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# Effect of Airborne-Particle Abrasion and Aqueous Storage on Flexural Properties of Fiber-Reinforced Dowels

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**Keywords**
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## Abstract

**Purpose:** A great range of clinical failures have been observed with fiber-reinforced dowels, often attributed to fracture or bending of the dowels. This study investigated flexural properties of fiber-reinforced dowels, with and without airborne-particle abrasion, after storage in aqueous environments over time. Scanning electron microscopy (SEM) was used to analyze the mode of failure of dowels.

**Materials and Methods:** Two dowel systems (ParaPost Fiber Lux and FibreKor) were evaluated. Ten dowels of each system were randomly assigned to one of six experimental groups: 1 – control, dry condition; 2 – dowels airborne-particle abraded and then stored dry; 3 – dowels stored for 24 hours in aqueous solution at 37°C; 4 – dowels airborne-particle abraded followed by 24-hour aqueous storage at 37°C; 5 – dowels stored for 30 days in aqueous solution at 37°C; 6 – dowels airborne-particle abraded followed by 30-day aqueous storage at 37°C. Flexural strength and flexural modulus were tested for all groups according to American Society of Testing and Materials (ASTM) standard D4476. One failed dowel from each group was randomly selected to be evaluated with SEM equipped with energy dispersive spectroscopy (EDS) to characterize the failure pattern. One intact dowel of each system was also analyzed with SEM and EDS for baseline information.

**Results:** Mean flexural modulus and strength of ParaPost Fiber Lux dowels across all conditions were 29.59 ± 2.89 GPa and 789.11 ± 89.88 MPa, respectively. Mean flexural modulus and strength of FibreKor dowels across all conditions were 25.58 ± 1.48 GPa and 742.68 ± 89.81 MPa, respectively. One-way ANOVA and a post hoc Dunnett's *t*-test showed a statistically significant decrease in flexural strength as compared to the dry control group for all experimental groups stored in water, for both dowel systems ($p < 0.05$). Flexural modulus for both dowel systems showed a statistically significant decrease only for dowels stored in aqueous solutions for 30 days ($p < 0.05$). Airborne-particle abrasion did not have an effect on flexural properties for either dowel system ($p > 0.05$). SEM and EDS analyses revealed differences in composition and failure mode of the two dowel systems. Failed dowels of each system revealed similar failure patterns, irrespective of the experimental group.

**Conclusions:** Aqueous storage had a negative effect on flexural properties of fiber-reinforced dowels, and this negative effect appeared to increase with longer storage times. The fiber/resin matrix interface was the weak structure for the dowel systems tested.

Fiber-reinforced dowels have been used to treat teeth with endodontic therapy since the early 1990s.[1] Since then fiber-reinforced prefabricated dowel systems have gained popularity mostly because of their improved esthetic properties and relative ease of placement as compared to metallic dowels.[1,2] In addition, studies have shown that fiber-reinforced dowels demonstrate mechanical properties similar to those of a natural tooth; more specifically the modulus of elasticity of these dowels is similar to that of the dentinal layer of a natural tooth.[3,4] Average values of the elastic modulus of dentin have been reported in the range of 25 to 30 GPa,[5] whereas the flexural modulus of various fiber-reinforced dowels has been in the range of 10 to 50 GPa.[6,7] It was initially assumed that the use of fiber-reinforced dowels would reduce previously experienced outcomes such as root fractures on endodontically treated teeth with dowels.[8-10]

Current and popular prefabricated fiber-reinforced dowel systems mainly consist of glass or silica fibers embedded in epoxy or Bis-GMA resin.[2,11] The percentage of glass fibers in the resin matrix appears to have an effect on the strength of the dowels: the higher the concentration of the glass fibers, the higher the strength.[12] However, the type of fiber used, silica or different glasses, does not appear to have an effect on the strength of the dowels as long as the fibers are in a high concentration in the dowel structure.[13]

