simple method which provides a basis for comparison of flexural properties between posts made of different materials (Seefeld et al 2007). Therefore, a three-point bending test according to the International Standards Organization 1999 (ISO 10477) was used to measure the flexural strength and modulus of FRC post specimens. Several studies concerning the mechanical properties of FRC posts have been published (Torbjörner et al 1996, Purton and Payne 1996, Asmussen et al 1999, Seefeld et al 2007). Lack of standardization of the testing conditions and methods has resulted in large variations in the reported mechanical properties.

In the current study, considerable variation was found in the calculated strength values of the studied posts. The individually formed continuous unidirectional E-glass FRC material (everStick), which was used as reference, presented the highest flexural strength values. This unexpected finding may be due to the difference in the polymer matrix of everStick compared to the matrices of other tested FRC posts. The existence of PMMA chains, which are able to plasticize the cross-linked bisGMA based matrix of the everStick FRC, reduces stress formation at the fibre-matrix-interface during deflection. This may be assumed to contribute to the higher strength of everStick FRC material (Vallittu 2001b).

Thick posts showed lower flexural strength values (MPa) than thin posts, although the fracture load values (N) behaved oppositely. It was shown that when using a three-point bending test to measure flexural properties of FRC posts, the results are related to the ratio of span length and specimen diameter (L/D ratio) of the test set-up. A low L/D-ratio produces more shear deformation during the bending in the FRC specimen, and the failure may occur at the fibre-matrix interfaces instead of on the outer surface of the specimen (Goldberg et al 1994, Alander et al 2005). This may be the case when testing short FRC specimens such as FRC posts. Therefore, it is not recommendable to compare the calculated flexural strength values (MPa) between FRC posts with different diameters. Instead, comparison of load values (N) should be made. The mechanical properties of posts depend largely on the diameter of the post (Lambjerg-Hansen and Asmussen 1997). In the present study, all FRC post specimens showed a linearly increasing resistance against loading force, along with an increase in diameter. Clinically, this means that thick posts contribute more favourably to the fracture resistance of the post-core system than thin posts, presuming that unnecessary preparation of the remaining dentin is at the same time avoided.

Thermocycling decreased the flexural properties of the studied posts, which is in accordance with previous studies (Torbjörner et al 1996). Snowpost specimens showed an approximately 40% reduction in flexural strength after thermocycling, whereas the flexural strength of the other studied posts decreased by approximately 18% as a result of thermocycling. When posts are exposed to thermocycling the differences between coefficients of thermal expansion (CTE) of the individual materials may influence the long-term stability of the FRC-post system. The thermo-mechanical behaviour of dental FRCs is not completely understood at the moment, but large variations in CTEs exist between reinforcing fibres and the matrix polymer used in FRC posts, which may influence the thermomechanical behaviour. The large reduction in flexural properties of SnowPost specimens after thermocycling could be related to the discrepancy in the CTEs between the SnowPost materials. The difference in CTE between silica-zirconium fibres and the polymer matrix of Snowpost is greater than that between E-glass, S-glass, carbon/graphite fibres and their matrix polymer. Moreover, internal voids, which were seen in the SEM photomicrographs of Snowpost, absorb water during thermocycling, and this may be one explanation for the reduction in mechanical properties after thermocycling. The present study may also be regarded as a short-term water exposure study. The results are in agreement with other studies showing that a decrease in mechanical properties takes place during 30 days of water storage, and is caused by plasticization of the polymer matrix by water (Vallittu 2000). On the other hand, thermocycling may cause thermal post-curing of initially light-polymerized FRC, and thus lead to increased flexural properties. In the present study, all the FRC posts studied were properly polymerized and, therefore, post-curing during thermocycling has probably not affected the results.

6.3 Degree of monomer conversion and microhardness

If a FRC post material is polymerized *in situ* in a root canal it is fundamental that it reaches a sufficient degree of conversion, thus ensuring adequate strength of the FRC post especially at the region of coronal opening of the root canal where high strength is needed. Furthermore, the polymer matrix will be fully polymerized and, therefore, few side effects from leachable monomers will occur.

The depth of polymerization of FRC in relation to the degree of conversion and microhardness after light-initiated polymerization in a dark cylinder were measured. The results of a 50 to 70% degree of conversion in up to 20 mm cylinder lengths lie within the range of typical degree of conversion for dental resins containing BisGMA monomers (Anusavice 2003). The correlation between the degree of conversion and the microhardness shown in the results is in accordance with earlier results (Yoshida and Greener 1993). The degree of conversion was considered acceptable for both groups at a depth of up to 20 mm, 15 min after initiation of polymerization. The slightly higher values of the degree of conversion in the FRC group, particularly in the longer cylinders, were probably due to the fibres' ability to conduct and scatter the light in the dark cylinder. From a clinical point of view, this approach would give new alternatives to improve the polymerization of resins, such as composite resin luting cements, in a root canal. The time period required to reach an adequate degree of conversion at room temperature was approximately 10 min for both the FRC and the resin group, which is in good accordance with previous investigations of resin composites (Peutzfeldt 1997). The velocity of polymerization in the FRC group seemed to be equal to that of the dimethacrylate monomer resin group.

It is evident that the cross-link density of the polymer matrix of the FRC group was lower than in the BisGMA-TEGDMA resin group, due to the presence of PMMA. On the other hand, the lower cross-link density does not necessarily influence the degree of conversion of the polymer matrix. The saturation of the C=C bonds by free radical polymerization could cause formation of cross-linked microgels, even though the cross-link density is generally, when bulk polymer is considered, at a lower level. The result that microhardness (VHN) values for the PMMA containing polymer (FRC group) were lower than for the Bis-GMA-TEGDMA copolymer (resin group) could be explained by the plastization effect and the lower cross-link density of the bulk polymer.

Interestingly, it was observed that the microhardness values in the FRC group close to the light-exposure surface (at the 0-mm measuring point) were lower than at the 4-mm measuring point (Figure 27). An "oxygen reservoir", in the spaces between the fibres may have been formed during cutting of the fibre reinforcements. This could have caused oxygen inhibition of the free radical polymerization, resulting in incomplete polymerization at the light-exposure surface. Thus, the VHN remained at a lower level. Furthermore, the gradual reduction in the degree of conversion and the microhardness seen in the results are not necessarily negative properties in a clinical situation. It may be beneficial to have a post material which has higher compliance apically, and therefore would cause less stress in the root. The highest rigidity for a FRC post is obviously needed at the region of coronal opening of the root canal. In the case of an individually formed FRC post, the coronal opening of the canal could be filled with an excess of FRC material, which would increase the strength and rigidity of the FRC construction through its increased dimensions. In order to further evaluate the directly polymerized individually formed FRC post more, emphasis needs to be put on polymerization shrinkage of unidirectional anisotropic FRC.

6.4 Bonding properties

Pull-out test

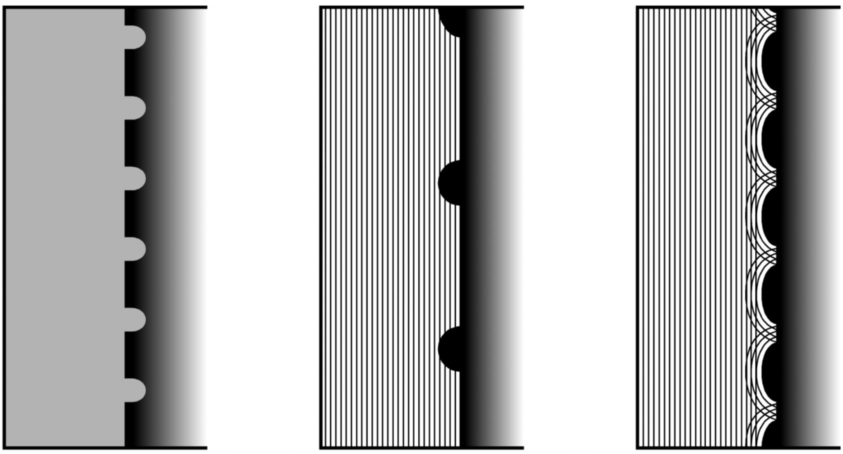
The pull-out test has been used to analyse the mechanical stability of the post-cement interface and to assess correct information about the bond strength between the different interfaces (De Santis et al 2000). The results of the pull-out test (study III) demonstrated the advantage of bonding composite resin luting cement to FRC posts with a semi-IPN polymer matrix (individually formed post) compared to FRC posts with a cross-linked polymer matrix (prefabricated posts).

Some methodological aspects must be taken into consideration when interpreting the results. The results were given in load values (N) for all posts, and calculations of shear bond stress (MPa) between the post and canal were done only for the smooth surface posts. This was due to the surface texture of the serrated posts which did not justify the calculation. On the other hand, the calculation would have considered the minor discrepancy in the diameters of the posts. However, in preliminary evaluation of the testing system, the calculation was done, but the influence of the discrepancy in diameter of the smooth posts was minor and would not have led to a different interpretation of the results.

