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Mechanical properties of glass fiber-reinforced endodontic posts

Nicolas Cheleux [a], Patrick J. Sharrock [b,*]

[a] *Faculty of Odontology, Paul Sabatier University of Toulouse, 3 chemin des Maraîchers, 31062 Toulouse, France*
[b] *LERISM, Paul Sabatier University of Toulouse, Castres Institute of Technology, Avenue Pompidou, Castres 81104, France*

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Abstract

Five types of posts from three different manufacturers (RTD, France, Carbotech, France and Ivoclar-Vivadent, Liechenstein) were subjected to three-point bending tests in order to obtain fatigue results, flexural strength and modulus. Transverse and longitudinal polished sections were examined by scanning electron microscopy and evaluated by computer-assisted image analysis. Physical parameters, including volume % of fibers, their dispersion index and coordination number, were calculated and correlated with mechanical properties. The weaker posts showed more fiber dispersion, higher resin contents, larger numbers of visible defects and reduced fatigue resistance. The flexural strength was inversely correlated with fiber diameter and the flexural modulus was weakly related to coordination number, volume % of fibers and dispersion index. The interfacial adhesion between the silica fibers and the resin matrix was observed to be of paramount importance.

Keywords: Composites; Endodontic posts; Glass fibers; Mechanical strength

1. Introduction

Wide acceptance of endodontic posts for dental root reconstructions has led to the development of new esthetic fiber posts. Practitioners have shifted from the original carbon fiber posts first described in 1990 [1] to more transparent posts reinforced with quartz, glass or silica–zirconium fibers. Different resins and manufacturing processes are used to produce fiber-reinforced posts, but unfortunately little information is available on these new materials. Previous investigations have focused on the mechanical properties [2–7], including fatigue resistance [8,9] and the influence of thermal cycling [10]. Grandini reported large variations in the response of fiber posts to a fatigue resistance test, but could not find any correlation with the observed structural characteristics [9]. Theoretically, the integrity of composite materials depends on the choice of proper matrix and fiber material combination as well as the geometry of the reinforcement and the interfacial strength and homogeneity of the final product [11,12]. Masticatory loads are transferred from the crown to the root through the core-post assembly. Endodontic posts with small diameter need high strength and modulus of elasticity to function properly in vivo [3].

In this work the in vitro flexural properties and fatigue resistance of different fiber post materials were studied and their structural characteristics observed by scanning electron microscopy (SEM) on transverse and longitudinal sections followed by computer-aided image analysis. The working hypothesis was that there exists a straightforward correlation between mechanical strength and fiber density in fiber-reinforced posts.

2. Materials and methods

2.1. Mechanical testing

Experimental posts of identical structure and composition as those in clinical use were specially made for this study by their respective manufacturers using their stan-

* Corresponding author. Tel.: +33 563631159; fax: +33562264783.
E-mail address: patrick.sharrock@iut-tlse3.fr (P.J. Sharrock).

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dard technology. Their compositions according to their manufacturer's specifications are listed in Table 1. All posts were 2 mm in diameter and 20 mm long. Ten posts among each of the five types investigated were subjected to a three-point bending test. The three-point bending test was performed according to ISO 14125. It consists in positioning the sample on two points which define the span length of the test, and applying the load on a third point midway in the span. With reference to the standard, the span length should be 20 times the diameter of the post. The load was applied to posts with a loading angle of 90° and at a cross-head speed of 1 mm min^{-1}. All the posts were tested with a material testing machine (MTS, Eden Prairie, MN, USA). The load–deflection curves were recorded with PC software Testworks, v. 4.0. The fracture load was recorded and the flexural strength (σ) of the posts was computed using the following equation:

$$\sigma = 8\ F_{Max} l / \pi d^3,$$

where F_{Max} is the applied load (in Newtons) at the highest point of the load–deflection curve, d is the diameter of posts, and l is the span length. All tests were carried out at room temperature and humidity. The axial flexural modulus (E) for the posts was computed using the following equation:

$$E = S4l^3/3\pi d^4,$$

where F_{Max} is the applied load (in Newtons) at the highest point of the load–deflection curve, d is the diameter of posts (in mm), l is the span length (40 mm), $S = F/D$ is the stiffness (N m^{-1}) and D is the deflection corresponding to load F at a point in the straightline portion of the curve.

