Fibre-reinforced composites in root canal anchoring:

Mechanical requirements, structure and properties of the fibre-reinforced composite

Pekka Vallittu

There has been increased interest in fibre-reinforced composites (FRC) in dentistry. FRC is a material combination of polymer matrix and reinforcing fibres. The fibres of the composite are reinforcing phases when the load is applied to the composite. Load is transferred to be carried by the fibres. The reinforcing fibres can be continuous unidirectional, continuous bidirectional, continuous random oriented of short random oriented fibres. Depending up to the fiber orientation and direction, FRC has different properties. FRCs have been used in removable prosthododontics, fixed partial dentures (FPD), periodontal splints and in orthodontic treatment as a retainer splint[1-4]. Due to appropriate biomechanical properties, the use of FRC in root-canal posts to anchore cores and crowns has rapidly increased. FRC is used in root canal posts as (1) prefabricated posts and (2) individually formed posts.

The prefabricated posts are made of reinforcing fibres (carbon/graphite, glass, quartz) and finally polymerised resin matrix forms a solid post with a predetermined diameter. Individually formed posts are made of non-polymerized fibre-resin prepregs, consisting typically glass fibres and light-curing resin matrix. The rationale of the individually formed FRC post is to fill the space existing in the root canal by FRC material. By this, load-bearing capacity of the system is higher due to high volume fraction of fibres, and biomechanics of a tooth can better be simulated, i.e. the fibers are to located close to the dentine, where highest stresses exist.

Understanding the structure and properties of FRC is required for succesful use of the material. Basically, the clinical success of any FRC device is dependent on adequate strength and design of the construction [5-7]. Strength and rigidity of the construction made from FRC are dependent on the polymer matrix of the FRC and the type of fiber reinforcement. Generally, the factors influencing the properties of FRC are:

- Properties of fibres vs. properties of matrix polymer
- Impregnation of fibres with resin
- Adhesion of fibres to matrix
- Quantity fibres
- Direction (orientation) of fibres
- Location and volume fraction of fibres in construction

In dental appliances of relatively small size, the quality of the FRC is of great importance. From this perspective, all of the aforementioned factors which influence the properties of FRC must be carefully be taken into consideration for clinical success of FRC. This is especially important because the masticatory system produces cyclic loads to the dental appliances. Therefore, not only adequate static strength of the appliance, but also adequate dynamic strength is needed. It should also be noticed that dental constuctions are multiphasic in nature. E.g. FRC reinforced root-canal-post-system consists of dentine, composite resin cement, core build-up composite resin, and, as a load-bearing material there is the FRC root canal post. All of these phases needs to have adequate strength and the phases needs to be adhered well to each others.

Loading conditions, static and dynamic strength

Mastication produces stress in teeth, and the magnitude of the stress varies considerably on the position of a tooth[8]. Significant occlusal forces are not developed until the teeth are in contact. Maximal occlusal forces can be up to 900 N in the molar region in young adults, but chewing forces are considerably lower, from 100 to 300 N. It has been stated in a DIN standard that the FPD as a whole, should withstand more than 1000 N occlusal force in a static fracture resistance test. No standards exist at the moment for root canal posts systems regarding load-bearing capacity. Maximum occlusal stress may be applied 3000 times per day. Therefore, a tooth restored with root canal posts system should be able to withstand cyclic loading of high magnitude for a long period of time without

Pekka K Vallittu, DDS, PhD, CDT, is Professor, Department of Prosthetic Dentistry & Biomaterials Science, Institute of Dentistry, University of Turku, Turku, Finland

Correspondence:
Pekka Vallittu
Institute of Dentistry, University of Turku
Lemminkäisenkatu 2
FIN-20520 Turku, Finland
E-mail: pekka.vallittu@utu.fi
Tel. 358-2-333 8332, Fax. 358-2-333 8390

catastrophic failure or marginal break down of the crown, which can predispose to secondary caries. Material failures are devided to the sudden fractures and fatigue fractures (8). The load-bearing phase of the root canal post system, i.e. the FRC root canal post should withstand the loads and remain the crown margins intact. Sudden fracture occurs when a construction is loaded until it fractures with one bend. In root-canal posts, this can cause fracture of the post, fracture of the root, or loosening of the post-core-crown system. The corresponding type of strength for the one-bend fracture is static strength and it is typically determined by three-point loading test according to the ISO standards for crown and bridge resins and denture base resins.

