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The flexural properties of endodontic post materials

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ABSTRACT

Objectives. To measure the flexural strengths and moduli of endodontic post materials and to assess the effect on the calculated flexural properties of varying the diameter/length (*D*/*L*) ratio of three-point bend test samples.

Methods. Three-point bend testing of samples of 2 mm diameter metal and fiber-reinforced composite (FRC) rods was carried out and the mechanical properties calculated at support widths of 16 mm, 32 mm and 64 mm. Weibull analysis was performed on the strength data.

Results. The flexural strengths of all the FRC post materials exceeded the yield strengths of the gold and stainless steel samples; the flexural strengths of two FRC materials were comparable with the yield strength of titanium. Stainless steel recorded the highest flexural modulus while the titanium and the two carbon fiber materials exhibited similar values just exceeding that of gold. The remaining glass fiber materials were of lower modulus within the range of 41–57 GPa. Weibull modulus values for the FRC materials ranged from 16.77 to 30.09. Decreasing the *L*/*D* ratio produced a marked decrease in flexural modulus for all materials.

Significance. The flexural strengths of FRC endodontic post materials as new generally exceed the yield strengths of metals from which endodontic posts are made. The high Weibull modulus values suggest good clinical reliability of FRC posts. The flexural modulus values of the tested posts were from 2–6 times (FRC) to 4–10 times (metal) that of dentin. Valid measurement of flexural properties of endodontic post materials requires that test samples have appropriate *L*/*D* ratios.

1. Introduction

The restoration of extensively damaged teeth presents a challenge for clinicians. Where there is little coronal tissue it is difficult to attach restorations to what remains. This will be of particular relevance to the smaller teeth in the jaws, those in the anterior region. In such situations it has historically been common practice to treat the tooth endodontically to allow a post to be placed into the root canal to achieve retention for a restoration placed over the coronal end of the post. This is most appropriate for anterior teeth which generally have single, long roots with little curvature. Post-restored teeth however, have a reputation as poor restorations with a high failure rate [1,2]. The main mode of failure is loss of retention, i.e. either a separation of the post from the luting cement or of the luting cement from the walls of the post space. This is followed, but less frequently, by root fracture [3,4]. While it may be possible simply to recement a loose post crown which can then continue to function adequately, the consequence of root fracture is far more serious as the tooth usually must be extracted. Traditionally, endodontic posts have been fabricated from cast or prefabricated metals and the influence of different design features of the post on root fracture has been extensively reported [5–7]. A number of different metal alloys are in clinical use, each with different elastic moduli and yield

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Table 1 – Endodontic post materials used in three-point bend testing; their diameters and composition.

Material	Manufacturer	Diameter (mm)	Composition (manufacturer's information except where indicated)
Carbon fiber composites (mean fiber diameter, filler volume fraction)			
Composipost	RTD, France	1.9	Carbon fibers 8 μm 64%; epoxy resin
Carbonite	Harald Nordin, Switzerland	2.1	Carbon 6 μm 65%; epoxy resin
Glass fiber composites (mean fiber diameter, filler volume fraction)			
Aesthetiplus	RTD, France	1.9	E-glass fibers 8 μm 62%; epoxy resin
Lightpost		2.5	Quartz glass 8 μm 60%; epoxy resin
Glassix	Harald Nordin, Switzerland	2.1	E-glass 8 μm 60%; epoxy resin
Snowpost	Carbotech Ganges, France	2.0	E-glass with 18% zirconia 8 μm 60%; epoxy resin
Snowlight			E-glass with 18% zirconia 8 μm 65%; polyester/methacrylate resin.
Postec	Ivoclar Schaan, Leichtenstein	2.5	E-glass 8 μm 55%;filler ytterbium trifluoride and dispersed silicon dioxide; urethane dimethacrylate/TEGMA
Easypost	Dentsply, Ballaigues, Switzerland	1.9	E-glass with 18% zirconia 8 μm 60%; epoxy resin
Metals (alloy composition)			
Stainless steel	Coltene/Whaledent, USA	1.7	Fe 72.21%, Cr 18.18%, Ni 8.62% [21]
Titanium		1.7	Ti 90%, Al 6%, Va 4%
Cast gold	Custom made BDH Dental Laboratory	2.1	Au 60%, Ag 22%, Cu 12.5%, Pd 4%, Zn, In < 2%