Clinical studies have shown different results in using fiber-reinforced dowels as a valuable treatment for endodontically treated teeth.[1,2,14] Numerous clinical trials have shown failure rates of fiber-reinforced dowels ranging from 0% to as high as 32.2%.[15-20] It appears that the most common failure of a fiber-reinforced dowel is that the dowel becomes debonded or uncemented.[2,14-20] Although the reason for dowel decementation can be multifactorial, it may be related to some deformation or flexure of the dowel occurring during occlusal loading. Interestingly several clinical studies have shown that the majority of failures with fiber-reinforced dowels occur on teeth with minimal remaining tooth structure.[2,14] In these cases, the dowel itself will have to withstand a greater occlusal load, and probably the strength of the dowel is not adequate for such loading.

Another explanation for the failures of fiber-reinforced dowel systems may be the degradation of the resin matrix of the dowels in the presence of an aqueous environment.[21] It has been shown that moisture is present in teeth with endodontic treatments. Even after the removal of pulpal tissues and completion of endodontic treatment, the moisture content of a pulpless tooth is similar to that of a vital tooth.[22] The presence of moisture may have different effects on the strength of resin structures, but most often sorption is observed, leading to reduction of mechanical properties.[21]

Since the dowels are cemented into prepared root canal spaces, researchers have investigated the bond of the fiber-reinforced dowel/cement/dentin interface. Several conditioning treatments of the dowels, such as silanization[23,24] or treatment with primers,[25,26] have negligible effects in improving the bond between a fiber-reinforced dowel and resin cement. Airborne-particle abrasion of the fiber-reinforced dowels prior to cementation significantly increases the retention between the dowel and resin cements.[25-28] However, the effect of airborne-particle abrasion on the mechanical properties of fiber-reinforced dowels has not been investigated. Airborne-particle abrasion of fiber-reinforced dowels can potentially weaken the dowel's outer surface, possibly resulting in mechanical property changes that may contribute to clinical failures.

The large variance of clinical success of fiber-reinforced dowels suggests that there are still unanswered questions concerning the behavior of such dowels.[2,14-20] A possible reason for fiber-reinforced dowels' failures may be their decreased strength or decreased flexural properties. A decrease of the fiber-reinforced dowels' flexural properties may lead to fracture or bending of the dowels, perhaps resulting in clinical failures. Therefore, the purpose of this study was to investigate the flexural properties (flexural strength, flexural modulus) of two prefabricated fiber-reinforced resin dowels with or without airborne-particle abrasion in dry and moist environments over time. The null hypothesis tested was that there will be no statistically significant differences in the flexural strength and the flexural modulus of dowels stored in a dry environment versus dowels stored in a moist environment with or without airborne-particle abrasion of the dowels. Selected failed dowels from each treatment group were viewed under a scanning electron microscope (SEM) equipped with energy dispersive spectroscopy (EDS) to better understand the mode of failure of fiber-reinforced dowels under loading.

**Table 1** Fiber-reinforced dowel systems tested

| Product | Manufacturer | Fiber type | Medium |
|---|---|---|---|
| ParaPost Fiber Lux | Coltène Whaledent, Cuyahoga Falls, OH | Glass fibers | Composite resin |
| FibreKor | Pentron Clinical Technologies LLC, Wallingford, CT | Glass fibers | Composite resin |

## Materials and methods

Two commercially available fiber-reinforced dowel systems were used in this study (Table 1). Ten dowels of each system were randomly assigned to the following experimental groups: 1 – control, dry conditions; 2 – dowels airborne-particle abraded and then stored dry; 3 – dowels stored for 24 hours in aqueous solution at 37°C; 4 – dowels airborne-particle abraded followed by 24-hour aqueous storage at 37°C; 5 – dowels stored for 30 days in aqueous solution at 37°C; 6 – dowels airborne-particle abraded followed by 30-day aqueous storage at 37°C.

Airborne-particle abrasion was accomplished using a microetching laboratory unit (MicroEtcher ERC, Danville Materials, San Ramon, CA) with 50 $\mu$m aluminum oxide particles under 60 psi. Each airborne-particle-abraded dowel was exposed to the abrasion process for 10 seconds from a distance of approximately 1 cm.