A fracture can also occur even if the stress is considerably lower than that required for the sudden fracture. Repeated stress cycles cause microscopic cracks mainly in the tension side of the construction and, after a period of time, a number of cracks have increased to such of size that a sudden fracture can occur even with a low stress level. Fatigue strength of the material is defined to be the highest stress that the material can withstand for 10^7 times. In dental applications the force produced by the masticatory system is limited to the known level. Therefore, a modified testing method for determining the fatigue behaviour of dental fibre-reinforced composites was developed instead of using test designs made for engineering applications.[9] One of the reported fatigue testing method was based on bending the test specimen for a constant deflection amplitude until the specimen fractured. The test produced fatigue profiles for the material describing how many loading cycles of a predetermined deflection can be applied to the material before the material fails. Reduction of the force described fatigue of the material. Fatigue strength of materials most commonly used in prosthodontics, cast metal alloys and ceramics, are, paradoxically prone to fatigue failure due to their brittle structure[10-12]. Clinically, the material based weakness is effectively compensated by designing and dimensioning the device, e.g. a cast metal or FRC post-and-core correctly. A group of materials which have high fatigue resistance is FRC with continuous fibres. Correctly oriented fibres behave as crack stoppers and effectively hinder propagation of the fatigue fracture. Recent experimental findings of using FRCs in removable prostheses suggest that the in elimination of the fatigue fracture initiation, the correct location of the fibres in the appliance is important. Correct location for the fibres is on the tension side of the appliance in masticatory function. In root canal post applications, this approach can be taken into consideration by fabricating the individually formed post instead of using prefabricated post.

All of the laboratory testing methods have their limitations. In root canal posts, the fatigue resistance of the material itself overrules the fatigue resistance of the root-canal-post-tooth-system with several adhesive interfaces. Thus, it is recommended that instead of testing pure materials, the restored tooth system should applied the fatigue testing.

The important parameters responsible for the strength of the FRC are impregnation of fibres with resin and the quantity

Table 1: Summary of the possible adhesion mechanisms for composite resin luting cements to the FRC post.

TYPE OF POST	TYPE OF FIBER	TYPE OF POLYMER MATRIX	ADHESION MECHANISM
Prefabricated	Carbon/graphite	Cross-linked	Mechanical
Prefabricated	Glass or quartz	Cross-linked	Mechanical Silane promoted
Individually formed (laboratory made)	UHMWP	Cross-linked	Mechanical
Individually formed (laboratory made)	Glass or quartz	Cross-linked	Mechanical Silane promoted
Individually formed (laboratory made)	Glass	Semi-IPN	Mechanical Silane promoted Secondary IPN
Individually formed (Chair-side made)	UHMWP, Glass	Cross-linked Semi-IPN	Mechanical Silane promoted Secondary IPN Free radical polymerisation