Ten posts from each group were tested in a fatigue machine (Procyon systems, Meylan, France). This device has a counter that measurers the number of cycles and stops when the specimen breaks. The load was applied perpendicularly to the long axis of the post at a frequency of 3 Hz. The load went from 25 to 100 N. The central loading anvil and the two supports had a 3 mm diameter and the distance between the two supports was 9 mm. Tests were voluntarily ended after 2 million cycles.

One-way analysis of variance (ANOVA) was computed to determine statistically significant differences at 5%. Multiple paired comparisons by the Tukey test were used to identify differences between pairs of groups. Multiple regression correlation coefficients R^2 were calculated as the ratio of the explained sum of squares divided by the total sum of squares proportional to the sample variance.

2.2. Scanning electron microscopy

Two posts of each type studied were used for SEM observations. Posts were embedded in methylmethacrylate resin inside 25 mm PTFE molds to obtain cylinders 6 mm high and 8 mm in diameter. The cylinders were cut perpendicularly to the long axis of the posts and polished with a MetaServe 3000 grinder (Buehler, Dardilly, France) using water-lubricated sandpaper following the sequence 240, 600, 1200 grit size and finishing with 6 μm diameter diamond paste. The same sequence was applied to longitudinal sections. All posts were examined at the same working distance and magnification. The broken posts were observed without polishing but following 60 s platinum sputtering with a model JFC 2300 HR sputter coater (JEOL, Tokyo, Japan). Surface topography was examined using a JEOL JSM 6700 F scanning electron microscope.

2.3. Image analysis

ImageJ software (Wayne Rasband, National Institute of Mental Health, Bethesda, MD, USA) was used to analyze the SEM micrographs. The mean diameters of the fibers and the standard deviations were calculated from measurements on more than 20 individual fibers from a randomly selected micrograph. The volume occupied by fibers was determined by summing the surface occupied by all the fibers and dividing by the total surface of the micrograph. The coordination number was obtained by considering the distance of a neighboring fiber to a central fiber for the six closest cases. Twelve measurements were averaged in order to plot distance vs. closest neighbor number. The maximum coordination number was derived where the distance rose above two standard deviations from the mean diameter of the fibers. In the ideal case where all fibers would be identical, the maximum coordination number would be 6. Lower numbers mean fewer fibers in close contact. The dispersion index evaluates the homogeneity of the distribution of fibers. This index was calculated by dividing the average distance between the centers of the six closest fibers to a central fiber by the average fiber diameter. The ideal case with the lowest possible dispersion index of 1 would mean the central fibers would have six touching surrounding

Table 1
Compositions of the experimental fiber posts provided by manufacturers.

Experimental posts ($n = 10$)	Fiber (% in vol)	Matrix (% in vol)	Manufacturer
Aestheti-Plus	Quartz (60%)	Epoxy (40%)	RTD, France
Light-Post	Quartz (59%)	Epoxy (41%)	RTD, France
Snowpost	Zircon rich glass (60%)	Epoxy (40%)	Carbotech, France
Snowlight	Zircon rich glass (64%)	Vinyl-polyestermethacrylate (36%)	Carbotech, France
FRC Postec	Glass (53%)	Urethanedimethacrylate (47%)	Ivoclar-Vivadent, Liechenstein

fibers. The larger the dispersion index is, the more the fibers are randomly scattered.

The fracture surface evaluations by SEM observations were classified as in tensile mode when the fibers separated by convex elongation or as in compression mode when they broke in concave geometry.