Dowels exposed to aqueous aging were stored in vials containing 10 ml of sterile deionized water. Each vial contained five dowels. The vials were then placed on an orbital shaker (60 rpm) at 37°C for their allotted time. For the experimental group stored in the aqueous solution for 30 days, after 2 weeks, the water was replaced with 10 ml of fresh sterile deionized water.

Following the respective experimental treatments, the flexural strength and flexural modulus of the dowels were measured using a universal testing machine (1125/5500R, Instron Corp, Canton, MA). A three-point bend test was performed following American Society of Testing and Materials (ASTM) standard 4476.[29] Prior to testing, the diameter of each dowel was measured to an accuracy of 0.01 mm using a digital micrometer (Mitutoyo Corp, Aurora, IL). The three-point bend fixture consisted of two rods, 2 mm in diameter, mounted parallel with a 12 mm support span beam. The specimen was loaded at the center of the dowel with a 2 mm striker. The loading rate to failure was 1 mm/min. For the experimental groups stored in aqueous solutions, mechanical testing was performed in a 100% moist environment.

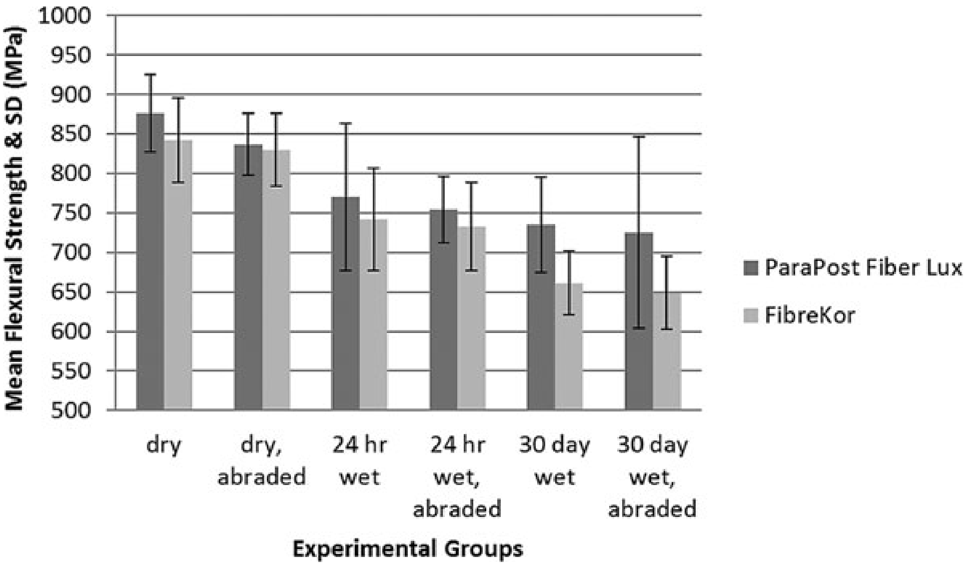


**Figure 1** Flexural strength mean and SD values (MPa) for the two dowel systems tested for the six experimental groups.

Flexural strength (S) and flexural modulus (E) were calculated using the tester software program (Merlin v. 5.31, Instron Corp) according to the following equations:

$$S = 8PL/\pi d^3 \text{ measured in MPa},$$

$$E = [(F/D)4L^3]/(3\pi d^4) \text{ measured in GPa},$$

where S = stress in the outer fiber throughout the load span, E = modulus of elasticity in bending, F = load (N) at a convenient point on the straight line portion of the load deflection curve, D = deflection (mm) at load F, P = maximum load (N), L = support span (mm), and d = diameter of the dowel (mm).

One-way ANOVA and post hoc comparisons using Dunnett's *t*-test were performed on the mean flexural strength and flexural modulus values at $\alpha = 0.05$. Dunnett's *t*-test was used to compare each experimental group to the control group, where control was the dry, non-airborne-particle-abraded dowel.

