Fatigue resistance and structural integrity of fiber posts: three-point bending test and SEM evaluation

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Abstract

Objectives: Aim of the present study was to assess the fatigue resistance of different types of fiber posts, and to observe their ultrastructure through scanning electron microscopy (SEM) before and after undergoing the fatigue test.

Methods: Eight types of fiber posts were selected for this study. Exp. GC fiber post (Group 1), Para Post Fiber White (Group 2), FibreKor (Group 3), DT Light-Post radiopaque (Group 4), FRC Postec (Group 5), Luscent Anchors (Group 6). Ten out of fifteen posts in each group were used for the fatigue test, and the other five were processed for SEM. A three-point bending machine, loading at an angle of 90° and a frequency of 3 Hz was employed for fatigue testing. The test was carried out until 2 million cycles were completed or fracturing of the post, fractured. SEM evaluation was performed using a 3-step scale method to assess the fiber/resin ratio and fibers dimension.

Results: The fatigue test showed statistically significant differences among the different posts. Groups 1, and 5 performed better than all the other groups, withstanding the entire load cycles. All the other posts fractured before the end of the test. SEM observations of the surface integrity of the fiber posts showed that Groups 1, 4, and 5 obtained better scores for both longitudinal sections and the cross sections.

Significance: There is a large variation of different kinds of fiber posts in response to a fatigue resistance test. The absence of correlation between the results of fatigue testing and parameters of structural integrity suggests that the latter reflects more of the divergence in the manufacturing process of fiber posts.

Keywords: fiber post, fatigue test, SEM.

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Introduction

Over the recent years a rapid development has occurred in the area of fiber posts. The introduction of carbon fiber posts in 1990[1] provided the dental profession with the first true alternative to metal posts, either cast or prefabricated. The material had an elastic modulus much closer to dentin than that of any metal post[2], and the clinical trials performed on fiber posts yielded convincing results[3,4,5,6,7,8]. However, the first produced posts had some limitations to their universal use, as they were radiolucent and difficult to mask under all-ceramic or composite restorations[9]. Later, radiopaque fiber posts were obtained, and more esthetic posts were made. These improvements brought about a drastic change in the acceptance of fiber posts by the dental profession.

As a consequence of practitioners finding esthetic fiber posts a viable alternative to metal posts[10], a number of different fiber posts were quickly introduced into the market. Many studies are available on the adhesion of fiber posts to root canal substrates[11,12,13], on the different luting procedures[14,15] and the abutment build-up[16,17,18], and all of them demonstrate the quality performances of fiber posts[19,20].

The rapid influx of these new esthetic fiber posts has imposed the need for a systematic evaluation of their mechanical properties and clinical performances. For that purpose, scanning electron microscopy (SEM) and fatigue test can provide an indication of what type of post would perform better under clinical conditions. Also, SEM observations can be useful to assess the fiber/resin matrix ratio, as well as the fibers diameter and the global integrity of the posts.

Fatigue is considered as one of the main causes of structural failure in restorative dentistry[21,22,23,24]. It has been reported that dental restorations fail much more frequently under cyclic loading that are well below the ultimate flexural strength of these materials, than for the application of a single, relatively high force[25]. Fatigue tests can reveal the resistence level of each type of post under a cyclic loading that simulates the normal occlusal and masticatory function[16,26,27].

Since fiber posts are in essence composite materials, it seems logical to expect that their mechanical properties would increase as a result of an increased fibers content.

The objectives of the present study were to assess the fatigue resistance of one experimental post (GC; Tokyo, Japan) compared to different types of fiber posts, and to get an

Table I. This table shows the structural characteristics of the 6 groups of tested posts

Group Number	Type of post	Post diameter (mm)	Fiber diameter (_m)	Fiber density (number of fibers per mm²)	Surface occupied by fibers per square millimeter of post surface (m/mm²)
Group 1	**Experimental GC Post**	2.0	12	33	380
Group 2	**Para Post Fiber White**	1.5	6	18	110
Group 3	**FibreKor**	1.5	18	28	505
Group 4	**DT Light-post radiopaque**	2.0	12	32	390
Group 5	**FRC Postec**	2.0	12	25	300
Group 6	**Luscent Anchors**	1.7	15	29	195

insight of their ultrastructure through scanning electron microscopy observations. The null hypotheses tested were: 1. there is no difference in the structural integrity and in the fiber/resin ratio of the posts and 1. there is no difference in the fatigue resistance among different kinds of fiber posts.