strengths but the impact on performance of these differences in mechanical properties has not attracted as much interest as the effects of the design of metal posts. With the introduction of alternative post materials, in particular fiber-reinforced composites (FRC), these factors have assumed greater importance to researchers. Opinion is divided as to whether a post should have an elastic modulus close to that of dentin [8,9] or whether it should be more rigid [10,11]. One of the principle advantages claimed for FRC posts is that their elastic moduli are close to that of dentin and that this will allow a more favorable distribution of stress in the root thereby leading to a lower incidence of root fracture than occurs with metal posts [12,13]. The mechanical properties of fiber-reinforced composites are determined not only by the properties of the different constituents but by the bond between filler and matrix and also by the shape, orientation and relative proportions of the reinforcing filler phase [14,15]. Endodontic posts from different manufacturers contain different matrix resins, different proportions, diameters and types of fiber and may vary in their interfacial bonding. Therefore, before comparing the relative performance of metal and FRC posts, it is first necessary to determine the mechanical properties of different post materials and ascertain to what extent they approach the properties of dentin. Three-point loading in a universal testing machine is commonly used to determine the flexural modulus and flexural strengths of samples of materials. The applied load is plotted against the resulting deflection of the sample until failure and, using an appropriate formula, the flexural modulus and, in the case of brittle materials, the flexural strength can be calculated [16]. Bending samples will induce shear stresses within the material affecting the validity of the calculated flexural properties [17]. The shear force is proportional to the diameter/length ratio of the sample [18]. To minimize this problem, standards organizations set appropriate dimensions for three-point bend testing of rods made of roving reinforced resin. ISO 3597-2:1993, Method 1008B:1996 stipulates that the distance between the supports should be at least 16 times the diameter of the rod. Despite this, three-point bend tests have been conducted on short endodontic posts which present a length/diameter (*L*/*D*) ratio far below this 16:1 ratio and the results then expressed as the flexural modulus and flexural strength for that post material [19,20]. Examining the effect that varying the aspect ratio of samples has on the derived property values will allow a better interpretation of the results of such studies on samples with small *L*/*D* ratios.

The aims of this study were therefore to measure the flexural strengths and flexural moduli of a range of currently available endodontic post materials and to assess the effect on these calculated flexural properties of varying the diameter/length ratio of three-point bend test samples.

2. Materials and methods

Lengths of 100 mm wrought stainless steel and titanium, glass fiber and carbon fiber composites were obtained from several manufacturers. To provide a comparison with a cast precious metal alloy, rods of a type IV gold alloy, Engelhard EC 620 (Engelhard-Clal (UK) Ltd., Chessington, England) were fabricated. The samples were cast by the lost wax process using rigid rods of non-residual plastic as the burn-out patterns. The composition, dimensions and manufacturers of all the tested materials are listed in Table 1.

2.1. Flexural testing of post materials

To carry out flexural testing, each material was cut into 48 mm lengths using a diamond disk (H 355C190, Horico, Berlin, Germany) running at slow speed in a dental handpiece. These were subjected to three-point bending in an Instron universal testing machine (Instron UK, High Wycombe, England), model 5544 according to ISO 3597-2. The distance between the supports was set at 32 mm. The diameter of each rod was measured at six points close to the center of the rod using a digital micrometer accurate to 0.01 mm (Mitutoyo, Japan), and a mean diameter calculated. A stainless steel loading nose with a 3 mm cylindrical cross-section was used and loads were applied at 1 mm/min. Data was exported to a computer spreadsheet programme, Excel 2003 (Microsoft Corp. USA) for analysis. Thirty samples of each material were tested and the mean flexural moduli and flexural strengths calculated using the appropriate equations [16].

Flexural modulus of a cylindrical rod using three-point bending [16].

$$E = \frac{4L^3}{3\pi D^4} \times \frac{F}{Y} \tag{1}$$

Flexural strength of a cylindrical rod using three-point bending [16].

$$\sigma = \frac{8F_m L}{\pi D^3} \tag{2}$$

where E was the flexural modulus (MPa), σ was the flexural strength (MPa), F was the applied load (N), F_m was the maximum load at break, L was the length of span between supports (mm), D was the mean diameter of the sample (mm), and F/Y was the slope of the initial linear segment of the load–deflection curve. For metal samples, the 0.2% offset yield strength was calculated. Data was entered into a statistical computer package SPSS V12 (SPSS Inc., Chicago, USA) for analysis. The Shapiro–Wilk and Levene's tests confirmed that the data had a normal distribution and homogeneity of variance and so a one-way ANOVA and post hoc Scheffé tests were used to identify any significant differences among the tested materials for both parameters ($p < 0.05$).