Following mechanical testing, one failed dowel from each experimental group was randomly selected to be viewed using SEM. An intact dowel of each of the two dowel systems was also viewed using SEM to obtain baseline information for comparisons. All dowels evaluated with SEM were sputter coated with gold-palladium prior to imaging. Different magnifications were used to better evaluate the dowel structures and the failed sites. In addition to the failure sites, other areas away from where the failure occurred were analyzed. EDS X-ray microanalysis was performed in conjunction with the SEM evaluation to analyze the composition of the structures of the dowels. A total of 14 dowels were evaluated in this manner.

## Results

### Mechanical testing

The mean flexural modulus and strength of ParaPost Fiber Lux dowels across all conditions were 29.59 ± 2.89 GPa and 789.11 ± 89.88 MPa, respectively. The mean flexural modulus and the strength of FibreKor dowels across all conditions were 25.58 ± 1.48 GPa and 742.68 ± 89.81 MPa, respectively.

Flexural strength measurements for both dowel systems (Fig 1) exhibited a significant decrease in strength across experimental conditions ($p < 0.0001$). The highest mean flexural strengths were observed in the control group for both dowel systems tested (876.2 ± 48.2 MPa for the ParaPost Fiber Lux and 841.8 ± 53.6 MPa for the FibreKor). The lowest mean values were observed in the 30-day wet, airborne-particle-abraded groups for both systems (725.3 ± 121.7 MPa for the ParaPost Fiber Lux and 648.7 ± 46.1 MPa for the FibreKor). Dunnett's *t*-test indicated that dowels stored in aqueous environments (for 24 hours or 30 days), whether they were airborne-particle abraded or not, demonstrated a statistically significant reduction ($p < 0.05$) in flexural strength as compared to the dry controls with both systems. The only experimental group that was not significantly different from the control in terms of the flexural strength was the dry, airborne-particle-abraded dowel group ($p > 0.05$).

Flexural modulus measurements (Fig 2) also exhibited a statistically significant difference ($p = 0.0015$) among the experimental groups. The highest mean flexural modulus values were observed again in the control group for both dowel systems tested (31.8 ± 0.9 GPa for the ParaPost Fiber Lux and 26.9 ± 1.35 MPa for the FibreKor). The lowest mean flexural modulus values recorded were 26 ± 2.1 GPa for the ParaPost Fiber Lux dowels in the 30-day wet, airborne-particle-abraded group and 24.7 ± 1.3 GPa for the FibreKor dowels in the 24-hour wet, airborne-particle-abraded group. Dunnett's *t*-test revealed that only dowels stored in aqueous solutions for 30 days, both airborne-particle abraded and non-abraded, showed a statistically significant decrease ($p < 0.05$) in flexural modulus as compared to the dry control group for both dowel systems. While storage in aqueous solution for 24 hours resulted in