One of the individually formed FRC posts with a semi-IPN polymer matrix (Stick) performed better than the other posts. When comparing FRC posts with the smooth surface, posts with a semi-IPN polymer matrix showed more reliable bonding than those with a cross-linked matrix. The difference in the results between the two types of FRC posts with a semi-IPN matrix (Stick and everStick) could be due to the larger amount of linear polymer phases in the matrix of the individually made Stick post, resulting in a semi-IPN structure with improved adhesional behaviour. The results from this study may also indicate that the adhesion between post and composite core material could be enhanced by using individually made FRC posts with a semi-IPN polymer matrix. In the pull-out test, an intermediate resin was not used on the FRC posts before cementation since the effect of treating the posts with an intermediate resin was not fully proved at that time. However, there is some evidence that intermediate resins are able to significantly enhance interdiffusion bonding of resin composites to FRCs with a semi-IPN type of polymer matrix (Kallio et al 2001). Therefore, it is assumed that bonding of composite resin luting cement to FRC posts with a semi-IPN polymer matrix can be even further improved by using an intermediate resin with similar solubility parameter to that of PMMA in the semi-IPN polymer matrix.

The serrated metal posts showed the highest attaching values, which can be explained by the mechanical retention of the composite resin luting cement provided by the surface serrations. The large volume of resin material in the serrations of the posts most probably influenced the attaching values (Figure 35). The surface topography of the prefabricated serrated metal and FRC posts differed from each other in terms of amount of resin material volume between the serrations (Figure 35a-b). In the FRC posts, the volume between the surface serrations into which the cement was attached was smaller in volume than that of the metal posts (compare Figure 35a and b). Due to its higher volume of cement penetration into the serrations the cement resisted more shear stress during the pull-out test in the case of metal posts.

One could suppose that a surface topography of the prefabricated FRC posts similar to that of the metal posts could have provided better attachment. However, in this context, it should be noted that the current FRC posts are anisotropic in nature and therefore weak against the shear stress caused by pull or push out forces. One alternative for optimizing prefabricated serrated FRC posts in terms of mechanical attachment would be to direct the fibres of the serrations not to be parallell to the long axis of the post (Figure 35c).



a **b** **c**

Figure 35. Schematic drawing of the threads and serrations on the studied posts (study III) and the amount of resin material in between the serrations: **a)** prefabricated threaded and serrated metal post and **b)** prefabricated serrated FRC post. A hypothetical optimized FRC post design, with the serrations closer together and the fibres in the serrations directed not parallell to the long axis of the post, is presented in **c**.

The serration of a FRC post seem to provide relatively little benefit for the attachment to cements. It is also of importance to notice that the effective diameter of the serrated FRC post with regard to the flexural properties is the thinnest dimension of the post.

Thermocycling increased the bonding values in the pull-out test. It should be noted that the transversal expansion by heat, in the case of continuous unidirectional FRC posts, is considerably higher than that in a longitudinal direction. This is due to the fact that FRCs have anisotropic thermo-mechanical properties (Tezvergil et al 2003). Metals, on the other hand, have thermal expansion which exceeds expansion of composites.

Push-out test

The push-out test has been claimed to be the most reliable technique to measure the bond strength of posts to dentin, and to simulate the clinical situation of a cemented post relatively well (Goracci et al 2004, Goracci et al 2005, Bouillaguet et al 2006). Furthermore, the push-out method has been reported to be more sensitive to the thickness of the tested disc, compared to the pull-out method (Hsueh 1993). The push-out test was used to investigate the bonding of two different FRC posts to root canal dentin discs and to compare them to that of serrated titanium posts (study IV). Various thicknesses of root canal dentin discs were tested to evaluate whether some of the posts could be attached to thinner discs, which would, clinically, mean that shorter posts could be used. Obviously, this is relevant only in terms of vertical debonding forces because a short post, even when well bonded and attached, may provoke root fractures. On the other hand, the fact that FRC posts possess flexural properties close to those of dentin may also allow their use in shorter post lengths without provoking root fractures.

When bonding composite resin luting cement to a prefabricated FRC post of a cross-linked nature, the surface of the post is well polymerized and little if any reactivity is left for free radical polymerization bonding (Kallio et al 2001). Therefore, no actual chemical bonding is taking place. When the FRC post with the semi-IPN polymer matrix is bonded with composite resin luting cement, the interdiffusion bonding can take place (Sperling 1994, Lastumäki 2003, Vallittu 2006). The FRC material with the semi-IPN polymer matrix used in the push-out test (everStick) consisted of both linear and cross-linked polymer phases. The linear phase in this material, which is polymethylmethacrylate (PMMA), can be dissolved if a suitable adhesive resin (intermediate resin) is added to the surface of the post (Kallio et al 2001). The suitable adhesive resin should contain monomers with dissolving parameters equal or close to that of PMMA. BisGMA-based adhesive resins have been shown to be capable of dissolving PMMA. When bonding composite resin luting cement to a metal post, the surface serrations are mechanically interlocked to the composite resin luting cement on the surface of the post. Contrary to the pull-out test (study III), all the posts in the push-out test (study IV) were treated with an intermediate dimethacrylate resin before the cementation. This presumably enhanced the bonding of the individually formed glass FRC posts with a semi-IPN polymer matrix, but may have negatively influenced the ability of the surface serrations of the titanium post to mechanically interlock the cement to the post surface. In the pull-out test, where the posts were cemented without an intermediate resin layer, the titanium post showed the highest bonding values, compared to the other posts, which was not the case in the push-out test.

The push-out force values for the prefabricated carbon/graphite FRC post (C-Post) and for the prefabricated titanium post (ParaPost XP) increased linearly when the height of the dentin discs increased, while the increase in the bonding force values of the individually formed glass FRC post (everStick) was non-linear. This finding suggests that with mechanical and friction attached posts (prefabricated carbon/graphite and titanium posts), the push-out force was in direct relation to the surface area. On the contrary, posts with better adhesion, i.e. interdiffusion bonding (individually formed glass FRC posts), may form a root-post system in which debonding stress is more evenly distributed, and less shear stress is formed at the interphase of dentin and post. This may have led to higher push-out forces with thick dentin discs in this type of post.

The bond strength and integration between luting materials, root dentin and FRC posts have been studied through push-out tests and SEM photomicrographs before. In these studies, the importance of the homogenity and integration between the materials (dentin, post, luting cement and core composite) has been emphasized (Pest et al 2002, Monticelli et al 2004). The assessment of failure mode and the SEM photomicrographs (study IV) showed that although the push-out forces at the point of failure were equal, the failure mode and site of the samples were different between the post groups. Contrary to the other posts, there were no adhesive (post-cement) failures with the individually formed glass FRC posts, and the post-cement-dentin system seemed to function as a homogenic unit in terms of the failure mode and the site of these posts. This is important because it indicates the quality of bonding between post and cement/dentin and, therefore, it can apparently influence the clinical longevity of a post system. The load-bearing capacity is not only related to the strength of the adhesive interfaces, but also to the design of the post system in simulating the structure of the tooth.

6.5 Load-bearing capacity

Fracture behaviour of post-core systems has been evaluated in the literature and is of importance when evaluating and comparing different post systems (Salameh et al 2006, Jung et al 2007). Fracture behaviour can be explained as the relationship between the load-bearing capacity (fracture resistance) and the failure mode of a post-core system (Fokkinga 2007). Therefore, fracture resistance, microstrain and acoustic emission were measured in order to evaluate the load-bearing capacity of incisors restored with different posts covered with a composite crown (study V). Assessment of failure mode was also made to determine the failure behaviour of the fractured specimens.

According to the results, the intact teeth (reference) without posts showed the highest initial fracture load. Obviously, the intact teeth also showed the highest microstrain at 50 N, which demonstrates the behaviour of a tooth without a post. An intact tooth is, at the same time, not only strong but also flexible to some extent. Apparently, the initial fracture load of the prefabricated serrated titanium posts did not differ significantly from the fracture load of the prefabricated or individually formed FRC posts. Interestingly, the results of the failure mode assessement showed some significant differences between the groups. In all the groups, most typically, fracture of the specimen occurred initially at the crown-root margin on the palatal side (loading side), after which the fracture continued towards the buccal root surface, sometimes above or towards the margin of the simulated bone level (favourable), sometimes below this level (unfavourable). The three groups with FRC posts showed more favourable failures than the group with titanium posts. Furthermore, the individually formed glass FRC posts, both the group with the canal full of fibres and the group with a “hollow” post structure, showed a higher percentage of favourable failures, 50% and 56%, respectively, compared to the serrated titanium posts. This may indicate fewer fatal failures and more repairable fractures for teeth restored with these kinds of posts.

When analyzing and comparing the fracture loading curves of the groups, it was noted that the initial failure usually occurred simultaneously with the final failure in the groups of titanium posts (Parapost XP) and carbon/graphite FRC posts (C-Post). This may indicate poor bonding of the posts to the cement, and show a lack of stress-relief capacity in these post systems. The shape of the loading curve of individually formed glass FRC posts with the “hollow” post structure (everStick Post B) was similar to that of the intact teeth (compare Figures 32b and 32c). After the initial rise, the curve started to rise more steeply until the initial failure occurred. In this group, an effort was made to simulate a so-called sandwich structure (Murphy 1998), or a hollow cylindrical structure, which is commonly used in technical industrial applications. In this structure, the reinforcement is placed as far away from the neutral axis as possible (Figure 1), producing a structure that is similar to the intact tooth which is hollow in the middle. A hollow-post structure may function more like an “internal ferrule” in a post system, and it may possibly reinforce the root in a similar way to the ferrule. This idea of a “hollow” individually formed structure (everstick Post B) differs from the original idea of an individually formed FRC post (everstickA), where the coronal opening of the canal is filled with FRC material. On the basis of the results, it is not clear whether this kind of “hollow” structure has any effect in terms of the load-bearing capacity on post-restored teeth, but mechanically, it would be optimal. In principal, the hollow FRC post design should be able to provide a load-bearing capacity close to that of an intact tooth. The present results partly support this hypothesis and encourage further development.