Materials and Methods

Six types of esthetic posts were selected for this study (Table I) They were Experimental fiber post (GC, Tokyo, Jaoan; Group 1, pre-tensioned glass fibers), Para Post Fiber White (Coltene/Whaledent, Mawhaw, NJ, USA; Group 2, glass fibers), FibreKor (Jeneric/Pentron, Wallingsford, CT, USA; Group 3, glass fibers), DT Light-Post radiopaque (RTD, Grenoble, France; Group 4, pre-tensioned glass fibers), FRC Postec (Ivoclar-Vivadent, Schaan, Liechtenstein; Group 5, glass fibers), Luscent Anchors (Dentatus, New York, NY, USA; Group 6, glass fibers). From each group fifteen posts of the largest available size (Table I) were collected. The size of the post in the different groups varied from 1.5 mm to 2.0 mm. Ten of them, randomly chosen, were used for fatigue test, whereas the other five were processed for microscopic evaluation.

SEM evaluation

Each post was cross-sectioned into two halves using a diamond saw (Isomet, Buehler, Lake Bluff, NY). One half was used for the observation of the surface exposed by the cross-sectional cut, whereas the other half was again sectioned longitudinally (with the same diamod saw described above), in order to examine the fibers along their longitudinal axes. The external surface of this half of each sectioned fiber post was also examined. The specimens were mounted on metallic stubs, and sputtered with gold in a Balzers device (Balzers Ltd., London, Great Britain). Then the specimens were analyzed under a scanning electron microscope (Philips 505, Eindoveen, The Netherlands), and microphotographs were taken for documenting the morphologic characteristics of posts. The diameter of the fibers, the number of fibers per mm², and the surface occupied by fibers per square millimeter of post surface were measured. Three micrographs were taken for evaluating each post, and the result was obtained calculating the mean of the score assigned to the three single micrographs. Also, the presence of voids/bubbles within the post and on its outer surface was assessed and expressed through a score system, which was thus defined (Table II): 0 = no voids or bubbles are visible; 1 = micro voids or bubbles can be detected (diameter < 20 microns); 2 = voids or bubbles (diameter > 20 microns) are evident and/or fiber detachments due to a loose bond with the resin matrix. The scoring method allowed for a quantitative evaluation of the structural integrity of the posts, as well as for a statistical evaluation of the differences among the various types of post. SEM scores were assigned by two different operators, who separately examined the micrographs taken from the specimens. In case of disagreement between the two investigators on the score assigned to a specimen, the worse

Table II. The score method meant to quantify the structural integrity of posts, as assessed under the scanning electron microscope.

Score 0	Score 1	Score 2
No voids/bubbles	Micro voids/bubbles (diameter < 20 microns)	Voids/bubbles (diameter > 20 microns) and/or fiber detachment

Fig. 1. The post ready to be tested.

score was chosen for the statistical analysis. The observations were repeated twice to verify the interexaminer reliability. The differences in the scores recorded for the eight groups of posts were tested for statistical significance with the Kruskall Wallis ANOVA by ranks, followed by the Mann-Whitney U test for multiple comparisons. The level of statistical significance was set at p<0.05.

Fatigue test

Ten posts from each group were tested in a fatigue machine (Procyon systemes, France). This device has a counter that measures the number of cycles and stops when the specimen breaks (Fig. 1). The three-point bending method of loading was applied, with a loading angle of 90° at a frequency of 3Hz. As the posts in the eight groups had different diameters, a calculation was done to establish the load to be applied on the different posts, according to the diameter itself (appendix 1). The two supports and the punch had a 3-mm diameter, and the distance between the two supports was 9 mm. All the tests were carried out at a room temperature of approximately 22°C. The machine was set to carry out 2,000,000 cycles, the assumption being that, as teeth normally come into contact once a minute, this number of cycles would simulate about four years of physiologic occlusal and masticatory activity[5,7].

For those fiber posts that failed prior to reaching the projected cycles, the actual number of resisted cycles as counted by the fatigue machine was recorded. The differences among the tested posts in the number of resisted cycles were tested for statistical significance with the One-Way ANOVA, followed by the Bonferroni test for multiple comparisons. The level of significance was set at p<0.05.