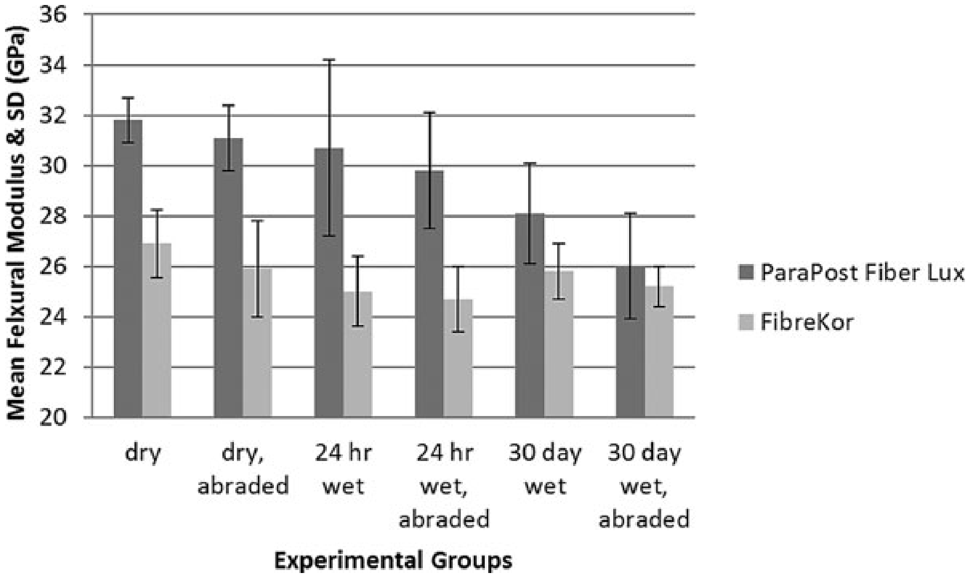


**Figure 2** Flexural modulus mean and SD values (GPa) for the two dowel systems tested for the six experimental groups.

decreased flexural modulus for both dowel systems, the differences were not statistically significant ($p > 0.05$). Similarly, there was no significant difference between the dry, airborne-particle-abraded group from the dry control with both dowels ($p > 0.05$). It is important to note that any observed significant decreases in flexural properties for both dowel systems were attributed to the aqueous storage effect and not to airborne-particle abrasion.

## SEM and EDS analyses

SEM analyses of failed dowels revealed differences in failure behavior and characteristics of the two dowel systems tested in this investigation. Within each dowel system, failed dowels revealed similar failure patterns, irrespective of experimental group. Micrographs of selected representative specimens are shown in Figures 3–7.

Both dowel systems tested in this investigation reveal stepped/indented shapes, even though these indentations were different for the two systems (Fig 3). All airborne-particle-abraded dowels from both dowel systems tested exhibited a smooth outer surface when viewed with SEM as compared to non-abraded dowels and also to intact, untested dowels (Fig 3).

All the failed specimens of ParaPost Fiber Lux revealed fractured fibers around the failure site in addition to the fracture of the resin matrix. The fibers had suffered mainly transverse fractures (Fig 4). Further evaluation of the ParaPost Fiber Lux system revealed sites away from the failure site that were mostly free of fibers and only resin matrix was present on the outer surfaces (Fig 5). This is probably attributed to the manufacturing of the dowels, wherein on the outer surface of the dowel there are few fibers, and the surface is mainly composed of resin material.

Failed specimens of FibreKor dowels revealed longitudinal fractures of the fibers in addition to transverse fractures (Fig 6).

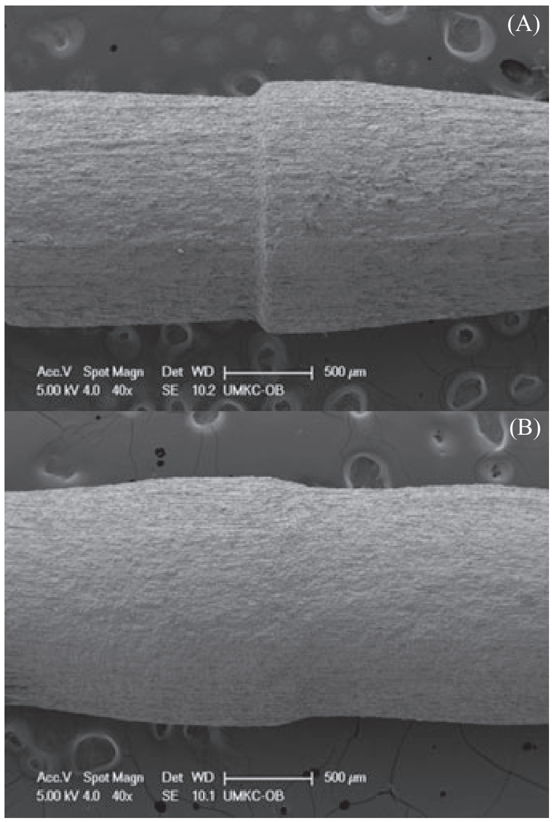


**Figure 3** SEM micrographs of: (A) ParaPost Fiber Lux and (B) FibreKor dowels. Both sections of the dowels shown above are from areas of the dowels away from the failure site. Both dowels have stepped shapes. Both dowels were from experimental groups that had been airborne-particle abraded and exhibited a smoother surface compared to non-abraded dowels.