The testing method, static loading until failure, has been criticized for not corresponding closely enough to the clinical situation. A cycling loading test may correspond better to the clinical situation, as it is known that fatigue most often causes root fractures (Torbjörner and Fransson 2004a). It can be assumed that the specimen groups of this study would have performed differently in dynamic loading conditions, where the quality of interfacial adhesive joints and the location of reinforcing material would probably have had a major influence. However, static loading is usually the first step in the evaluation process of a novel dental material and is commonly used in order to obtain basic knowledge regarding the fracture behaviour and load capacity of a post-restored tooth.

The absence of a simulated periodontal ligament and also the absence of root treatment, e.g. a gutta-percha-filled canal before post preparation, must also be taken into consideration. However, the results of a static loading test on incisors restored with different posts and composite crowns should not be influenced by the elasticity of the periodontal ligament, contrary to a dynamic loading test where a ligament may influence the results. It is not clear whether a possible root treatment, leaving traces of gutta-percha and sealer in the post-prepared canal, as well as the action of different chemicals used during root treatment, would have influenced the results of the bonding of the resin cement to the root dentin (Bolhuis et al 2001, Morris et al 2001). Another matter for discussion is the possible use of a metal ceramic crown on top of the post-core system in this type of load testing. It has been claimed that the placement of a crown on top of a post-treated tooth, in order to assure a ferrule effect, is advisable when testing *in vitro* (Sorensen and Engelman 1990, Naumann et al 2005b). Clinically, it is an accepted fact that the ferrule effect is of great importance when restoring an endodontically treated tooth (Torbjörner and Fransson 2004b, Pereira et al 2006). On the other hand, it is claimed that the type of post is of little importance when looking at the fracture behaviour, if the tooth is covered with a complete cast crown with a limited ferrule (Hoag and Dwyer 1982, Fokkinga et al 2006a). If a crown with a ferrule is included in an *in vitro* study design, only small differences among post material may be expected, which is the reason for not including a crown in the study design.

Large variations in fracture resistance, microstrain values and standard deviations could be seen within the groups. This is one of the disadvantages of testing real human teeth (Yoldas et al 2005). Variation among individual teeth, e.g. the mechanical and physical properties inside and outside the root canals may be different, and existing microcracks in the dentin may not always be seen before testing. This leads to large standard deviations and variations in the results, as was also seen in the current study.

6.6 Clinical considerations and future investigations

It has been stated in the literature that the extrapolation of clinical recommendations from work of a purely *in vitro* nature, such as the current study, must always be made with caution (Sidoli et al 1997).

From a clinical perspective, it is interesting to speculate on the possible clinical outcome of making *in situ* polymerized FRC root canal posts. An individually constructed FRC post does not necessarily require a large drilled post space, and could therefore be considered as a tissue-saving alternative. According to the current studies, the individually formed FRC post with a semi-IPN polymer matrix appears to possess suitable flexural, light-transmitting and bonding properties to be used as a post material. A recent study reported adequate bond strength for the semi-IPN FRC post material to several different resin luting cements (Le Bell-Rönnlöf et al 2007). Furthermore, this post material seems to function as a homogenic unit with the resin cement and composite core materials, as was seen when evaluating the mode and site of failure. Additionally, with this kind of post material the failures may more often be favourable, which clinically means repairable failures. An additional benefit of an individually formed FRC post is that the coronal part of the post can be bent to the desired angulation. Thus, it can be formed optimally to meet the needs of a core, a crown, a filling or can even be used as part of a bridge construction.

All these aspects can be seen as advantages in clinical terms. Therefore, even with the cautious approach in extrapolating the findings of the present study to the clinical situation, individually formed FRC posts offer at least a very promising alternative, which may lead to an improved clinical outcome.

In future investigations, the main focus should be on development and evaluation of the design of the individually formed FRC post. Moreover, evaluation of the fatigue behaviour of an individually formed FRC post system could be conducted. A post system that combines the root canal filling material with a root canal post could also be evaluated. Furthermore, clinical trials are needed to finally demonstrate the potential clinical advantages of individually formed FRCs in restorative and prosthetic dentistry.

7. CONCLUSIONS AND SUMMARY

The main findings and conclusions were:

1. Considerable variation was found in the calculated strength values of the studied post brands. Prefabricated FRC posts showed lower flexural properties than an individually polymerized FRC material.

2. The experimental glass FRC material in a simulated root canal showed almost the same degree of monomer conversion after light-curing, as monomer resin without fibres. However, in the longest cylinders, FRC showed a slightly higher degree of conversion compared to resin only, which might be due to the fibres' ability to conduct light.

3. Individually formed FRC posts with a semi-IPN polymer matrix could offer better bonding to composite resin luting cement than prefabricated FRC posts with a cross-linked polymer matrix.

4. Contrary to the other posts, there were no adhesive (post-cement) failures with the individually formed glass FRC posts, which suggests better interfacial adhesion of cement to these posts.

5. Only minor variations could be seen in fracture resistance and microstrain between the post groups. The individually formed glass FRC posts with a "hollow" structure showed the highest percentage of favourable failures, which clinically means more repairable failures.

These studies suggest that it is possible to use individually formed FRC material with a semi-IPN polymer matrix as root canal post material. An acceptable degree of conversion is achieved when polymerizing the FRC material *in situ* in a simulated root canal. They also indicate that there are benefits regarding the flexural properties and especially regarding the bonding properties to composite resin luting cements and dentin with this material, compared to prefabricated metal posts or prefabricated FRC post material with a cross-linked matrix. Thus, the hypothesis of the study is verified. Furthermore, the clinically more repairable failures with this material, compared to those of prefabricated FRC posts, support its use in clinical situations.

ACKNOWLEDGEMENTS

These studies were carried out at the Department of Prosthetic Dentistry and Biomaterials Science, at the Institute of Dentistry, University of Turku, during the years 2001-2006.

During this time I have had the privilege to work in a dynamic, inspiring and pioneering research group with the best spirit ever! The people and the very fine facilities have made it a unique atmosphere to do research in. It has always been fun to come to work!

I would like to express my deepest gratitude especially to the following persons:

Above all, my supervisor and mentor Professor Pekka Vallittu. Pekka, it has been an enormous privilege to work with you. Your creativity and positivity affect everybody around you. From the beginning I have admired you in so many ways and I am very lucky to have had the opportunity to work with you. You have all the characteristics of a good supervisor: innovatism, wide scientific knowledge, extraordinary practical skills; you are always encouraging, and try to find the time for small but important matters. You have made it interesting and inspiring to do research and from you I have learned a lot. We also share the same interest, art. Your artistic eye and your way of visualizing research in your very excellent presentations are things I really admire. I thank you for giving me this opportunity to work with such an interesting topic.

My second and very important mentor, docent Eva Söderling. Eva, you introduced me to research already in the years 1996-1998, when I was working one summer as a student in the dry-mouth project. This led to my "syventävät" opinnot and further dry-mouth studies in 2000. You taught me how to analyze and how to write. Most of all you are positive and engaged, you always have time to listen and answer questions, a person one can rely on! Without you I would not have experienced the fantastic IADR-conferences in Nice 1998 and San Diego 2002. Thank you also for always being so encouraging.

My co-author and supervisor in the Biomaterials lab, the ice swimmer and doggyman Lippo Lassila. I thank you for your time and engagement in this research. Your extraordinary knowledge in biomaterials and biomechanics, and your great practical help in the lab and with statistics, have meant a lot to me. You have a peculiar way of seeing and saying things, not always easily understood, but you often make us laugh. By the way, you have not got me in the ice cold water yet…

My co-author and dear friend Johanna Tanner. In the beginning I admired you as my wise and friendly assistant, later on as my co-author and very good friend. You have always been interested in our work and always been very supportive. Your great skills in writing scientific text, pointing out the essential things and teaching computer applications have helped me a lot. We share many of the same interests (and the same taste) and have had wonderful times on conferences (Nice 1998…) and in the archipelago.

My co-author, docent Ilkka Kangasniemi, I would like to thank you for your inventive ideas in this work. Without you this project idea would not have existed. Your long experience in science and biomaterial topics has helped especially in making the research plan.

I would like to thank the official reviewers, professor Kristina Arvidson Fyrberg and docent Leo Tjäderhane for their careful reading, valuable comments and constructive criticism during the review process of this thesis. Leo, your fast and extremely thorough reading helped me a lot.

I wish to thank Professor Pekka Vallittu, the Dean of the Institute of Dentistry and the former Deans, Professor Pentti Kirveskari, Professor Jorma Tenovuo and Professor Stina Syrjänen for kindly providing the facilities to carry out this work. I am also very grateful to Professor Antti Yli-Urpo, who is always very encouraging to young scientists. I would also like to thank the PeGaSOS Graduate School, and especially professor Juha Varrela.

I want to thank my dear friends and colleagues Katja Narva, Helena Yli-Urpo and Arzu Tezvergil-Mutluay. Katja, your positive attitude towards people and life is something to live up to. You are always ready to share everything and you have a big heart. With you one can sometimes forget to catch a plane… Helena, you are always ready to share your knowledge and your efficiency is amazing. Thank you for good advice both in research and children's (boys) matters. Arzu, my other ambitious room-mate, thank you for all the important chats, for sharing pleasent coffe-sessions, and thanks for listening.