3. Results

3.1. Mechanical properties

All the stress–strain plots showed reversible elastic behavior which was linear up to about 50% of the maximum stress before fragile rupture. The flexural strengths of tested posts are presented in Table 2. Statistical analysis showed significant differences between the posts. The multiple comparison test showed the highest flexural strength obtained with Aestheti-Plus was significantly different (with a probability level of $P < 0.001$) as listed in Table 2. Conversely, Snowpost exhibited the lowest value, about half that of Aestheti-Plus. Flexural moduli are also presented in Table 2. FRC Postec showed the highest flexibility, whereas Aestheti-Plus and Snowlight were statistically equivalent with the highest modulus. Following the fatigue tests, all Light-Post, Aestheti-Plus and FRC Postec posts reached 2 million cycles without fracture. Seven out of 10 Snowpost posts reached the limit of our test without breaking, whereas all the Snowlight posts fractured before 2 million cycles were completed. The fracture modes differed among the posts. For Aestheti-Plus, the fracture mode was tensile for the inferior side (opposite to the load) and in compression for the superior side (in contact with the load). For the Light-Post and FRC Postec it was tensile for the inferior side. For Snowpost and Snowlight, the fracture mode was like that if Aestheti-Plus but with shear deformation.

Table 2
Three-point bending results. Different letters indicate statistically different values.

Experimental posts ($n = 10$)	Flexural strength (MPa, mean (SD))	Flexural modulus (GPa, mean (SD))	Fatigue failures (2 million cycles)
Snowpost	936.3 (30.4)^{a}	48.0 (0.7)^{b}	3^{b}
Snowlight	1242.5 (44.2)^{b}	53.8 (1.4)^{b}	10^{c}
FRC Postec	1294.8 (39.4)^{c}	45.7 (1.1)^{a}	0^{a}
Light-Post	1524.8 (40.8)^{d}	49.5 (1.6)^{c}	0^{a}
Aestheti-Plus	1889.6 (32.4)^{e}	52.8 (1.3)^{c}	0^{a}

3.2. Image analysis

Visual analysis of SEM micrographs revealed large differences between the posts studied. Selected micrographs are presented in Fig. 1. The upper line illustrates sections perpendicular to the fiber axes while the middle line shows oblique sections nearly parallel to the fiber axes. Both visions reveal the packing densities and show communicating resin matrix zones devoid of fibers. On cross-sections of the posts, the mean diameters of the fiber reinforcements were found to be smallest for Aestheti-Plus (7.9 μm) and largest for Snowpost (20.2 μm). The results are listed in Table 3. The homogeneity of the fiber diameters can be appreciated from the value of the standard deviations, which were also small (0.5 μm) for Aestheti-Plus and large (1.8 mm) for Snowpost. The volume % of fibers in the posts ranged from 49.5% to 65.1%. The post with the lowest fiber density had the smallest coordination number of 1.5, meaning very few fibers were adjacent or in close contact. Aestheti-Plus reached the highest coordination number of 5.1, close to the ideal closest-packing case with six fibers surrounding a central fiber. Fig. 2 shows a case of nearly six-coordination for a central fiber in the Snowlight case and a case of five-coordination illustrating the presence of more resin space between adjacent surrounding fibers.