At the completion of the fatigue test, the posts were processed for a SEM evaluation, which was aimed at verifying whether any changes had occurred in the structure of the post as a result of loading. The detected modifications were documented through microphotographs.

Correlation analyses

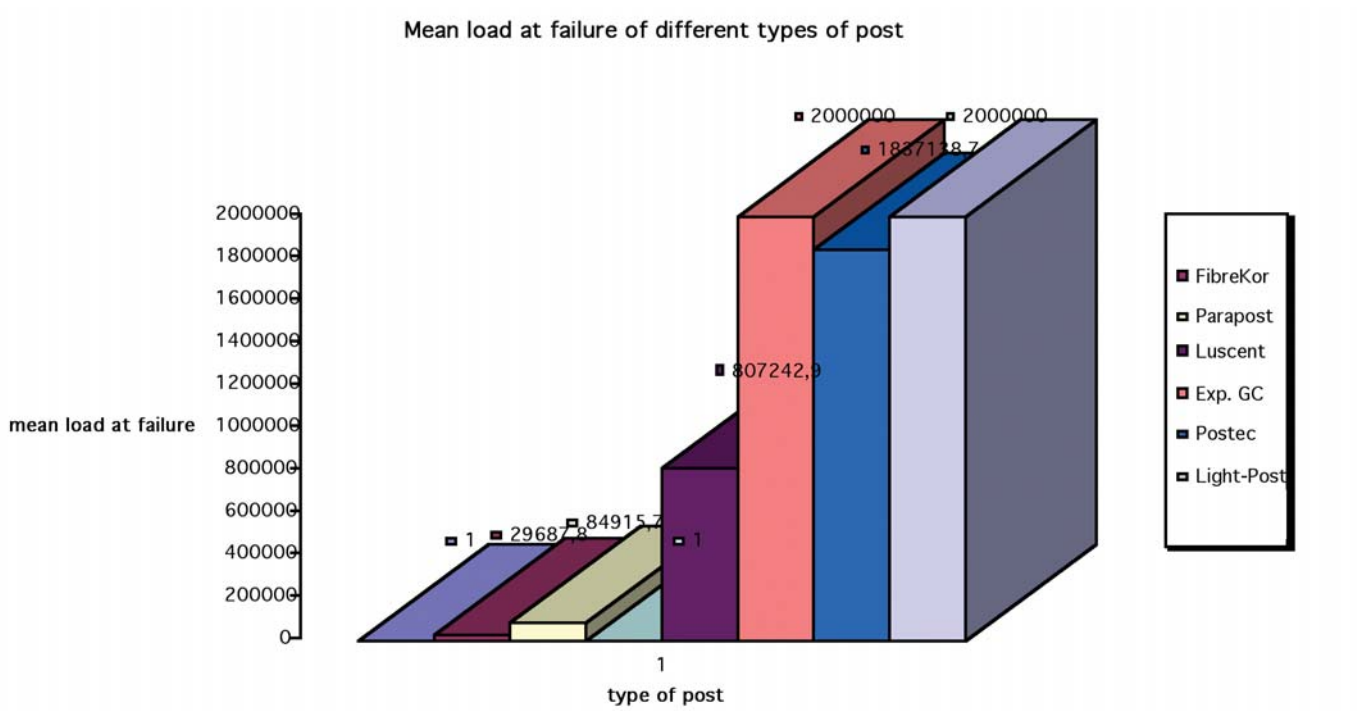
A further objective of the investigation was to verify the existence of a correlation between the fatigue resistance exhibited by the different types of posts and their structural characteristics, namely fiber diameter, fiber density, and the surface occupied by fibers per square millimetre of post surface. For that purpose, the strength of the correlation between the number of resisted cycles and each one of the mentioned structural variables of the posts was measured by

Table III. Mean and standard deviation of the number of cycles that each type of post proved able to withstand before breaking.

Group number	Type of post	Mean number of resisted cycles	Standard deviation
Group 1	***Experimental GC fiber post***	2.000.000	0
Group 2	***Para Post Fiber White***	84.915,7	106039
Group 3	***FibreKor***	29.687,8	24327,5
Group 4	***DT Light-post radiopaque***	2.000.000	0
Group 5	***FRC Postec***	1.837.138,7	371.387
Group 6	***Luscent Anchors***	807.242,9	2.008

Fig. 2. Graph representing the mean number of cycles that each type of post was able to resist before failing. Columns underlined by the same line represent groups which gave statistically similar results. In the table, the star sign indicates that the difference between the groups was statistically significant. The minus sign indicates that the difference between the two mean values was negative.