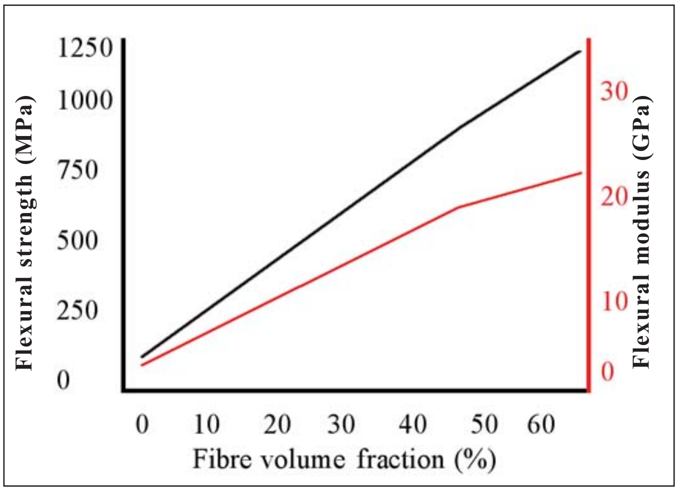

Figure 1. Ultimate flexural strength and modulus of elasticity of unidirectional FRC plotted against the E-glass fibre volume fraction (upper curve: flexural strength; lower curve: flexural modulus) (three-point bending test, span 10 mm).

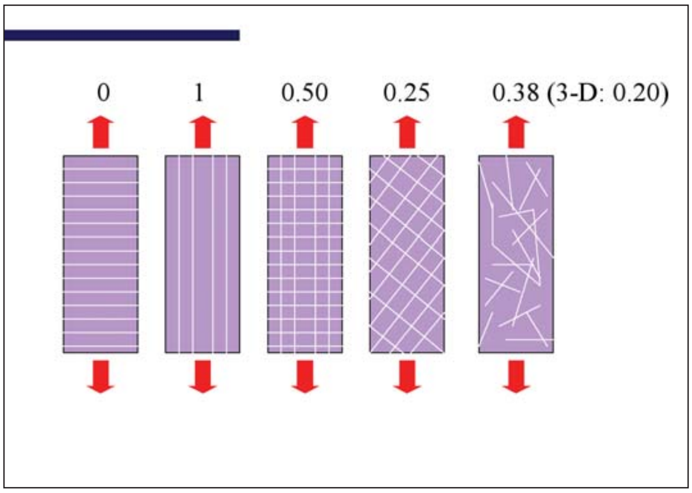

Figure 2. Reinforcing efficiency (Krenchel´s factor) of fibres with different fibre orientation in plane.

of fibres in the polymer matrix. Reinforcing fibres are difficult to impregnate with resin systems of high viscosity [13-15]. Such high viscous resin systems are especially those mixed from polymer powder and monomer liquid which are used in denture bases and provisional FPDs, or with those made of light curing resins and particluate fillers. Also, problems might occur when fibres are tried to impregnate with highly viscous mixture of light polymerizable or autopolymerizing non-filled resins. These, including some of the dimethacrylate monomer systems and epoxy resins, are used in FRC root canal posts. An industrial resin impregnation process for fibres is recommeded to ensure full impregnation of the fibres by the resin. An effective impregnation by the resin monomers allows the resin to come into the contact with the surface of every fibre. If the effective impregnation is not reached due to high viscosity or polymerisation shrinkage of the resin the mechanical properties of FRC do not reach the optimal values which could be calculated.

Fabrication of prefabricated FRC root canal posts is based on impregnation of fibres with various thermoset resins, like dimethacrylate or epoxy resins. Thermoset resins form cross-linked polymer. The use of these resins should enable proper impregnation of fibres. However, there are prefabricated FRC root canal posts on the market which do not entirely fullfil the requirement of complete impregnation, and thus the strength of the post is lower than expected from the constituents[16]. There are also impregnation methods based on using combination of thermoset and thermoplastic type of resins. Thermoplastic resins form non-cross-linked polymer. The resin matrix combination of thermoset and thermoplastic resins of FRC is multiphasic, and it is, by the definition a semi-interpenetrating polymer network (semi-IPN) having dimethacrylate monomers partially diffused into the polymer structure of linear preimpregnation monofunctional polymer[17,18]. In polymerization the dimethacrylate monomers formed cross-linked semi-IPN structure with phases of the linear polymer. In root canal post applications semi-IPN FRCs are used in some individually formed root canal posts.