Brittle materials such as fiber-reinforced composites fail as a consequence of crack growth from flaws within the material. Obtaining a mean flexural strength value does not give an indication as to the variability in strength, as this is dependent on the distribution of flaws. A more complete description of the variability in strength can be derived by determining the Weibull distribution [21]. The Weibull modulus (m) (or shape parameter) is a constant which describes the slope of the distribution and indicates the variation in the distribution of strength values which in turn may reflect clinical reliability. The characteristic strength (scale parameter) is the stress responsible for 63.2% of the sample failures. The flexural strength data was placed in rank order and an Anderson–Darling test used to confirm that the data was described by a Weibull distribution using the computer programme Easy-Fit 5.2 (MathWave Technologies, USA). This showed that the A^2 statistic was less than the critical value for each material's strength data at the 95% significance level. A regression method was then carried out [22] to derive the characteristic strength and Weibull modulus for each FRC material. Statistical differences in modulus values were determined by comparing the upper and lower bounds of the 95% confidence intervals for each material. Where no overlap occurred, the differences were considered to be significant. Plots of survival probability were also created to assess the distribution of flexure strengths.

2.2. Effect of variation of sample aspect ratio

To examine the effects of altering the L/D ratio on the calculated flexural properties, ten rods of each of the post materials were also tested in three-point bend with inter-support distances of 64 mm and 16 mm. This provided samples with aspect ratios which were twice and half the length of the 32 mm samples. Because long samples of the cast gold could not be fabricated, this material was excluded from this part of the study. As a further examination of the effects on flexural modulus values of varying the length of the samples, three-point bending was carried out on five samples of a metal—steel, a carbon fiber composite (Composipost) and a glass fiber composite (Aesthetiplus) at gradually decreasing support widths from 80 mm to 12 mm. Statistical analysis with separate one-way ANOVA and post hoc Scheffé tests was carried out for all nine products with support widths ($n = 3$) as the independent variable.

3. Results

In the three-point bend test, all the fiber composites demonstrated a linearly elastic behavior up to an initial point where a sharp drop in the load/extension plot occurred. It was assumed that this indicated the initiation of fiber fracture and the load at this point was used to calculate the flexural strength. After this point, the remaining portion of the rod with unbroken fibers continued to behave elastically up to the next drop in the plot at which a further group of fibers were assumed to have broken. This pattern continued until total division of the rod occurred. The mode of failure consisted mostly of buckling and fracture of the fibers in the midpoint of the rod on the compression side. Some fracture of the surface fibers and delamination on the tension side was also noticed in some samples, but was less pronounced among the glass fiber materials. The metals exhibited the classically observed behavior, with an early linear elastic phase followed by elastic/plastic deformation. The mean flexural strengths (yield strengths for metals) and flexural moduli for the materials are detailed in Table 2. The flexural strengths of all the FRC post materials exceeded the yield strengths of the gold and stainless steel samples, and the flexural strengths

Table 2 – Flexural strengths and moduli of the tested post materials. Similar letters in columns indicate no significant differences between property values as determined by Scheffé post hoc tests ($p < 0.05$).

Material	Diameter	Flexural strength MPa (SD)	Scheffé	Flexural modulus GPa (SD)	Scheffé
Composipost	1.9 mm	1394.44 (26.35)	A	116.90 (0.48)	B
Carbonite	2.1 mm	867.91 (44.97)	D, E	99.38 (1.96)	C
Aesthetiplus	1.9 mm	1412.15 (40.47)	A	56.16 (0.63)	E
Lightpost	2.5 mm	1131.08 (38.48)	C	41.87 (0.81)	H
Glassix	2.1 mm	1076.43 (79.24)	C	50.20 (1.67)	F, G
Snowpost	2.0 mm	911.61 (43.62)	D, E	47.74 (1.11)	G, H
Snowlight	2.0 mm	849.70 (44.48)	E	52.05 (1.26)	E, F
Postec	2.5 mm	1215.26 (49.72)	B	44.44 (0.62)	H
Easypost	1.9 mm	949.52 (33.22)	D	43.96 (0.71)	H
Stainless steel	1.7 mm	742.56 (99.35)	F	193.73 (6.98)	A
Titanium	1.7 mm	1477.89 (94.02)	A	110.02 (1.39)	B
Gold	2.15 mm	355.45 (44.72)	G	86.70 (11.75)	D

Table 3 – Weibull moduli, 95% confidence intervals, coefficients of determination and characteristic strengths of FRC post materials derived from three-point bend testing.