Para Post, FibreKor,	*vs*	* (-)Light-post, Postec, Exp.GC post, Luscent Anchors
Luscent Anchors	*vs*	* (-)Light-post, Postec, Ex. GC post * FibreKor, Para Post
FRC Postec, DT Light-post, Exp. GC post	*vs*	* FibreKor, Para Post, Luscent



calculating the Pearson's correlation coefficients. The statistical significance of the correlations was also assessed (p<0.05).

Results

Fatigue tests

Table III reports mean and standard deviation of the number of cycles that the different types of posts were able to withstand before breaking. The results of the statistical analysis performed on these data are summarized in Figure 2.

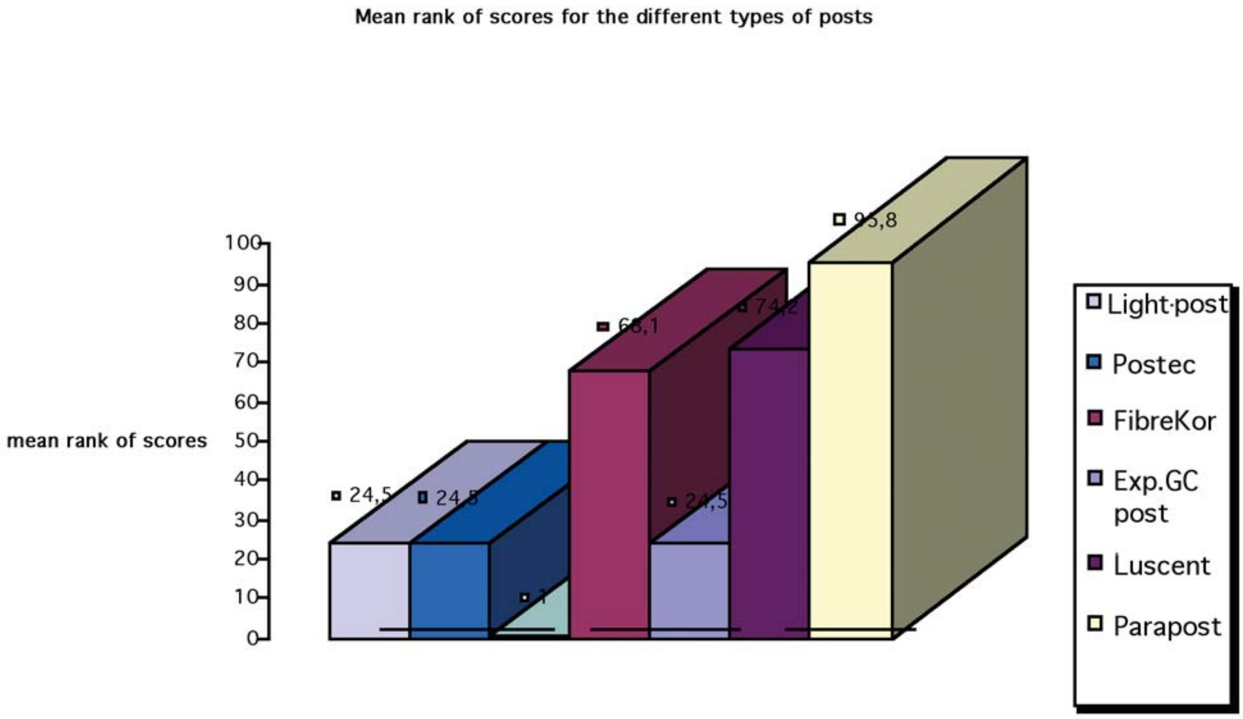
The highest resistance to cyclic loads was exhibited by the Experimental GC post and DT Light-post group (Group 1 and 4), followed by the FRC Postec group (Group 6). None of the specimens from the Experimental GC post and DT Light-Post group was broken after two million cycles, whereas among the FRC Postec posts only one failure occurred. From a statistical standpoint the results given by these three groups were similar (Fig. 2).

On the other hand, FibreKor, Luscent and Para Post (Groups

Table IV. Mean and standard deviation of the number of cycles that each type of post proved able to withstand before breaking.