I thank my dutch friends and the members of FDPA, especially my colleague and co-author, Wietske Fokkinga. Your positive attitude towards life, your efficient way of working and your drawing skills are wonderful!

I thank all of you people at the Institute of Dentistry; Riikka Mattila, Pia Meurman, Tiina Ranne, Teemu Tirri, Tuomas Waltimo, Jaana Rautava, Jaana Willberg, Merja Ruutu and all the others for making working days fun and conferences unforgettable. Professor Timo Närhi and many other professors I thank for continuous encouragement.

Also everybody in the FRC research group and the Biomechanical Testing Laboratory are thanked: Milla, Minttu, Eiju, Anne, Riina, Jasmina, Jukka, Mervi, Jenni, Mutlu, Sari, Scott and all the others. Especially I want to thank Milla Lahdenperä, Mikko Jokinen and Pasi Alander. Milla, my dear friend and my most important "right hand" in the lab. Thank you for your valuable, precise and extraordinary help in cementing, pushing- and pulling the posts. We share the same intrests and we have had a lot of fun with our big bellies and small children! Mikko, thank you for helping me with the testings.

I want to thank my dear colleagues and good friends Roosa Prinssi and Saija Vahe for always being there for me. I am also grateful to Patricia Stoor for giving me good advice along the way.

I owe deep gratitude to Sirpa Laakso, Riitta and Hannu Moberg, Päivi Mäkimattila, Orvokki Reima, Annukka Wallenius and Annikki Vaisto, who have always helped me with practical matters. Also, I would have been lost without our computer brain, Jaro Saarikoski, thank you for helping me out on numerous occasions. Timo Kattelus at Kuvapalvelut, thank you for your great and friendly help and your excellent skills in designing figures and posters. Thank you Jacqueline Välimäki for revising the language of this thesis. The personnel of the Medical Library are thanked for providing me with all the references I needed. Asko Kuusilehto and his nurse Irja Moisio are thanked for their help in collecting teeth.

I would also like to thank all the people at City Tandläkarna in Helsinki, especially Leif Grans, the ladies at the information desk and my good nurse Marja Tanner for being flexible and understanding with me and my individually formed fibre posts.

I want to thank all of you at Stick Tech, especially Karri Airola.

Finally, I would like to thank my family. Above all, my big-hearted, hardworking and always understanding Mother, Yrsa Le Bell, without you I don't know what I would do. Thank you for helping me out with everything; with both work and taking care of me and the boys. My father, Jean Le Bell, who is my very important supporter (and soulmate). I admire you in many ways; you are the best father, grandfather and summer cottage builder! You have always listened to me and encouraged me to believe in myself. Thank you for inspiring me to do research and helping me in so many ways. Alexander Le Bell, my twin brother and special other half. You have always stood by my side (although living on the other side of the planet) and encouraged me, thank you for always cheering me up when I have felt down. I am also deeply grateful to my mother-in-law, Gudrun Engman, for taking care of the boys when most needed. I cannot thank you all enough.

I owe my deepest and dearest thanks to my husband Petter Rönnlöf, who has listened to me in good and in bad times. Thank you for always being there for me. And to Casimir and Casper, my precious ones, you are my everything!

This study was conducted with the financial support of the Finnish National Technology Agency (TEKES). Financial support in the form of grants from the Finnish Dental Society Apollonia, Odontologiska Samfundet i Finland (OSF), Turun Yliopistosäätiö and Turun Hammaslääkäriseura is gratefully acknowledged. Stick Tech is warmly thanked for providing the material.

Turku 7.11.2007

Anna-Maria Le Bell-Rönnlöf

REFERENCES

Ahlstrand WM, Finger WJ. Direct and indirect fiber-reinforced fixed partial dentures: case reports. Quintessence Int 2002;33:359-365.

Akişli I, Özcan M, Nergiz I. Resistance of core materials against torsional forces on differently conditioned titanium posts. J Prosthet Dent 2002;88:367-374.

Alander P, Lassila LVJ, Tezvergil A, Vallittu PK. Acoustic emission analysis of fiber-reinforced composite in flexural testing. Dent Mater 2004;20:305-312.

Alander P, Lassila LVJ, Vallittu PK. The span length and cross-sectional design affect values of strength. Dent Mater 2005;21:347-353.

Albuquerque RdeC, Polleto LTdeA, Fontana RHBTS, Cimini CA. Stress analysis of an upper central incisor restored with different posts. J Oral Rehabil 2003;30:936-943.

Al-harbi F, Nathanson D. In vitro assessment of retention of four esthetic dowels to resin core foundation and teeth. J Prosthet Dent 2003;90:547-555.

Al-Tayyan M, Watts DC, Kurer HG, Qualtrough A. Fatigue reststance of four post systems placed in decoronated premolars. Abstract n:o 2088. The 85th general session and exhibition of the International Association for Dental Research (IADR). New Orleans, USA, 2007.

Anusavice KJ. Phillips' Science of Dental Materials. Philadelphia: Saunders, 2003. 11th edition.

Asmussen E, Peutzfeldt A, Heitmann T. Stiffness, elastic limit, and strength of newer types of endodontic posts. J Dent 1999;27:275-278.

Asmussen E, Peutzfeldt A, Sahafi A. Finite element analysis of stresses in endodontically treated, dowel-restored teeth. J Prosthet Dent 2005;94:321-329.

Assif D, Ferber A. Retention of dowels using a composite resin as a cementing medium. J Prosthet Dent 1982;48:292-296.

Assif D, Bitenski A, Pilo R, Oren E. Effect of post design on resistance to fracture of endodontically treated teeth with complete crowns. J Prosthet Dent 1993;69:36-40.

Bandlish RB, McDonald AV, Setchell DJ. Assessment of the amount of remaining coronal dentine in root-treated teeth. J Dent 2006;34:699-708.

Baraban DJ. The restoration of pulpless teeth. Dent Clin North Am 1967:633-653.

Beech DE, Brown D. The role of the filler-matrix interface in composite restorative materials based on poly(methylmetacrylate). Br Dent J 1972;133:297-300.

Behr M, Rosentritt M, Handel G. Fiber-reinforced composite crowns and FPDs: a clinical report. Int J Prosthodont 2003;16:239-243.

Belli S, Cobankara FK, Eraslan O, Eskitascioglu G, Karbhari V. The effect of fiber insertion on fracture resistance of endodontically treated molars with MOD cavity and reattached fractured lingual cusps. J Biomed Mater Res Part B: Appl Biomater 2006;79B:35-41.

Bergman B, Lundqvist P, Sjögren U, Sundqvist G. Restorative and endodontic results after treatment with cast posts and cores. J Prosthet Dent 1989;61:10-15.

Bitter K, Meyer-Lueckel H, Priehn K, Kanjuparambil JP, Neumann K, Kielbassa AM. Effects of luting agent and thermocycling on bond strengths to root canal dentine. Int Endod J 2006;39:809-818.

Bitter K, Noetzel J, Neumann K, Kielbassa AM. Effect of silanization on bond strengths of fiber posts to various resin cements. Quintessence Int 2007;38:121-128.

Bolhuis HP, De Gee AJ, Feilzer AJ, Davidson CL. Fracture strength of different core build-up designs. Am J Dent 2001;14:286-290.

Bolhuis HP, De Gee AJ, Pallav P, Feilzer AJ. Influence of fatigue loading on the performance of adhesive and nonadhesive luting cements for cast post-and-core buildups in maxillary premolars. Int J Prosthodont 2004;17:571-576.

Bouillaguet S, Troesch S, Wataha JC, Krejci I, Meyer J-M, Pashley DH. Microtensile bond strength between adhesive cements and root canal dentin. Dent Mater 2003;19:199-205.

Bouillaguet S, Scütt A, Alander P, Schwaller P, Buerki G, Michler J, Cattani-Lorente M, Vallittu PK, Krejci I. Hypothermal and mechanical stresses degrade fiber-matrix interfacial bond strength in dental fiber-reinforced composites. J Biomed Mater Res Part B: Appl Biomater 2006;76B:98-105.

Butz F, Lennon AM, Heydecke G, Strub JR. Survival rate and fracture strength of endodontically treated maxillary incisors with moderate defects restored with different post-and-core systems: an in vitro study. Int J Prosthodont 2001;14:58-64.

Clark HA, Plueddemann EP. Bonding of silane coupling agents in glass-reinforced plastics. Modern Plastics 1963;40-133-138.

Cohen BI, Pagnillo M, Musikant BL, Deutsch AS. Comparison of the retentive and photoelastic properties of two prefabricated endodontic post systems. J Oral Rehabil 1999;26:488-494.

Cohen BI, Pagnillo MK, Newman I, Musikant BL, Deutsch AS. Retention of a core material supported by three post head designs. J Prosthet Dent 2000;83:624-628.

Cormier CJ, Burns DR, Moon P. In vitro comparison of the fracture resistance and failure mode of fiber, ceramic, and conventional post systems at various stages of restoration. J Prosthodont 2001;10:26-36.

Corsalini M, Genovese K, Lamberti L, Pappalettere C, Carella M, Carossa S. A Laboratory comparison of individual Targis/Vectris posts with standard fiberglass posts. Int J Prosthodont 2007;20:190-192.