	Weibull modulus	Bounds of the 95% confidence interval		r^2	Characteristic strength (MPa)
		Upper	Lower		
Composipost	30.09	32.64	27.54	0.954	1398.55
Carbonite	22.45	25.47	19.42	0.892	879.97
Aesthetiplus	27.97	31.16	24.78	0.920	1439.40
Lightpost	25.90	30.29	21.50	0.839	1168.02
Glassix	16.77	18.06	15.48	0.962	1098.05
Snowpost	26.09	28.38	23.80	0.951	931.16
Snowlight	18.08	20.56	15.61	0.889	871.35
Postec	22.42	25.16	19.67	0.909	1213.96
Easypost	17.09	19.70	15.00	0.910	958.82

of the Aesthetiplus and Composipost materials were comparable with the yield strength of titanium. The stainless steel recorded the highest flexural modulus while the titanium and the two carbon fiber materials exhibited similar values which just exceeded that of gold. The remaining glass fiber materials were of lower modulus within the range of 41–57 GPa.

3.1. *Weibull analysis of strength data*

The derived Weibull moduli (m), 95% confidence intervals, coefficients of determination and the characteristic strengths of the FRC materials are given in Table 3. The highest moduli and characteristic strengths were associated with a glass fiber and a carbon fiber material from one manufacturer. However, there was no significant difference in the Weibull modulus of the four materials with the highest moduli. Considerable overlap of the confidence intervals of the remaining materials was also observed. The survival plots in Fig. 1 show similar and regular profiles among the FRC materials.

3.2. *Sample aspect ratio*

The derived moduli and flexural strengths of samples with support widths of 16 mm, 32 mm and 64 mm are displayed as bar charts in Figs. 2 and 3. The one-way ANOVA and post hoc Scheffé tests showed that for all the materials, there was a statistically significant difference in the calculated flexural modulus associated with increasing the three-point bend support width from 16 mm to 32 mm which represented increases in modulus values of between 30% and 75%. Much smaller increases in modulus values were noted when increasing the support width from 32 mm to 64 mm, but these were not significant for Snowpost ($p = 0.85$), Snowlight ($p = 0.96$) or Easypost ($p = 0.99$) and amounted to increases of between 0% and 9%. Calculated flexural strength values of the FRC samples also increased as the support widths increased. There was a statistically significant difference between 16 mm and 32 mm for each material with the exception of Snowpost ($p = 0.46$) and Easypost ($p = 0.06$). The increase in values ranged from 10% to 39%. Between support widths of 32 mm and 64 mm the difference was not statistically significant for Snowpost ($p = 0.58$), Postec ($p = 0.98$) and Easypost ($p = 0.97$) and overall was between 2% and 21%. For the two metals, yield strength

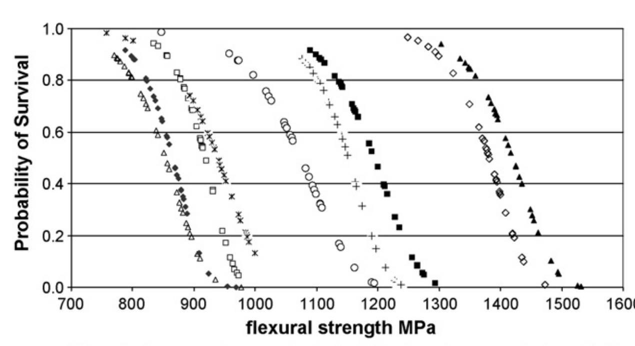

Fig. 1 – Plot of flexural strength against survival probability for the FRC post materials.

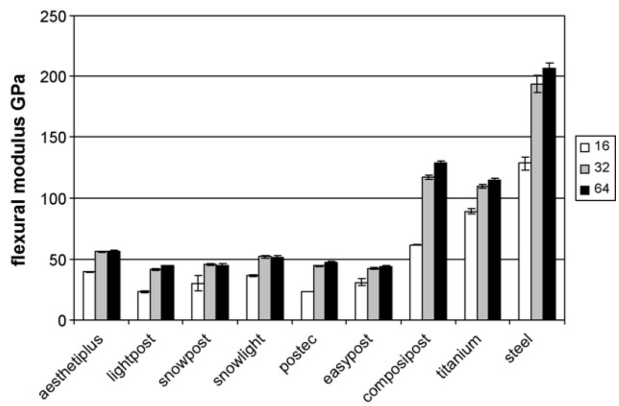

Fig. 2 – Flexural modulus values (GPa) for the FRC and metal materials calculated from three-point bend testing at support widths of 16 mm, 32 mm and 64 mm. Errors bars indicate standard deviations.