Group number	Type of post	Scores		
		Cross section of the post	Longitudinal section of the post	External surface of the post
Group 1	*Experimental GC fiber post*	0	0	0
Group 2	*Para Post Fiber White*	2	2	1
Group 3	*FibreKor*	0	1	1
Group 4	*DT Light-post radiopaque*	0	0	0
Group 5	*FRC Postec*	0	0	0
Group 6	*Luscent Anchors*	1	2	1

Fig 3. **Fig. 3** Mean of the ranks that the statistical analysis (Kruskall Wallis test) assigned to the scores of each group of posts. The columns underlined by the same line represent groups of post that recorded statistically similar scores.



3, 6 and 2 respectively) showed fatigue resistance that were significantly lower than that of any other tested post (Fig. 2).

Structural integrity

The scores assigned to the different types of posts in order to quantify their structural integrity, as revealed by SEM observations, are summarized in Table IV. The specimens from the Para Post, and Luscent groups (Groups 2, and 6 respectively) exhibited voids and/or bubbles within the post structure on both the cross and the longitudinal sections. The Para Post group recorded scores significantly higher than those of any other type of post ($p<0.05$; Fig. 3). Only on the specimens from DT Light-post (Group 5), FRC Postec (Group 6), and Experimental GC post (Group 1) were no structural defects visible either on the cross and longitudinal sections or on the outer surface of the post. The scores assigned to these three types of posts were significantly lower than those of any other group ($p<0.05$; Fig. 3).

When the posts that were fractured after load cycling were observed under the SEM, their lost of structural integrity was evident (Fig 4). On the other hand, the DT Light-post, Experimental GC post and the FRC Postec posts, which were able to withstand the fatigue test, exhibited only a small circumferential depression in the area of contact of the loading punch (Fig 5).

Correlation analyses

The data expressing the strength of the correlation between fatigue resistance and structural characteristics of the posts are summarized in Table V. No correlation was found to be statistically significant ($p>0.05$).

Discussion

Fiber-reinforced materials, as composite materials, owe their mechanical properties not only to the characteristics of fibers and matrix, but also to the strength of the bond at the interface between these components and to the geometry of reinforcement. The addition of fibers to a polymer matrix leads to a significant increment in fracture toughness, stiffness, and fatigue resistance of the material. In the fabrication of endodontic posts, glass, quartz, carbon, and ceramic fibers have been used[2,10,28].

The posts produced by GC, RTD and Ivoclar-Vivadent contain silanized glass fibers and an epoxy resin. In particular, during the manufacturing process of GC and RTD posts, the fibers are placed in tension and then soaked in a resin, which is finally polymerized. On the final cure of the resin, the tension in the fibers is released and, as a result, the resin surface is placed under compression. For this reason, when the post is subjected to a flexural force, the tensile stresses which are introduced can easily be absorbed. For the Ivoclar-Vivadent posts, they are made using the Vectris technology[29]. The methods of fabrication of Experimental GC post, DT Light-post and FRC Postec can provide an explanation for the significantly higher resistance to fracture under cyclic bending forces demonstrated by the mentioned types of posts in the present study. Unfortunately manufacturers do not declare the modulus of elasticity of the resin employed as the resin matrices of these posts: it could eventually play an important role in the determination of the fatigue resistance of the post. Another important factor is whether the fibers are silanized prior to embedding in the resin matrices: in particular, it can affect both the resistance of these fiber posts to the fatigue tests as well as the structural integrity of these posts. Actually

Table V. Strength and statistical significance of the correlation between posts' fatigue resistance and their structural characteristics.

Variable	Variable			
		Fibers diameter	***Fibers density***	***Surface occupied by fibers per square millimeter of post surface***
Mean number of resisted cycles	Pearson's correlation coefficient	r = 0.128	r = 0.028	r = 0.112
	Statistical significance	p = 0.257	p = 0.806	p = 0.322

a good interfacial bonding can ensure load transfer from the matrix to the reinforcement, and is a primary requirement for effective use of reinforcement properties. In his scholar thesis Gu[30] states that '…a fundamental understanding of interfacial properties and a quantitative characterization of interfacial adhesion strength can help in evaluating the mechanical behavior and capabilities of composite materials…'.