Creugers NHJ, Kreulen CM, Fokkinga WA, Mentink AGM. A 5-year prospective clinical study on core restorations without covering crowns. Int J Prosthodont 2005a;18:40-41.

Creugers NHJ, Mentink AGM, Fokkinga WA, Kreulen CM. 5-year follow-up of a prospective clinical study on various types of core restorations. Int J Prosthodont 2005b;18:34-39.

Dallari A, Rovatti L, Dallari B, Mason PN, Suh BI. Translucent quartz-fiber post luted in vivo with self-curing composite cement: case report and microscopic examination at a two-year clinical follow-up. J Adhes Dent 2006;8:189-195.

DeBoer J, Vermilyea SG, Brady RE. The effect of carbon fiber orientation on the fatigue resistance and bending properties of two denture resins. J Prosthet Dent 1984;51:119-121.

De Santis R, Prisco D, Apicella A, Ambrosio L, Rengo S, Nicolais L. Carbon fiber post adhesion to resin luting cement in the restoration of endodontically treated teeth. J Mater Sci Mater Med 2000:11:201-206.

DiBenedetto AT. Tailoring of interfaces in glass fiber reinforced polymer composites: a review. Mater Sci and Eng 2001;A302:74-82.

Dietschi D, Romelli M, Goretti A. Adaptation of adhesive posts and cores to dentin after fatigue testing. Int J Prosthodont 1997;10:498-507.

Dietschi D, Ardu S, Rossier-Gerber A, Krejci I. Adaptation of adhesive post and cores to dentin after in vitro occlusal loading: evaluation of post material influence. J Adhes Dent 2006;8:409-419.

Drummond JL. In vitro evaluation of endodontic posts. Am J Dent 2000;13:5B-8B.

Duret B, Reynaud M, Duret F. A new concept of corono-radicular reconstruction: the Composipost (2). Chir Dent Fr 1990;60:69-77.

Dyer SR, Lassila LVJ, Jokinen M, Vallittu PK. Effect of fiber position and orientation on fracture load of fiber-reinforced composite. Dent Mater 2004;20:947-955.

Dyer SR, Lassila LVJ, Alander P, Vallittu PK. Static strength of molar region direct technique glass fibre-reinforced composite fixed partial dentures. J Oral Rehabil 2005;32:351-357.

Eckerbom M, Magnusson T. Restoring endodontically treated teeth: a survey of current opinions among board-certified prosthodontists and general dental practitioners in Sweden. Int J Prosthodont 2001;14:245-259.

Ellner S, Bergendal T, Bergman B. Four post-and-core combinations as abutments for fixed single crowns: a prospective up to 10-year study. Int J Prosthodont 2003;16:249-254.

Feilzer AJ, De Gee AJ, Davidson CL. Setting stress in composite resin in relation to configuration of the restoration. J Dent Res 1987;66:1636-1639.

Fennis WMM, Tezvergil A, Kujis RH, Lassila LVJ, Kreulen CM, Creugers NHJ, Vallittu PK. In vitro fracture resistance of fiber reinforced cusp-replacing composite restorations. Dent Mater 2005;21:565-572.

Fernandes AS, Shetty S, Coutinho I. Factors determining post selection: a literature review. J Prosthet Dent 2003;90:556-562.

Ferrari M, Vichi A, García-Godoy F. Clinical evaluation of fiber-reinforced epoxy resin posts and cast post and cores. Am J Dent 2000a;13:15B-18B.

Ferrari M, Vichi A, Mannocci F, Mason PN. Retrospective study of the clinical performance of fiber posts. Am J Dent 2000b;13;9B-13B.

Ferrari M, Mannocci F, Vichi A, Cagidiaco MC, Mjör IA. Bonding to root canal; structural characteristics of the substrate. Am J Dent 2000c;13:255-260.

Finger WJ, Ahlstrand WM, Fritz UB. Radiopacity of fiber-reinforced resin posts. Am J Dent 2002;15:81-84.

Fokkinga WA, Kreulen CM, Vallittu PK, Creugers NHJ. A structured analysis of in vitro failure loads and failure modes of fiber, metal and ceramic post-and-core systems. Int J Prosthodont 2004;17:476-482.

Fokkinga WA, Le Bell A-M, Kreulen CM, Lassila LVJ, Vallittu PK, Creugers NHJ. Ex vivo fracture resistance of direct resin composite complete crowns with and without posts on maxillary premolars. Int Endod J 2005;38:230-237.

Fokkinga WA, Kreulen CM, Le Bell-Rönnlöf A-M, Lassila LVJ, Vallittu PK, Creugers NHJ. In vitro fracture behavior of maxillary premolars with metal crowns and several post-and-core systems. Eur J Oral Sci 2006a;114:250-256.

Fokkinga WA, Kreulen CM, Le Bell-Rönnlöf A-M, Lassila LVJ, Vallittu PK, Creugers NHJ. Fracture behavior of structurally compromised non-vital maxillary premolars restored using experimental fiber-reinforced composite crowns. Am J Dent 2006b;19:326-332.

Fokkinga WA. Post it? Reconstruction of the endodontically treated tooth. Thesis. Radboud University Nijmegen, Nijmegen, The Netherlands 2007.

Fokkinga WA, Kreulen CM, Bronkhorst EM, Creugers NHJ. Up to 17-year controlled clinical study on post-and-cores and covering crowns. J Dent 2007;35:778-786.

Fox K, Gutteridge DL. An in vitro study of coronal microleakage in root-canal-treated teeth restored by the post and core technique. Int Endod J 1997;30:361-368.

Fredriksson M, Astbäck J, Pamenius M, Arvidson K. A retrospective study of 236 patients with teeth restored by carbon fiber-reinforced epoxy resin posts. J Prosthet Dent 1998;80:151-157.

Freilich MA, Karmaker AC, Burstone CJ, Goldberg AJ. Development and clinical applications of a light-polymerized fiber-reinforced composite. J Prosthet Dent 1998;80:311-318.

Gallo JR, Miller T, Xu X, Burgess JO. In vitro evaluation of the retention of composite fiber and stainless steel posts. J Prosthodont 2002;11:25-29.

Garoushi SK, Ballo AM, Lassila LVJ, Vallittu PK. Fracture resistance of fragmented incisal edges restored with fiber-reinforced composite. J Adhes Dent 2006;8:91-95.

Giachetti L, Russo DS, Bertini F, Giuliani V. Translucent fiber post cementation using a light-curing adhesive/composite system: SEM analysis and pull-out test. J Dent 2004;32:629-634.

Glazer B. Restoration of endodontically treated teeth with carbon fibre posts- a prospective study. J Can Dent Assoc 2000;66:613-618.

Goldberg AJ, Burstone CJ. The use of continuous fiber reinforcement in dentistry. Dent Mater 1992;8:197-202.

Goldberg AJ, Burstone CJ, Hadjinikolaou I, Jancar J. Screening of matrices and fibers for reinforced thermoplastics intended for dental applications. J Biomed Mater Res 1994;28:167-173.

Goodacre CJ, Spolnik KJ. The prosthodontic management of endodontically treated teeth: a literature review. Part III. Tooth preparation considerations. J Prosthet Dent 1995;4:122-128.

Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JYK. Clinical complications in fixed prosthodontics. J Prosthet Dent 2003;90:31-34.

Goracci C, Tavares AU, Fabianelli A, Monticelli F, Raffaelli O, Cardoso PC, Tay F, Ferrari M. The adhesion between fiber posts and root canal walls: comparison between microtensile and push-out bond strength measurements. Eur J Oral Sci 2004;112:353-361.

Goracci C, Raffaelli O, Monticelli F, Balleri B, Bertelli E, Ferrari M. The adhesion between prefabricated FRC posts and composite resin cores: microtensile bond strength with and without post-silanization. Dent Mater 2005;21:437-444.

Grandini S, Sapio S, Simonetti M. Use of anatomic post and core for reconstructing an endodontically treated tooth: a case report. J Adhes Dent 2003;5:243-247.

Grandini S, Goracci C, Tay FR, Grandini R, Ferrari M. Clinical evaluation of the use of fiber posts and direct resin restorations for endodontically treated teeth. Int J Prosthodont 2005;18:399-404.

Gutmann JL. The dentin-root complex: anatomic and biologic considerations in restoring endodontically treated teeth. J Prosthet Dent 1992;67:458-467.

Guzy GE, Nicholls JI. In vitro comparison of intact endodontically treated teeth with and without endo-post reinforcement. J Prosthet Dent 1979;42;39-44.

Göhring TN, Roos M. Inlay-fixed partial dentures adhesively retained and reinforced by glass fibers: clinical and scanning electron microscopy analysis after five years. Eur J Oral Sci 2005;113:60-69.

Healey HJ. Restoration of Treated Pulpless Tooth. In: Healey HJ (ed). Endodontics. St Louis: Mosby, 1960:267-291.

Hedlund S-O, Johansson NG, Sjögren G. A retrospective study of pre-fabricated carbon fibre root canal posts. J Oral Rehabil 2003;30:1036-1040.

Hemmings KW, King PA, Setchell DJ. Resistance to torsional forces of various post and core designs. J Prosthet Dent 1991;66:325-329.

Hew YS, Purton DG, Love RM. Evaluation of pre-fabricated root canal posts. J Oral Rehabil 2001;28:207-211.