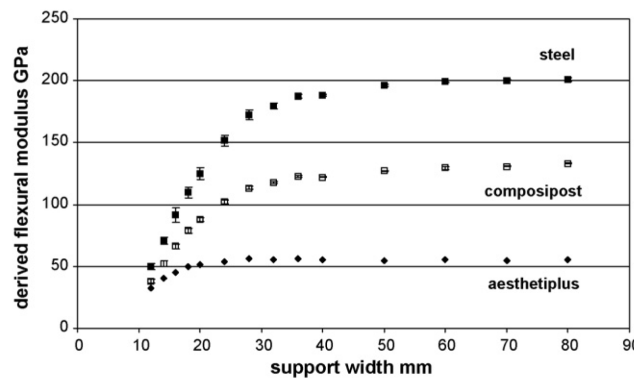

Fig. 4 – Flexural modulus values calculated from three-point bend testing at decreasing support widths for steel, Composipost and Aesthetiplus samples.

values decreased as the support width increased and the differences between 16 mm and 32 mm and between 32 mm and 64 mm were statistically significant for both metals.

The flexural moduli calculated for the three representative materials at decreasing support widths between 80 mm and 12 mm are plotted in Fig. 4. It may be seen that as the support widths approach 12 mm, the derived modulus values begin to converge and that this apparent reduction of modulus starts to occur at greater support widths for the stiffer steel and carbon fiber materials than it does for the glass fiber composite.

4. Discussion

To be of use in retaining restorations, endodontic posts need to withstand the flexural loads applied to them during function. The mean flexural strengths of the FRC materials identified in this study suggest that endodontic posts made from any of these new materials would resist higher loads than gold or steel posts and that the mean flexural strengths of two of these FRC materials are comparable with titanium. The range of flexural strengths recorded here was considerable for both the carbon fiber and the glass fiber materials and despite the apparent similarity of matrix resins there was no obvious correlation of fiber type with flexural strength. In this study, as in several other reports [23–25], Weibull analysis was carried out using a linear regression (LR) rather than a maximum likelihood estimate (MLE) method as it is considered adequate for many situations, is the easiest method to understand [26] and can be accomplished using standard computer programmes. MLE is more likely to overestimate than underestimate the Weibull modulus leading to lower safety estimates in reliability prediction than the LR method [27]. However, it should be recognized that MLE is regarded as a superior statistical method, particularly in design, which derives more consistent Weibull moduli with tighter confidence intervals. Although values of Weibull modulus can vary between MLE and LR, estimates of characteristic strength show less disparity between methods.

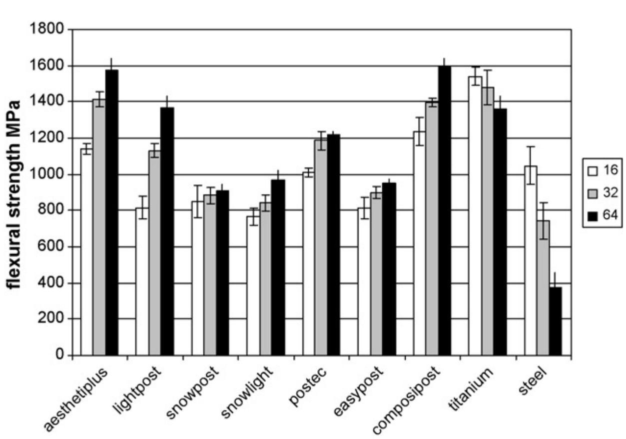

Fig. 3 – Derived flexural strength values (MPa) for the FRC and metal materials at support widths of 16 mm, 32 mm and 64 mm. Errors bars indicate standard deviations.

Weibull analysis showed that the characteristic strengths were also similar to these mean strengths and that the Weibull moduli for most of the FRC materials exceeded 20. Values of $m > 20$ indicate that materials possess structural integrity and are likely to display good clinical reliability [28,29] especially when combined with a high characteristic strength. By way of comparison, m values of 5–15 are reported for ceramics, and 30–90 for metals [28]. The absence of overlap in the confidence intervals indicated significant differences in the Weibull moduli of some of the materials. However, it should be borne in mind that where intervals do overlap, a significant difference may still be present [30].