During daily normal occlusal and masticatory function, both the natural and the restored teeth are subjected to a number of cyclic loads. The failure due to fatigue stress is a phenomenon of paramount importance from a clinical standpoint [19,20,21]. In the explanation of the occurrence of this type of failure, it is assumed that failure commences from a small structural defect within the material. From this area of weakness, as a result of the cyclic functional loading, a line of fracture can gradually propagate through the material, finally resulting in catastrophic failure[31]. Potential areas of weakness in a fiber-reinforced post can be seen in the voids present within the resin or in the discontinuities along the interfaces between fibers and matrix. Thus, a solid (with fibers evenly distributed) structure of the fiber-reinforced posts seems to be critical for their clinical success.

Areas of potential weakness are also considered those where the section of the post has an abrupt change[22]. For this reason, the addition of a notch on the post for retention's purposes does not seem to do well to the post's fatigue resistance. The SEM observation of posts that fractured under load showed how their structure was altered by the fatigue stress.

In the fatigue test, as in a repeated masticatory action, the load varies between a minimum (Kmin) and a maximum (Kmax). Theoretically the moment in which a rapid fracture occurs has to be related to the Kmax value. On the other hand, the difference between the maximum and the minimum values (K) corresponds to the cyclic dissipation of stress energy, and tells us more about fatiguing phenomenon. Anyhow the two different values (Kmax and K) combined give us an important information, and are likely to be simulating what really happens in the mouth.[32]

In the present study a load ranging from 20 to 100 Newtons was applied at a 3 Hz frequency . With the 20-Newton force the loading unit was kept in stable contact with the specimen. As regards the highest level force, usually in fatigue tests this does not exceed the fifty percent of the ultimate strength of the material on trial[17]. This criterion was applied also in the

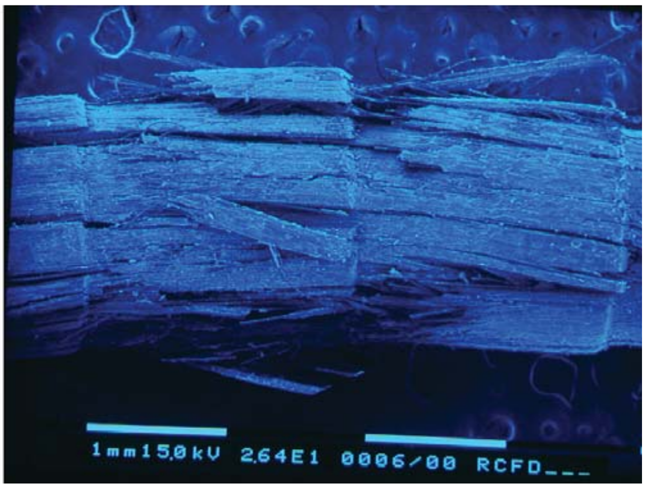


Fig. 4 A sample from group 3. The fatigue test caused the breaking of the post.

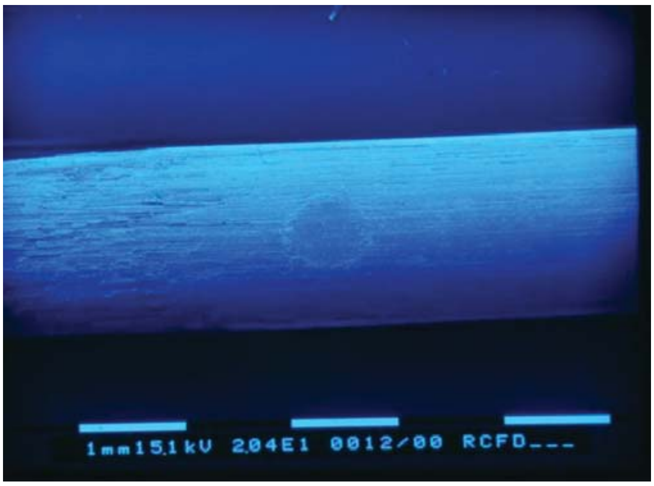


Fig. 5 Group 4 sample. After 2.000.000 cycles the post is still unbroken. The point where the loading punch worked is evident.

present study, and the results showed that specimen failure could occur when a cyclic force as low as one half of the material's ultimate strength was exerted.