Differences of the thermoset and thermoplastic (including the semi-IPN matrix) polymer matrix FRCs is in the mechanical properties and surface adhesion toward adhesive resins. Cross-linked polymer matrix forms stiffer FRC than that obtained by thermoplastics or semi-IPN polymers. On the other hand, thermoplastic and semi-IPN polymer matrix FRCs have higher toghness than FRCs made of highly cross-linked thermosets.

The static strength (ultimate flexural strength) of the FRC is linearly dependent on the fibre quantity to the level of approximately 70 vol% . Proper resin impregation method produce FRC material with high fibre quantity and high flexural properties (with E-glass ad 1250 MPa) (Fig. 1). Water sorption of the polymer matrix reduce the strength and modulus of the FRC by approximately 15 % within 30 days water storage time at 37^{O}C. A positive correlation exists between water sorption of polymer matrix and the reduction of flexural properties. The reduction of the flexural properties was reversible, i.e. dehydration of the FRC recovered the mechanical properties[19]. No significant reduction of flexural strength and modulus even in long term water storage (ad 4 years) occurred[20].

The strength of FRC is also dependent on the fibre direction. The efficiency of the fibre reinforcement (Krenchel´s factor) varies in FRC laminates with different fibre orientations (Fig. 2). The continuous unidirectional fibres gives the highest strength and modulus for the FRC but this property is available only in the stress direction equal to that of direction of the fibres. The anisotropic nature of unirectional FRCs is of great importance in designing the FRC appliance such as root canal post – tooth

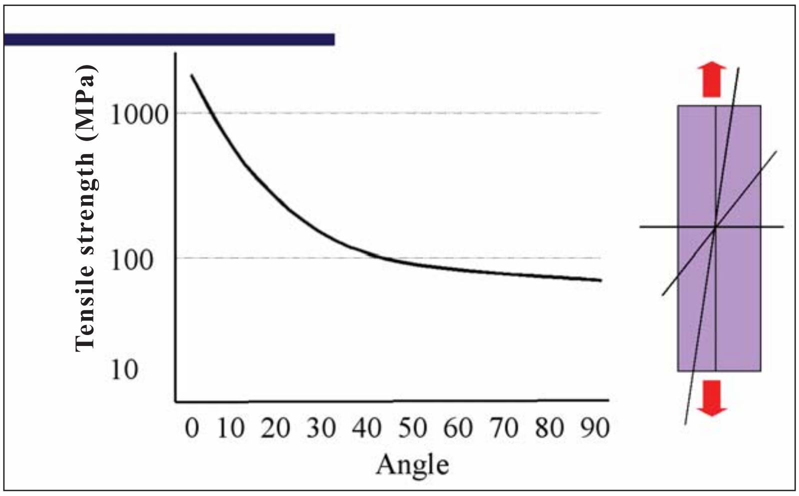

Figure 3. Influence of fibre misalignment (degrees) on the tensile strength of continuous unidirectional FRC.

system. The reinforcing capacity of fibres can be devided into two or more directions and the corresponding FRCs are called orthotropic and isotropic with regard to the mechanical properties. It should be emphasized that even small fibre misalignment greatly influence the properties of unidirectional FRC (Fig. 3).

The variation of the fibre reinforcement type from continuous unidirectional (fibre bundle) to the continuous bi-directional (fibre weave) makes also a substantial difference in the stress-strain diagram of the material. Figure 4 shows the variation of high strength-high modulus unidirectional FRC to high toughness FRC with bi-directional fibres. This allows combination of various mechanical properties to the same construction. E.g. the pontic of FPD, or root canal post, where high strength and adequate rigidity is needed can be reinforced with continuous unidirectional fibres, and crown margins, where toughness is needed, can be reinforced with woven (bi-directional) fibres. For a comparison, Figure 4 also shows that the conventional prosthetic materials of metal alloys and ceramics are brittle and cannot be tailor-made to have high strength-high modulus and high toughness-low modulus properties in the same appliance, as can be made with FRCs.