Examination of flexural test samples after failure suggested that a similar failure mode had occurred among all of the FRC posts, namely fracture of the fibers on the upper compression aspect of the rods with fewer fibers failing by fracture and separation from the matrix on the opposite tension surface. However, unlike more brittle materials which tend to fail catastrophically, these FRC materials containing longitudinal fibers failed progressively. The precise nature of the initiating failure mode was therefore difficult to determine and may have been due to fiber fracture under compression or tension or by delamination initiated at a surface flaw. Support for the possibility of two or more modes of failure occurring is provided by the coefficients of determination produced in plotting the Weibull distributions since r^2 values ≥ 0.95 are associated with a single mode of failure [31]. The r^2 values exceeded 0.95 in only 3 of the FRC samples tested and suggests that more than one mode of failure had occurred in the remaining samples [32]. Since the principal failure mode of FRC posts has not been determined, the assessment of flexural strength as a predictor of clinical performance should not be over-emphasized. Because they display brittle behavior, fracture toughness and fatigue resistance of FRC endodontic posts may be of equal relevance. It should also be considered that the test results reported here were obtained from cylindrical rods of uniform diameter. Endodontic posts manufactured from these materials are frequently machined to create tapered shapes and produce surface features designed to increase mechanical locking with luting cements and core materials. The resulting surface damage will create flaws and disrupt the integrity of FRC materials which will greatly affect their resistance to breakage. Before extrapolating the results of this study to clinical performance, the impact of any such finishing processes must be taken into consideration.

The proponents of the use of endodontic posts made from fiber-reinforced composites assert that these materials have elastic moduli which are close to that of dentin [8,33]. A range of values has been reported for the elastic modulus of dentin [34]. This disparity reflects the difficulty of preparing tissue samples and differences among test methods, some of which assess different aspects of the heterogeneous structure of dentin at the microscopic level [35,36] while others consider its bulk properties [37]. Other techniques are affected by the viscoelastic nature of dentin [38]. However, it has been suggested that dentin may be considered as an elastic solid and that an appropriate value for the effective elastic modulus at physiological strain rates is 18–20 GPa [34]. Notwithstanding the imprecise value of the elastic modulus of dentin, it is apparent that the metal alloy endodontic posts tested here exhibit a range of flexural moduli which are of the order of 4–10 times that of dentin. The original FRC materials manufactured as endodontic posts and promoted because of their elastic properties were carbon fiber based. It has been reported by others that carbon fiber posts are as stiff as metal posts [39,40] and the carbon fiber composite materials tested in this study recorded moduli comparable with titanium. Therefore, it is not appropriate to attribute the reported clinical success of carbon fiber posts [41–43] to a dentin-like modulus of the posts. The flexural moduli of the glass fiber posts were clustered within a 20 GPa range and, although they were the closest to dentin, were between 2 and 3 times greater than that of dentin. The narrow range of flexural modulus values of the glass fiber composites was distinct from the higher values of the carbon fiber materials. Unlike flexural strength, elastic modulus appears to be related to fiber type. If the goal is to place posts which have the same elastic modulus as dentin, then current FRC posts do not achieve this goal. If it is sufficient merely to have a "low" modulus (and there has been no agreement as to what might be an appropriately low modulus), then there are metal alloys whose moduli are similar to some of the FRC materials investigated here. Therefore, when assessing the effect of elastic modulus differences on the performance of metal and FRC endodontic posts, it is important that the mechanical properties of the specific materials are determined as they cannot necessarily be predicted from knowledge of their composition alone.

Varying the *L*/*D* ratio in three-point bend testing confirms that attempting to use short lengths of materials leads to an underestimation of flexural modulus and strength [44]. When testing manufactured endodontic posts, the available support width will be approximately 10 mm and although the diameter of such samples would be of the order of 1.3 mm [20], the plots shown in Fig. 4 indicate that at such widths there is a significant departure from the values which are obtained at *L*/*D* ratios greater than 16:1. While the load required to fracture manufactured endodontic posts may be measured in order to compare different post types, the fundamental material properties of flexural strength and flexural modulus cannot be accurately ascertained using short samples. Despite this, researchers continue to perform such tests and in so doing, derive inappropriate characteristic values [19,20,45,46].

5. Conclusions

FRC endodontic posts exhibit flexural strengths which generally exceed the yield strengths of metals from which endodontic posts are made.

In comparison with dentin, the flexural modulus values of the FRC posts tested here were between 2 and 6 times that of dentin.

The flexural moduli but not the flexural strengths of FRC posts appear to correlate with fiber type.

Valid measurement of flexural properties of endodontic post materials can only be achieved when samples with recommended *L*/*D* ratios are tested.

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