Heydecke G, Butz F, Strub JR. Fracture strength and survival rate of endodontically treated maxillary incisors with approximal cavities after restoration with different post and core systems: an in-vitro study. J Dent 2001;29:427-433.

Hoag EP, Dwyer TG. A comparative evaluation of three post and core techniques. J Prosthet Dent 1982;47:177-181.

Hsueh C-H. Interfacial debonding and fiber pull-out stresses of fiber-reinforced composites IX: A simple treatment of Poisson's effect for frictional interfaces. Mater Sci and Eng 1993;A161:L1-L6.

Hunter AJ, Feiglin B, Williams JF. Effects of post placement on endodontically treated teeth. J Prosthet Dent 1989;62:166-172.

Isidor F, Brøndum K. Intermittent loading of teeth with tapered, individually cast or prefabricated, parallel-sided posts. Int J Prosthod 1992;5:257-261.

Isidor F, Ödman P, Brøndum K. Intermittent loading of teeth restored using prefabricated carbon fiber posts. Int J Prosthodont 1996;9:131-136.

Isidor F, Brøndum K, Ravnholt G. The influence of post length and crown ferrule length on the resistance to cyclic loading of bovine teeth with prefabricated titanium posts. Int J Prosthod 1999;12:78-82.

Jacoby WE. Practical technique for the fabrication of a direct pattern for a post-core restoration. J Prosthet Dent 1976;35:357-360.

Johnson JK, Sakamura JS. Dowel form and tensile force. J Prosthet Dent 1978;40:645-649.

Jokstad A, Mjör IA. Ten years' clinical evaluation of three luting cements. J Dent 1996;24:309-315.

Jung S-H, Min K-S, Chang H-S, Park S-D, Kwon S-N, Bae J-M. Microleakage and fracture patterns of teeth restored with different posts under dynamic loading. J Prosthet Dent 2007;98:270-276.

Junge T, Nicholls JI, Phillips KM, Libman WJ. Load fatigue of compromised teeth: a comparison of 3 luting cements. Int J Prosthodont 1998;11:558-564.

Kalkan M, Usumez A, Ozturk AN, Belli S, Eskitascioglu G. Bond strength between root dentin and three glass-fiber post systems. J Prosthet Dent 2006;96:41-46.

Kallio TT, Lastumäki TM, Vallittu PK. Bonding of restorative and veneering composite resin to some polymeric composites. Dent Mater 2001;17:80-86.

Kallio TT, Lastumäki TM, Vallittu PK. Effect of resin application time on bond strength of polymer substrate repaired with particulate filler composite. J Mater Sci;Mater in Med 2003;14:999-1004.

Kargül B, Caglar E, Kabalay U. Glass fiber-reinforced composite resin as fixed space maintainers in children: 12-month clinical follow-up. J Dent Child 2005;72:109-112.

Karlsson S. A clinical evaluation of fixed bridges, 10 years following insertion. J Oral Rehabil 1986;13:423-432.

Keski-Nikkola MS, Alander PM, Lassila LVJ, Vallittu PK. Bond strength of Gradia veneering composite to fibre-reinforced composite. J Oral Rehabil 2004;31:1178-1183.

King PA, Setchell DJ. An in vitro evaluation of a prototype CFRC prefabricated post developed for the restoration of pulpless teeth. J Oral Rehabil 1990;17:599-609.

Krenchel H. Fibre reinforcement- theoretical and practical investigations of the elasticity and strength of fibre-reinforced materials. Thesis. Copenhagen: Akademisk Forlag, 1964.

Kvist T, Rydin E, Reit C. The relative frequency of periapical lesions in teeth with root canal-retained posts. J Endod 1989;15:578-580.

Kwiatkowski SJ, Geller W. A preliminary consideration of the glass-ceramic dowel post and core. Int J Prosthodont 1989;2:51-55.

Ladizesky NH, Chow TW, Ward IM. The effect of highly drawn polyethylene fibres on the mechanical properties of denture base resins. Clin mater 1990;6:209-225.

Lambjerg-Hansen H, Asmussen E. Mechanical properties of endodontic posts. J Oral Rehabil 1997;24:882-887.

Lang H, Korkmaz Y, Schneider K, Raab WH-M. Impact of endodontic treatments on the rigidity of the root. J Dent Res 2006;85:364-368.

Lanza A, Aversa R, Rengo S, Apicella D, Apicella A. 3D FEA of cemented steel, glass and carbon posts in a maxillary incisor. Dent Mater 2005;21:709-715.

Larato DC. Single unit cast post crown for pulpless anterior tooth roots. J Prosthet Dent 1966;16:145-149.

Lassila LVJ, Nohrström T, Vallittu PK. The influence of short-term water storage on the flexural properties of unidirectional glass fiber-reinforced composites. Biomater 2002;23:2221-2229.

Lassila LVJ, Tezvergil A, Lahdenperä M, Alander P, Shinya A, Shinya A, Vallittu PK. Evaluation of some properties of two fiber-reinforced composite materials. Acta Odontol Scand 2005;63:196-204.

Lastumäki TM, Kallio TT, Vallittu PK. The bond strength of light-curing composite resin to finally polymerized and aged glass fiber-reinforced composite substrate. Biomater 2002;23:4533-4539.

Lastumäki TM, Lassila LVJ, Vallittu PK. The semi-interpenetrating polymer network matrix of fiber-reinforced composite and its effect on the surface adhesive properties. J Mater Sci Mater Med 2003;14:803-809.

Leary JM, Aquilino SA, Svare CW. An evaluation of post length within the elastic limits of dentin. J Prosthet Dent 1987;57:277-281.

Le Bell-Rönnlöf A-M, Lahdenperä M, Lassila LVJ, Vallittu PK. Bond strength of composite resin luting cements to fiber reinforced composite root canal post. J Contemp Dent Pract 2007, accepted.

Lloyd PM, Palik JF. The philosophies of dowel diameter preparation: A literature review. J Prosthet Dent 1993;69:32-36.

Lovdahl PE, Nicholls JI. Pin-retained amalgam cores vs. cast-gold dowel-cores. J Prosthet Dent 1977;38:507-514.

Love RM, Purton DG. The effect of serrations on carbon fibre posts-retention within the root canal, core retention, and post rigidity. Int J Prosthodont 1996;9:484-488.

Magni E, Mazzitelli C, Papacchini F, Radovic I, Goracci C, Coniglio I, Ferrari M. Adhesion between fiber posts and resin luting agents: a microtensile bond strength test and an SEM investigation following different treatments of the post surface. J Adhes Dent 2007;9:195-202.

Malferrari S, Monaco C, Scotti R. Clinical evaluation of teeth restored with quartz fiber-reinforced epoxy resin posts. Int J Prosthodont 2003;16:39-44.

Mannocci F, Innocenti M, Ferrari M, Watson TF. Confocal and scanning electron microscopic study of teeth restored with fiber posts, metal posts, and composite resins. J Endod 1999;25:789-794.

Martinez-Insua A, da Silva L, Rilo B, Santana U. Comparison of the fracture resistances of pulpless teeth restored with a cast post and core or carbon-fiber post with a composite core. J Prosthet Dent 1998;80:527-532.

Matinlinna JP, Lassila LVJ, Özcan M, Yli-Urpo A, Vallittu PK. An introduction to silanes and their clinical applications in dentistry. Int J Prosthodont 2004;17:155-164.

Matinlinna JP, Vallittu PK. Silane based concepts on bonding resin composite to metals. J Contemp Dent Pract 2007;8:1-13.

Mattison GD, Delivanis PD, Thacker Rw Jr, Hassell KJ. Effect of post preparation on the apical seal. J Prosthet Dent 1984;51:785-789.

McDonald AV, King PA, Setchell DJ. An in vitro study to compare impact fracture resistance of intact root-treated teeth. Int Endod J 1990;23:304-312.

Meiers JC, Duncan JP, Freilich MA, Goldberg AJ. Preimpregnated, fiber-reinforced prostheses. Part II. Direct applications: splints and fixed partial dentures. Quintessence Int 1998;29:761-768.

Meiers JC, Freilich MA. Design and use of a prefabricated fiber-reinforced composite substructure for the chairside replacement of missing premolars. Quintessence Int 2006a;37:449-454.

Meiers JC, Freilich MA. Use of a prefabricated fiber-reinforced composite resin framework to provide a provisional fixed partial denture over an integrating implant: a clinical report. J Prosthet Dent 2006b;95:14-18.

Mendoza DB, Eakle WS, Kahl EA. Root reinforcement with a resin-bonded preformed post. J Prosthet Dent 1997;78:10-15.

Mentink AGB, Meeuwissen R, Käyser AF, Mulder J. Survival rate and failure characteristcs of the all metal post and core restoration. J Oral Rehabil 1993;20:455-461.

Meyenberg KH, Lüthy H, Schärer P. Zirconia posts: a new all-ceramic concept for nonvital abutment teeth. J Esthet Dent 1995;7:73-80.

Miettinen VM, Vallittu PK. Water sorption and solubility of glass fiber-reinforced denture polymethyl-methacrylate resin. J Prosthet Dent 1997;77:531-534.

Monticelli F, Goracci C, Ferrari M. Micromorphology of the fiber post-resin core unit: a scanning electron microscopy evaluation. Dent Mater 2004;20:176-183.

Monticelli F, Toledano M, Tay FR, Cury AH, Goracci C, Ferrari M. Post-surface conditioning improves interfacial adhesion in post/core restorations. Dent Mater 2006;22:602-609.