Test design of FRC specimens of small dimensions, such as root canal posts can cause misleading results. It is known that the commonly used mathematical formulas to calculate flexural strength and modulus of elasticity of root canal posts are highly dependent up to the diameter of the post and span length.[21] With a constant span length, thinner posts reveal higher flexural strength and modulusof elasticity values than obatained with posts of the same material but smaller diameter. Thus, only the strength values of posts of exactly the same diameter and span length in test set-up are comparable.

Fatigue profiles of cobalt-chromium alloy and continuous unidirectional urethanedimethacrylate – E-glass FRC is presented in Figure 5. The profiles show that cobalt-chromium alloy bar fractures due to the fatigue at certain number of loading cycles, whereas the FRC bar did not fracture in the same test set-up. The profiles also show that the rigidity, i.e. modulus of elasticity of the FRC bar is lower than that of cobalt-chromium bar. The modulus of elasticity of continuous FRC is at the same range than that of dentine.

INTERFACIAL ADHESION

Adhesion of particulate filler composite (PFC) resin luting cement or core build-up composite to the FRC post of the system plays an important role for the load transfer from crown to root and jaw bone. The FRC post as a bonding substrate contains different types of materials from polymers to inorganic glass fibre fillers (Fig. 6). Internal adhesion of the FRC influencing "the cohesional" strength of the FRC is based on bonding the fibres to the matrix polymer. In this respect, the most suitable fibres are glass and silica fibres which can be silanated for the adequate adhesion to the polymer matrix [22,23]. Less suitable fibres are ultra-high molecular weight polyethylene fibres (UHMWP) which have been proved to be

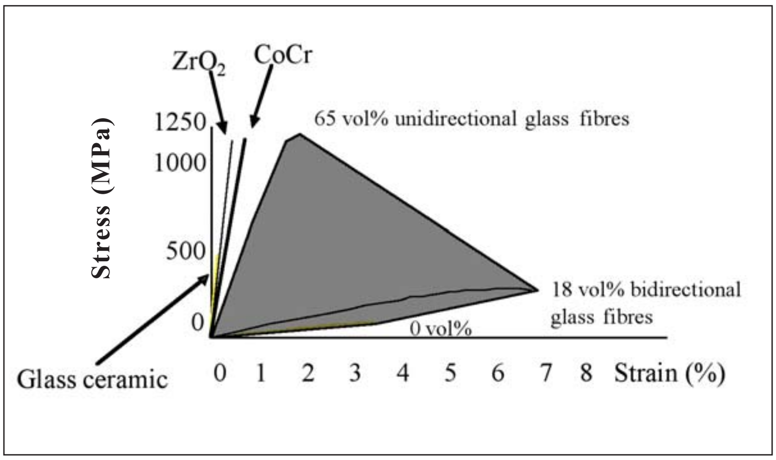

Figure 4. Stress-strain curve for FRC with unidirectional and bi-directional fibres, and for conventional prosthetic materials (cobalt-chromium alloy, zirconium oxide, Empress 2 type glass ceramic).