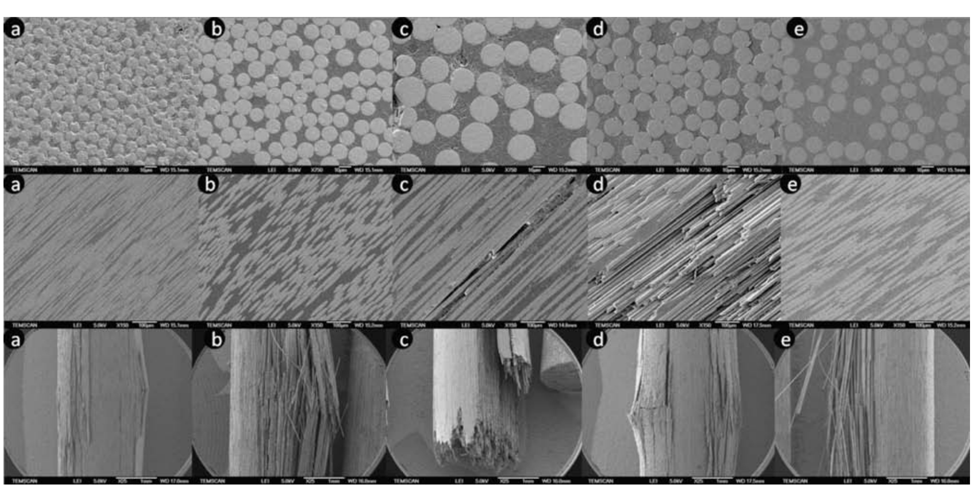

Fig. 1. SEM micrographs of the fiber posts posts (a, Aestheti-Plus; b, Light-Post; c, Snowpost; d, Snowlight and e, FRC Postec). Upper line: transverse section, magnification 750, bar = 10 μm; middle line: longitudinal section, magnification 150, bar = 100 μm; lower line: failure mode, magnification 25, bar = 1 mm.

Table 3
Experimentally determined physical parameters for the posts. Standard deviations in parenthesis followed by coefficient of variation. Different letters indicate statistically significant classified values.

Experimental post type	Mean fiber diameter (μm)	Fiber contents (vol.%)	Dispersion index	Coordination number
Aestheti-Plus	7.9 (0.5; 6.3%)[a]	65.1 (0.5)[a]	1.16 (0.09)[a]	5.1 (0.1)[a]
Light-Post	12.8 (1.2; 9.3%)[b]	63.3 (0.5)[b]	1.11 (0.08)[a]	4.6 (0.1)[b]
Snowpost	20.2 (1.8; 8.9%) [c]	51.7 (0.4)[d]	1.37 (0.11)[b]	2.6 (0.2)[d]
Snowlight	13.7 (1.1; 8.0%) [b]	60.1 (0.5)[c]	1.19 (0.10)[a]	4.2 (0.2)[c]
FRC Postec	13.9 (0.9; 6.5%) [b]	49.5 (0.4)[e]	1.44 (0.12)[b]	1.5 (0.3)[e]

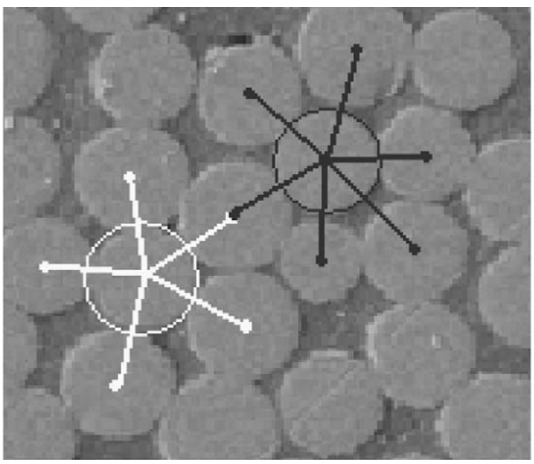

Fig. 2. SEM micrograph of a Snowlight post illustrating nearly 6-coordination (in black) and 5-coordination (in white) around a central fiber.

The dispersion index was largest for FRC Postec (1.44) and smallest for Light-Post (1.11), meaning the fibers were randomly distributed in the former and well organized in the latter. Several posts showed porosities, and Snowpost had more than the others. The parallel sections revealed dramatic differences between the posts. The Snowpost and Snowlight posts showed poor fiber cohesion to the resin matrix and fibers fractured by polishing. In some cases, porosities were seen running parallel to the fibers.

3.3. Statistical evaluation

Any existing relationships between mechanical properties and fiber density were tested by cross-correlation evaluations. The results are presented in Table 4. Clearly, there is no correlation between flexural strength and flexural modulus ($r^2 = 0.21$). The flexural strength is mostly related to fiber diameter ($r^2 = 0.92$), with the smallest fibers producing the best results, as illustrated in Fig. 4. On the other hand, the flexural modulus is principally related to coordination number ($r^2 = 0.74$), and secondarily to the fiber volume contents ($r^2 = 0.67$). The fiber contents are also well correlated with coordination number ($r^2 = 0.97$), and dispersion index ($r^2 = 0.94$).