Morgano SM, Milot P. Clinical success of cast metal posts and cores. J Prosthet Dent 1993;69:11-16.

Morgano SM, Hashem AF, Fotoohi K, Rose L. A nationwide survey of contemporary philosophies and techniques of restoring endodontically treated teeth. J Prosthet Dent 1994;72:259-267.

Morgano SM. Restoration of pulpless teeth: application of traditional principles in present and future contexts. J Prosthet Dent 1996;75:375-380.

Morgano SM, Brackett SE. Foundation restorations in fixed prosthodontics: current knowledge and future needs. J Prosthet Dent 1999;82:643-657.

Morris MD, Lee KW, Agee KA, Bouillaguet S, Pashley DH. Effects of sodium hypochlorite and RC-prep on bond strengths of resin cement to endodontic surfaces. J Endod 2001;27:753-757.

Mullarky RH. Aramid fiber reinforcement of acrylic appliances. J Clin Orthod 1985;19:655-658.

Murphy J. Reinforced plastics handbook. Oxford: Elsevier Science Ltd., 1998. 2nd edition.

Möllersten L, Lockowandt P, Lindén L-Å. A comparison of strengths of five core and post-and-core systems. Quintessence Int 2002;33:140-149.

Narva KK, Vallittu PK, Helenius H, Yli-Urpo A. Clinical survey of acrylic resin removable denture repairs with glass-fiber reinforcement. Int J Prosthodont 2001;14:219-224.

Naumann M, Blankenstein F, Kießling S, Dietrich T. Risk factors for failure of glass fiber-reinforced composite post restorations: a prospective observational clinical study. Eur J Oral Sci 2005a;113:519-524.

Naumann M, Sterzenbach G, Pröschel P. Evaluation of load testing of postendodontic restorations in vitro: linear compressive loading, gradual cycling loading and chewing simulation. J Biomed Mater Res Part B Appl Biomater 2005b;74B:829-834.

Naumann M, Preuss A, Rosentritt M. Effect of incomplete crown ferrules on load capacity of endodontically treated maxillary incisors restored with fiber posts, composite build-ups, and all-ceramic crowns: an in vitro evaluation after chewing simulation. Acta Odontol Scand 2006;64:31-36.

Naumann M, Preuss A, Frankenberger R. Reinforcement effect of adhesively luted fiber reinforced composite versus titanium posts. Dent mater 2007;23:138-144.

Nergiz I, Schmage P, Platzer U, McMullan-Vogel CG. Effect of different surface textures on retentive strength of tapered posts. J Prosthet Dent 1997;78:451-457.

Nergiz I, Schmage P, Özcan M, Platzer U. Effect of length and diameter of tapered posts on the retention. J Oral Rehabil 2002;29:28-34.

Nissan J, Dmitry Y, Assif D. The use of reinforced composite resin cement as compensation for reduced post length. J Prosthet Dent 2001;86:304-308.

Nixon C, Vertucci FJ, Swindle R. The effect of post space preparation on the apical seal of root canal obturated teeth. Todays FDA 1991;3:1C,6C.

O'Brien WJ. Dental materials and their selection. Chicago: Quintessence, 2002. 3rd edition.

Paul SJ, Werder P. Clinical success of zirconium oxide posts with resin composite or glass-ceramic cores in endodontically treated teeth: a 4-year retrospective study. Int J Prosthodont 2004;17:524-528.

Pegoretti A, Fambri L, Zappini G, Bianchetti M. Finite element analysis of a glass fibre reinforced composite endodontic post. Biomat 2002;23:2667-2682.

Pereira JR, de Ornelas F, Conti PCR, do Valle AL. Effect of a crown ferrule on the fracture resistance of endodontically treated teeth restored with prefabricated posts. J Prosthet Dent 2006;95:50-54.

Perel ML, Muroff FI. Clinical criteria for posts and cores. J Prosthet Dent 1972;28:405-411.

Peroz I, Blankenstein F, Lange K-P, Naumann M. Restoring endodontically treated teeth with posts and cores-a review. Quintessence Int 2005;36:737-746.

Pest LB, Cavalli G, Bertani P, Gagliani M. Adhesive post-endodontic restorations with fiber posts: push-out tests and SEM observations. Dent Mater 2002;18:596-602.

Peutzfeldt A. Resin composites in dentistry: the monomer systems. Eur J Oral Sci 1997;105:97-116.

Pilo R, Cardash HS, Levin E, Assif D. Effect of core stiffness on the in vitro fracture of crowned, endodontically treated teeth. J Prosthet Dent 2002;88:302-306.

Purton DG, Payne JA. Comparison of carbon fiber and stainless steel root canal posts. Quintessence Int 1996;27:93-97.

Purton DG, Love RM, Chandler NP. Rigidity and retention of ceramic root canal posts. Oper Dent 2000;25:223-227.

Qualtrough AJE, Chandler NP, Purton DG. A comparison of the retention of tooth-colored posts. Quintessence Int 2003;34:199-201.

Reid LC, Kazemi RB, Meiers JC. Effect of fatigue testing on core integrity and post microleakage of teeth restored with different post systems. J Endod 2003;29:125-131.

Rosen H. Operative procedures on mutilated endodontically treated teeth. J Prosthet Dent 1961;11:973-986.

Ruemping DR, Lund MR, Schnell RJ. Retention of dowels subjected to tensile and torsional forces. J Prosthet Dent 1979;41:159-162.

Ruyter IE, Ekstrand K, Björk N. Development of carbon/graphite fiber reinforced poly(methyl methacrylate) suitable for implant-fixed dental bridges. Dent mater 1986;2:6-9.

Sahafi A, Peutzfeldt A, Asmussen E, Gotfredsen K. Bond strength of resin cement to dentin and to surface-treated posts of titanium alloy, glass fiber, and zirconia. J Adhes Dent 2003;5:153-162.

Sahafi A, Peutzfeldt A, Asmussen E, Gotfredsen K. Retention and failure morphology of prefabricated posts. Int J Prosthodont 2004;17:307-312.

Salameh Z, Sorrentino R, Papacchini F, Ounsi HF, Tashkandi E, Goracci C, Ferrari M. Fracture resistance and failure patterns of endodontically treated mandibular molars restored using resin composite with or without translucent glass fiber posts. J Endod 2006;32:752-755.

Salvi GE, Siegrist Guldener BE, Amstad T, Joss A, Lang NP. Clinical evaluation of root filled teeth restored with or without post-and-core systems in a specialist practice setting. Int Endod J 2007;40:209-215.

Schaeffer MA, White RR, Walton RE. Determining the optimal obturation length: a meta-analysis of literature. J Endod 2005;31:271-274.

Schmage P, Sohn J, Nergiz I, Özcan M. Various conditioning methods for root canals influencing the tensile strength of titanium posts. J Oral Rehabil 2004;31:890-894.

Schmitter M, Rammelsberg P, Gabbert O, Ohlmann B. Influence of clinical baseline findings on the survival of 2 post systems: a randomized clinical trial. Int J Prosthodont 2007;20:173-178.

Schreiber CK. Polymethylmethacrylate reinforced with carbon fibres. Br Dent J 1971;130:29-30.

Seefeld F, Wenz H-J, Ludwig K, Kern M. Resistance to fracture and structural characteristics of different fiber reinforced post systems. Dent Mater 2007;23:265-271.

Segerström S, Astbäck J, Ekstrand K. A retrospective long term study of teeth restored with prefabricated carbon fiber reinforced epoxy resin posts. Swed Dent J 2006;30:1-8.

Sevón LA, Ampula L, Vallittu PK. Rehabilitation of a periodontal patient with rapidly progressing marginal alveolar bone loss: 1-year follow-up. J Clin Periodontol 2000;27;615-619.

Shillingburg Jr HT, Fisher DW, Dewhirst RB. Restoration of endodontically treated posterior teeth. J Prosthet Dent 1970;24:401-409.

Shillingburg HT, Kessler JC. Restoration of the Endodontically treated tooth. Chicago: Quintessence, 1982.

Shillingburg HT, Jacobi R, Brackett SE. Preparation modifications for damaged teeth. In: Shillingburg HT, Jacobi R and Brackett SE (eds). Fundamentals of tooth preparations. Chicago: Quintessence, 1987:321-358.

Sidoli GE, King PA, Setchell DJ. An in vitro evaluation of a carbon fiber-based post and core system. J Prosthet Dent 1997;78:5-9.

Silness J, Gustavsen F, Hunsbeth J. Distribution of corrosion products in teeth restored with metal crowns retained by stainless steel posts. Acta Odontol Scand 1979;37:317-321.

Silverstein WH. The reinforcement of weakened pulpless teeth. J. Prosthet Dent 1964;14:372-381.

Smith DC. Recent developments and prospects in dental polymers. J Prosthet Dent 1962;12:1066-1078.

Sorensen JA, Martinoff JT. Intracoronal reinforcement and coronal coverage: a study of endodontically treated teeth. J Prosthet Dent 1984a;51:780-784.

Sorensen JA, Martinoff JT. Clinically significant factors in dowel design. J Prosthet Dent 1984b;52:28-35.

Sorensen JA, Engelman MJ. Ferrule design and fracture resistance of endodontically treated teeth. J Prosthet Dent 1990;63:529-536.