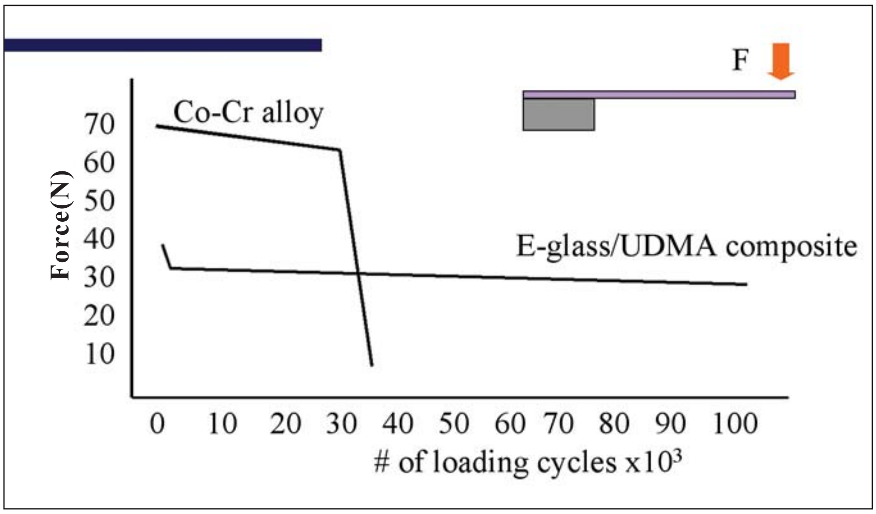

Figure 5. Fatigue profiles from constant deflection fatigue test for cobalt-chromium alloy and continuous unidirectional E-glass-FRC bar.

difficult to adhere to resins even though the fibre surface has been treated with e.g. various types of plasma treatments [24,25]. However, also UHMWP fibers have succesfully used in root canal post applications when high FRC volume in the root canal compensated the effect of weak interfacial adhesion of UHMWP fibres to the polymer matrix. If the fibres of the FRC are exposed on the bonding surface of the FRC, like is the case when prefabricated FRC posts as cemented, the adhesional properties of the fibres it selves play a role in adhering the adhesive resin and composite resin luting cement to the FRC: glass fibres can be adhered to PFR by silanation. Problems may occur with other typeas of fibres. Beside of the adhesive properties of reinforcing fibres itselves, the polymer matrix plays an important role. Due to cross-linked nature of the polymer matrix of the most of the prefabricated FRC posts, there are only two possibilities to get adhesion of the cement to the post. These are mechanical interlocking, and, in the case of glass or quartz fibres, the bonding cn be based on using silane coupling agents. Many of the FRC posts of prefabricated type are serrated for increasing macroscopic mechanical retention to the luting cement and core-built-up composites. If the post contains non-cross linked phases, i.e. they are made of thermoplastics or semi-IPN polymers, the adhesion of the

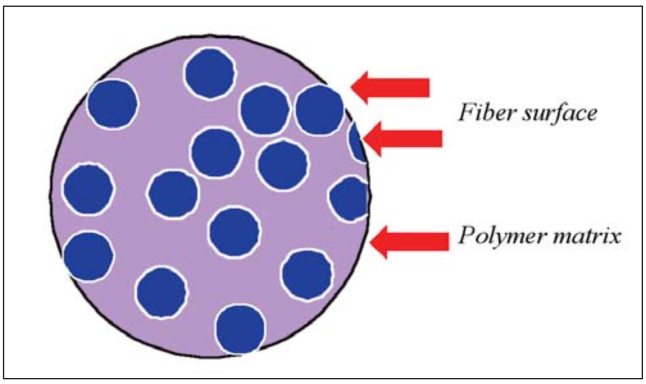

Figure 6. Cross-sectional structure of FRC post showing the multiphasic nature of FRC as an adhesional substrate.

luting cement can also be based on diffusion of monomers of the cement into to the non-cross-linked polymer matrix. In polymerisation of the cement, a bond based on a secondary semi-IPN structure is formed. A typical example of the secondary semi-IPN structure is found in repairs of fractured denture bases by the repair acrylic resin. The repair acrylic resin monomers dissolves the surface and forms durable secondary semi-IPN structure. The function of secondary semi-IPN structures to bond composite resin luting cement to individually formed FRC post has been reported recently[26,27].

Adhesion of a chair-side made individually formed posts differs to that of prefabricated FRC posts. It is known that in polymerisation of the FRC post in air, a non-polymerised surface layer, called oxygen inhibited layer will remain on the surface. Resin cements can adhere to this layer by free radical polymerization of the composite resin luting cement and for a durable bond.