4. Discussion

4.1. Mechanical properties

For anatomical reasons, root canal posts are necessarily thin at the root level, and relatively wider right at the root exit and inside the core [13]. This tapered design is intended to provide more flexibility in the apical region and greater stiffness in the coronal part even though the modulus of elasticity of the composite material remains constant [14,15]. Comparing the results of Tables 1–3, it may be noticed that the post fiber contents found experimentally are higher than the manufacturer's claims by an average factor of 8% for Aestheti-Plus and Light-Post, while they are lower by an average factor of 9% for the other posts. The post with the lowest flexural strength (Snowpost) has the largest fiber deficit (expected: 60%; found: 51.7%). On the other hand, the FRC Postec post with the lowest amount of fibers claimed (53%) and found (49.5%) has an adequate flexural strength of 1295 MPa, close to the average value of 1377 MPa found for all posts studied. These results show that the fiber density contributes only partly to mechanical performance. Endodontic posts are mainly subject to flexural stresses, and the conical apical portion is adapted to prevent root fracture caused by excessive post rigidity. Duret first considered that the anisotropy of unidirectional carbon fiber reinforcement of posts would be suitable for minimizing strain values longitudinally and perpendicularly to the post axis and thus match more closely the properties of dentine [16–19].

Table 4
R^2 correlation coefficients between investigated parameters. The parameters that best correlate with flexural strength and modulus are in bold.

	Fiber diameter	Vol.% fibers	Coordination number	Dispersion index	Flexural modulus
Flexural strength	**0.92**	0.59	0.46	0.39	0.21
Fiber diameter		0.54	0.41	0.36	0.29
Vol.% fibers			0.97	0.94	0.67
Coordination number				0.93	**0.74**
Dispersion index					0.63

Previous work has confirmed that silica fiber-reinforced posts present adequate flexural properties combined with good aesthetic and bonding properties [20]. The static and dynamic strength of posts were reported to decrease by exposure to moisture, but this was not expected to be critical with properly sealed reconstructions. However, different results were reported by authors investigating the mechanical properties of various posts [4,10]. The discrepancy in flexural strengths reported for similar materials can be attributed to differences in experimental design, method of specimen preparation, thickness and shape [3]. Other reasons for discrepancy in test results arise from the fact that the flexural strength depends on the loading rate and the length-to-diameter ratio of the specimen [21,22]. In fact, the clinical situation is better represented by cyclic loads much lower than the fracture load. During normal mastication, the yielding mechanism is most probably related to the gradual growth of a crack originating from a defect point [8].

Theoretically, the mechanical properties of fiber posts depend on many factors including volume fraction of fibers, their orientation, aspect ratio, thickness, bonding to resin matrix, polymerization-induced stress as well as differences in intrinsic properties of fibers and matrix [9]. Grandini concluded that differences exist between different brands of fiber posts in terms of their structural characteristics and fatigue resistance, but little correlation was observed between these two attributes [9]. Most likely, a combination of size, density, distribution of fibers and the nature of their bonding to the matrix may be a determining factor.

The results of this work can be compared to those previously reported concerning the range of fracture loads. The flexural strengths go from a minimum value of 936 MPa to a maximum value of 1889 MPa. The lowest value of 936 MPa is near the value of 1080 MPa found by Mannocci [4] for Snowpost, but far from the value of 760 MPa given by Lassila [3]. The highest strength found for Aestheti-Plus (1896 MPa) is significantly higher than the value of 1280 MPa reported by Mannocci [4] or the value 1045 MPa of Drummond [2]. Seefeld published flexural strength values ranging from 562 MPa to a maximum value of 898 MPa for DT White [6]. We note Lassila concluded that the strengths were related to post thickness, decreasing significantly with increase in post diameter [3]. In any case, we believe our results better conform to the standardized test design, particularly concerning the length-to-diameter ratio, and correspond to true values for the materials themselves.

4.2. Scanning electron microscopy

One feature of micrographs often described is the presence of visible bubbles in the resin matrix or voids on fractured fiber surfaces. Such irregularities were thought to be responsible for weakening the integrity of fiber-reinforced posts by creating unevenness which leads to deformation, cavitation and microfracture development. We have also observed empty spaces in the resin matrix of several posts which seem to be random and would require further quantification if possible. There was an evident difference in fiber–matrix cohesion for the weakest posts as revealed by the detachment of fiber clusters during the polishing process despite the gradual procedure used. This uncovered deep depressions inside the posts, running parallel to the post axis. Such discontinuities along the interfaces between the matrix and the fibers present proof that interfacial bond strength is critical. Promotion of chemical bonding between fiber and resin by appropriate silane treatment of the fibers prior to resin embedding is not detailed by manufacturers but may be of paramount importance for composite performance [23,24].