With respect to the number of cycles that is applied in order to simulate fatigue, Wiskott et al.[32] have indicated that this should be at least one million cycles. In the present study, a maximum of two millions cycles was applied, with the intention of simulating about four years of normal occlusal and masticatory activity[5,7]. It should be pointed out that the cyclic fatigue test, as it was performed in this trial, most likely exposed the specimens to higher tensile stresses than those actually transmitted to an endodontic post cemented inside a root, as failure of the bonded cement could have occurred prior to post fracture. For this, in order to have a fatigue resistance appraisal that can be closer to the clinical reality, the same study should be repeated on roots with cemented posts instead of just posts. This requires a completely different study design that does not involve three-point bending test. From a statistical standpoint, Groups 1, 4 and 5 showed better results than all the other groups. Due to physical considerations, any fiber direction diverging from the longitudinal axis of the post results in a stress transmission to the matrix. For this reason, posts with parallel fibers should, at least theoretically, withstand loads more efficiently than posts containing obliquely-oriented fibers.

The stress acts on the matrix particularly when a compressive force is exerted on the post or when the forces are directed obliquely or diagonally to the post's longitudinal axis. The high stresses on the fiber/resin interface are responsible for a gradual inelastic behaviour, which occurs as a consequence of interface detachment between the fibers and the matrix. Also plastic deformation of the matrix and resin microcracking occur. Such stresses are minimum in the equidistant areas of the fibers, and maximum immediately next to the same fibers [33].

Since fibers represent the stiffer component in a post, as compared with the resin matrix, the posts that exhibit a higher fiber density (Figure 4) would be expected to yield a greater fracture resistance than those presenting with a less amount of fibers (Figure 5)[28].

Recently, DT Light-post and FRC Postec fiber posts have also been clinically evaluated. Prospective clinical trials have shown that with FRC Postec posts and DT translucent posts, neither a post nor a root fracture has occurred over a two-year period of clinical service. These data support the clinical use of translucent fiber posts for the restoration of endodontically treated teeth[3,4,5,6,7,8]. As regards the other types of posts tested in this trial, no data are yet available on their clinical performance. However, noting the mechanical and structural characteristics of group 1 samples (exp. GC post) it can be aspected that they will work properly when used under clinical conditions too.

In this study thermal cycling was not performed. Several studies[10] have shown that as a result of thermal variations, the fibers from certain types of fiber posts may be detached from the adjacent resin matrices. In addition, if the fibers and the resin components have different thermal expansion coefficients, the flexural strength of the post can be negatively affected. This aspect can be clinically important, as temperature changes are normally occurring in the oral cavity.

The three types of posts that most efficiently held the fatigue stress, Exp. GC post, DT Lightpost and FRC Postec, were also among those that exhibited the highest structural homogeneity on microscopic evaluation. The other posts showed different degrees of structural defects and a limited survival to fatigue loading.

The adhesion between the fiber and the resin matrix may be important to understand the quality of the post itself. As it is a variable that is difficult to measure, the strength of these bonds can only be speculated by examining the results of the fatigue test, the SEM scores regarding structural integrity and the SEM images of the fractured posts. In some cases catastrophic failures were evident, with fibers spread over and no link between the fibers and the resin matrix (Fig 4 and 5).

Regarding the fracture mode of the post, it is speculated that when failure commences under compression the more brittle fibers break due to variability in individual fiber surface defects. This leads to interfacial slip between the broken fiber and the matrix, and consequently stress magnification in the adjacent fibers. As the interfacial bond is probably still effective, tensile stress in the broken fiber along the bond transfer length will gradually build-up. If the bond strength is exceeded, delamination of the fiber from the matrix will commence and propagate[33]. With interfacial bond lost progressive fiber fracture will occur leading to overall catastrophic failure. Further detailed fractographic analysis should be performed to validate the results of this study.

Given the results of this study, Exp. GC post, DT Light-post and FRC Postec can be expected to function efficiently in their ability to resist fatigue stresses. This factor adds to the reliability of these materials when used clinically for the restoration of endodontically treated teeth.

Conclusions

Both the tested null hypotheses were rejected. The ultrastructural variation in fiber posts probably reflects differences employed in the manufacturing process. Different kinds of fiber posts give different results when they undergo a fatigue resistance test. A correspondence existed between fatigue test and structural integrity of the post.

APPENDIX 1. Load applied according to the diameter of post

$$\delta = \frac{8 \times F \times l}{\pi \times d^3}$$

δ = stress (N / mm² = MPa)

F = load or force (Newton)

l = span (mm)

d = diameter (mm)

Load applied according to the diameter of post

$$F = \frac{\delta \times \pi \times d^3}{8 \times l}$$

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