REFERENCES

1. Körber HK, Körber S. Experimentelle Untersuchungen zur Passgenauigkeit con GFK-Bruckengerusten "Vectris". Quintessenz Zahntech 1998;24:43-53.

2. Behr M, Rosentritt M, Lang R, Handel G. Flexural properties of fiber reinforced composite using a vacuum/pressure or a manual adapatation manufacturing process. J Dent 2000;28:509-514.

3. Vallittu PK. Glass fiber reinforcement in repaired acrylic resin removable dentures: preliminary results of a clinical study. Quintessence Int 1997;28:39-44.

4. Friskopp J, Blomlof L. Intermediate fibreglass splints. J Prosthet Dent 1984;51:334-337.

5. Gegauff AG, Pryor HG. Fracture toughness of provisional resins for fixed prosthodontics. J Prosthet Dent 1987:58:23-29.

6. Osman YI, Owen CP. Flexural strength of provisional restorative materials. J Prosthet Dent 1993;70:94-96.

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

8. Vallittu PK, Könönen M. Biomechanical aspects and material properties. In: A textbook of fixed prosthodontics. A Scandinavian

approach. Karlsson S, Nilner K, Dahl BL (eds). Gothia, Stockholm, Sweden, 116 –130.

9. Vallittu PK. Fatigue resistance and stress of wrought-steel wire clasps. J Prosthod 1996;5:186-192.

10. Oh S-A, Dong J-K, Luthy H, Schärer P. Strength and microstructure of IPS Empress 2 glass ceramic after different treatments. Int J Prosthodont 2000;13:468-472.

11. Kelly JR, Nishimura I, Campbell SD. Ceramics in dentistry: Historical roots and current perspectives. J Prosthet Dent 1996;18:18-32.

12. White SN, Zhao XY, Yu Z, Li ZC. Cyclic mechanical fatigue of feldspathic dental porcelain. Int J Prosthodont 1995;8:413-420.

13. Vallittu PK. The effect of void space and polymerisation time on transverse strength of acrylic-glass fiber composite. J Oral Rehabil 1995;22:257-261.

14. Vallittu PK. Impregnation of glass fibers with polymethylmethacrylate using powder-coating method. Appl Composite Mater 1995;2:51-58.

15. Vallittu PK. Oxygen inhibition of autopolymerization of polymethylmethacrylate-glass fiber composite. J Mater Sci Mater Med 1997;8:489-92.

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

17. Sperling LH. Over view of IPNs. Interpenetrating polymer networks. Klempner D, Sperling LH, Utracti LA (eds.). Advances in chemistry series; 239, American Chemical Society, Washington, DC 1994; 4-6.

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

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

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

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

22. Rosen MR. From treating solution to filler surface and beyond. The life history of a silane coupling agent. J Coat Technol 1978;50:70-82.

23. Matinlinna JP, Areva S, Lassila LVJ, Vallittu PK. Characterization of siloxane films on titanium substrate derived from three aminosilanes. Surf Interfacial Anal 2004;36:1314-1322.

24. Vallittu PK. Ultra-high-modulus polyethylene ribbon as reinforcement for denture polymethyl methcarylate. A short communication. Dent Mater 1997:13:381-382.

25. Takagi K, Fujimatsu H, Usami H, Ogasawara S. Adhesion between high strength and high modulus polyethylene fibers by use of polyethylene gel as an adhesive. J Adhesion Sci Technol 1996;9:869-882.

26. Mannocci F, Sheriff M, Watson TF, Vallittu PK. Penetration of bonding resins into fiber posts: a confocal microscopic study. Endodont J 2005;38:46-51.

27. LeBell A-M, Tanner J, Lassila LVJ, Kangasniemi I, Vallittu PK. Bonding of composite resin luting cement to fibre-reinforced composite root canal post. J Adhesive Dent, in press