4.3. Statistical correlations

Our results indicate that the more rigid posts have more regular fiber distributions with higher coordination numbers and higher fiber densities. Conversely, the weaker posts show larger fiber dispersion, larger resin contents and increased defect numbers. As can be perceived looking at Figs. 3 and 4, the flexural strength is well correlated with fiber diameter ($r^2 = 0.92$), whereas the flexural modulus is poorly correlated with coordination number ($r^2 = 0.74$). Pegoretti et al. derived the flexural modulus for a glass fiber-reinforced post (45 GPa) by combining the high fiber modulus (72.4 GPa) and its volume fraction with the low matrix modulus (3.4 GPa) of the acrylic resin used [25].

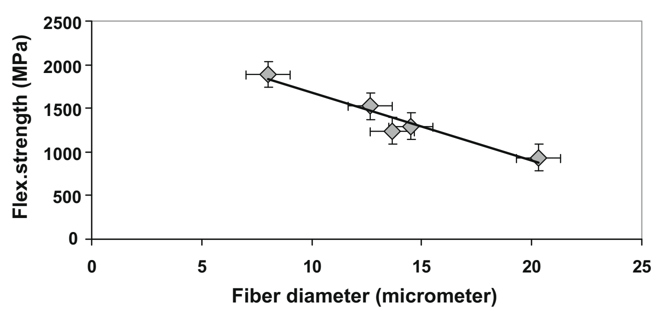

Fig. 3. Flexural strength of fiber posts vs. fiber diameter.

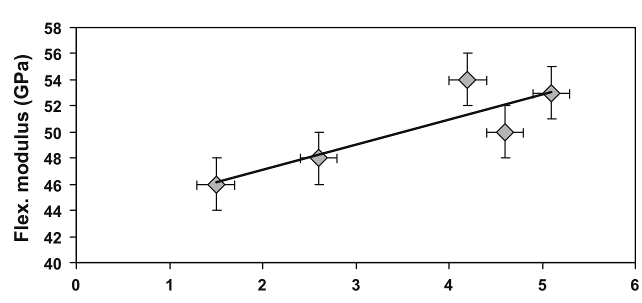

Fig. 4. Flexural modulus of fiber posts vs. coordination number.

According to Ferrari [26], 2 million cycles of fatigue testing would simulate about 4 years of physiological occlusal and masticatory activity. It is noteworthy that the posts found to have the lowest flexural strengths were found to fail the fatigue test, confirming that internal defects, as much as intrinsic fiber and matrix properties, contribute to the performances of the posts. However, despite large differences in the mechanical properties of fiber posts, they all resisted significantly more to compression fracture in teeth than did titanium or metal posts [27–29]. Based on a review of fiber-based systems [30], Ricketts et al. have concluded that aesthetic fiber posts are likely to increase in popularity [31]. Recent work confirms the mechanical compatibility of glass fiber posts with human root dentine [5,32–34].

5. Conclusion

The working hypothesis must be rejected: the mechanical properties of fiber-reinforced posts are not solely related to fiber densities. Within the limitations of this study (dry testing conditions, no thermal cycling or surface treatments [35] and a limited number of specially made posts) the flexural strength is closely correlated with smaller fiber diameters, and the modulus is weakly related to fiber coordination numbers. For equivalent fiber contents, posts with lower dispersion index fare better than posts with a less homogeneous fiber distribution. Interfacial defects, more difficult to quantify but easily detected in longitudinal sections, dramatically contribute to intrinsic post properties. Based on these in vitro results, Aestheti-Plus posts demonstrate the best integrity under mechanical stress. However, in clinical practice, the performance will also depend on other factors such as proper sealing and adaptation to the patient's root canal geometry as well as compliance with uniform stress distribution from occlusal forces to residual tooth structure.

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