Sperling LH. Interpenetrating Polymer Networks: An Overview. In: Klempner D, Sperling LH, Utracki LA (eds). Interpenetrating Polymer Networks. Washington: American Chemical Society, 1994:3-39, 356. 1st edition.

Standlee JP, Caputo AA, Hanson EC. Retention of endodontic dowels: effects of cement, dowel length, diameter, and design. J Prosthet Dent 1978;39:400-405.

Standlee JP, Caputo AA, Holcomb J, Trabert KC. The retentive and stress-distributing properties of a threaded endodontic dowel. J Prosthet Dent 1980;44:398-404.

Standlee JP, Caputo AA, Holcomb JP. The Dentatus screw: comparative stress analysis with other endodontic dowel designs. J Oral Rehabil 1982;9:23-33.

Standlee JP, Caputo AA. The retentive and stress distributing properties of split threaded endodontic dowels. J Prosthet Dent 1992;68:436-442.

Stankiewicz NR, Wilson PR. The ferrule effect: a literature review. Int Endod J 2002;35:575-581.

Stern N, Hirshfeld Z. Principles of preparing endodontically treated teeth for dowel and core restorations. J Prosthet Dent 1973;30:162-165.

Stockton LW. Factors affecting retention of post systems: a literature review. J Prosthet Dent 1999;81:380-385.

Stockton LW, Williams PT. Retention and shear bond strength of two post systems. Oper Dent 1999;24:210-216.

Tan PLB, Aquilino SA, Gratton DG, Stanford CM, Tan SC, Johnson WT, Dawson D. In vitro fracture resistance of endodontically treated central incisors with varying ferrule heights and configurations. J Prosthet Dent 2005;93:331-336.

Tanner J, Carlén A, Söderling E, Vallittu PK. Adsorption of parotid saliva proteins and adhesion of streptococcus mutans ATCC 21752 to dental fiber-reinforced composites. J Biomed Mater Res B: Appl Biomater 2003;66B:391-398.

Tay FR, Hiraishi N, Schuster GS, Pashley DH, Loushine RJ, Ounsi HF, Grandini S, Yau JY, Mazzoni A, Donnelly A, King NM. Reduction in antimicrobial substantivity of MTAD after initial sodium hypochlorite irrigation. J Endod 2006;32:970-975.

Terry DA, Triolo PT, Swift EJ. Fabrication of direct fiber-reinforced posts: a structural design concept. J Esthet Restor Dent 2001;13:228-240.

Tezvergil A, Lassila LVJ, Vallittu PK. The effect of fiber orientation on the thermal expansion coefficients of fiber-reinforced composites. Dent Mater 2003;19:471-477.

Tezvergil A, Lassila LVJ, Vallittu PK. The effect of fiber orientation on the polymerization shrinkage strain of fiber-reinforced composites. Dent Mater 2006;22:610-616.

Tjan AH, Miller GD. Comparison of retentive properties of dowel forms after application of intermittent torsional forces. J Prosthet Dent 1984;52:238-242.

Tjan AH, Whang SB. Resistance to root fracture of dowel channels with various thicknesses of buccal dentin walls. J Prosthet Dent 1985;53:496-500.

Torbjörner A, Karlsson S, Ödman PA. Survival rate and failure characteristics for two post designs. J Prosthet Dent 1995;73:439-444.

Torbjörner A, Karlsson S, Syverud M, Hensten-Pettersson A. Carbon fiber reinforced root canal posts. Mechanical and cytotoxic properties. Eur J Oral Sci 1996;104:605-611.

Torbjörner A. Post and Cores. In: Karlsson S, Nilner K and Dahl B (eds). A textbook of Fixed Prosthodontics. The Scandinavian Approach. Stockholm: Förlagshuset Gothia AB, 2000:173-186.

Torbjörner A, Fransson B. A literature review on the prosthetic treatment of structurally compromised teeth. Int J Prosthodont 2004a;17:369-376.

Torbjörner A, Fransson B. Biomechanical aspects of prosthetic treatment of structurally compromised teeth. Int J Prosthodont 2004b;17:135-141.

Trabert KC, Caput AA, Abou-Rass M. Tooth fracture- a comparison of endodontic and restorative treatments. J Endod 1978;4:341-345.

Trope M, Maltz DO, Tronstad L. Resistance to fracture of restored endodontically treated teeth. Endod Dent Traumatol 1985;1:108-111.

Vallittu PK, Lassila VP. Reinforcement of acrylic resin denture base material with metal or fibre strengtheners. J Oral Rehabil 1992;19:225-230.

Vallittu PK, Lassila VP, Lappalainen R. Acrylic resin-fiber composite-Part I: The effect of fiber concentration on fracture resistance. J Prosthet Dent 1994;71:607-612.

Vallittu PK. Comparison of the in vitro fatigue resistance of an acrylic resin removable partial denture reinforced with continuous glass fibers or metal wires. J Prosthodont 1996a;5:115-121.

Vallittu PK. A review of fiber-reinforced denture base resins. J Prosthod 1996b;5:270-276.

Vallittu PK. Curing of silane coupling agent and its effect on the transverse strength of autopolymerizing polymethylmethacrylate-glass fiber composite. J Oral Rehabil 1997a;24:124-130.

Vallittu PK. Transverse strength, ductility, and qualitative elemental analysis of cobalt-chromium alloy after various durations of induction melting. J Prosthodont 1997b;6:55-60.

Vallittu PK, Ruyter IE. The swelling phenomenon of acrylic resin polymer teeth at the interface with denture base polymers. J Prosthet Dent 1997;78:194-199.

Vallittu PK. Experiences of using glass fibres with multiphase acrylic resin systems. Theoretical background and clinical examples. In: Vallittu PK (ed). The first symposium on fibre reinforced plastics in dentistry. University of Turku, Institute of Dentistry, 1998a.

Vallittu PK. Some aspects of the tensile strength of unidirectional glass fibre-polymethyl methacrylate composite used in dentures. J Oral Rehabil 1998b;25:100-105.

Vallittu PK. Prosthodontic treatment with a glass fiber-reinforced resin-bonded fixed partial denture: a clinical report. J Prosthet Dent 1999a;82:132-135.

Vallittu PK. Flexural properties of acrylic resin polymers reinforced with unidirectional and woven glass fibers. J Prosthet Dent 1999b;81:318-326.

Vallittu PK. Effect of 180-week water storage on the flexural properties of e-glass and silica fiber acrylic resin composite. Int J Prosthodont 2000;13:334-339.

Vallittu PK, Könönen M. Biomechanical aspects and material properties. In: Karlsson S, Nilner K and Dahl B (eds). A textbook of Fixed Prosthodontics. The Scandinavian Approach. Stockholm: Förlagshuset Gothia AB, 2000:116-130.

Vallittu PK, Sevelius C. Resin-bonded, glass fiber-reinforced composite fixed partial dentures: a clinical study. J Prosthet Dent 2000;84:413-418.

Vallittu PK. Case report: a glass fibre reinforced composite resin bonded fixed partial denture. Eur J Prosthodont Rest Dent 2001a;9;35-38.

Vallittu PK. Strength and interfacial adhesion of FRC-tooth system. In: Vallittu PK (ed). The second symposium on fibre-reinforced plastics in dentistry. University of Turku, Institute of Dentistry, 2001b.

Vallittu PK. Survival rates of resin-bonded, glass fiber-reinforced composite fixed partial dentures with a mean follow-up of 42 months: a pilot study. J Prosthet Dent 2004;91:241-246.

Vallittu PK. Fibre-reinforced composites in root canal anchoring: Mechanical requirements, structure and properties of the fibre-reinforced composite. Int Dent South Afr 2006;8:20-27.

van Noort R. Mechanical properties. In: van Noort R (ed). Introduction to dental materials. Edinburgh: Mosby, 2002:42-49. 2nd edition.

Vano M, Goracci C, Monticelli F, Tognini F, Gabriele M, Tay FR, Ferrari M. The adhesion between fibre posts and composite resin cores: the evaluation of microtensile bond strength following various surface chemical treatments to posts. Int Endod J 2006;39:31-39.

Väkiparta M, Yli-Urpo A, Vallittu PK. Flexural properties of glass fiber reinforced composite with multiphase biopolymer matrix. J Mater Sci Mater Med 2004;15:7-11.

Williams CB, Joyce AP, Roberts S. A comparison between in vivo radiographic working length determination and measurement after extraction. J Endod 2006;32:624-627.

Xie Q, Wu W. Fatigue resistance of flared residual roots restored with FRC posts. Abstract n:o 1442. The 85th general session and exhibition of the International Association for Dental Research (IADR). New Orleans, USA, 2007.

Yang HS, Lang LA, Molina A, Felton DA. The effects of dowel design and load direction on dowel-and-core restorations. J Prosthet Dent 2001;85:558-567.

Yoldas O, Akova T, Uysal H. An experimental analysis of stresses in simulated flared root canals subjected to various post-core applications. J Oral Rehabil 2005;32:427-432.

Yoshida K, Greener EH. Effects of two amine reducing agents on the degree of conversion and physical properties of an unfilled light-cured resin. Dent Mater 1993;9:246-251.

Zalkind M, Hochman N. Esthetic considerations in restoring endodontically treated teeth with posts and cores. J Prosthet Dent 1998;79:702-705.

Zmener O. Adaptation of threaded dowels to dentin. J Prosthet Dent 1980;43:530-535.

ORIGINAL PUBLICATIONS (I-V)