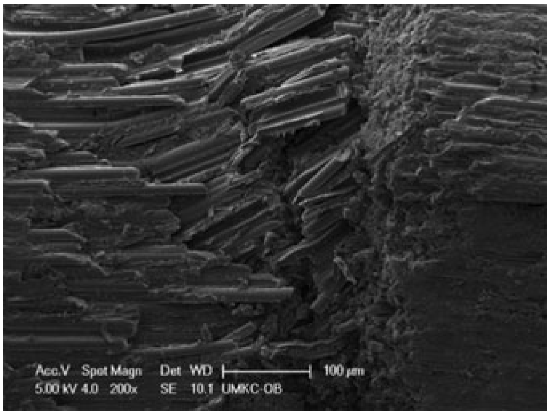


**Figure 4** SEM micrograph of the failure site of a tested ParaPost Fiber Lux dowel; this specific dowel came from the dry, non-abraded experimental group. Transverse fractures of the glass fibers can be observed on the superficial part of the dowel.

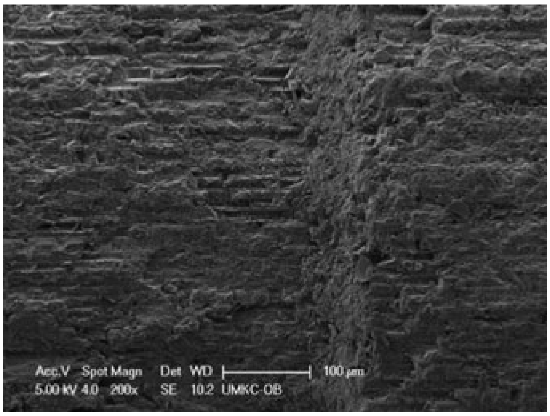


**Figure 5** SEM micrograph of a failed ParaPost Fiber Lux dowel, but from a site away from the failure. This specific dowel came from the dry, airborne-particle-abraded experimental group. Mostly resin matrix with few fibers can be seen.

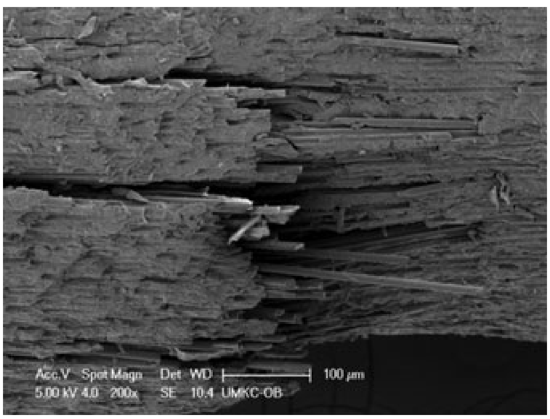


**Figure 6** SEM micrograph of the failure site of a tested FibreKor dowel; this specific dowel came from the dry, airborne-particle-abraded experimental group. Some fibers have fractured transversely, but longitudinal fracture of the glass fibers is also evident.

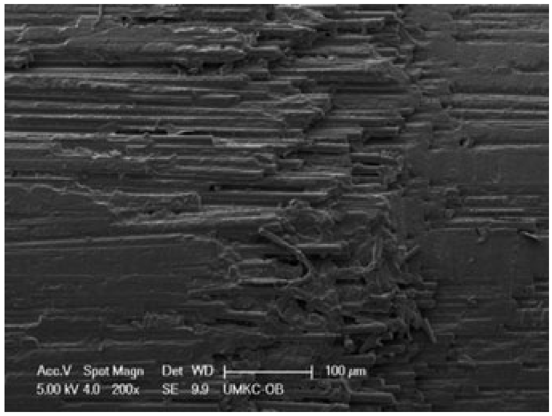


**Figure 7** SEM micrograph of a failed FibreKor dowel from a site away from the failure. The site viewed is along one of the multiple stepped formations on the dowel. This specific dowel came from the dry, non-abraded experimental group. Rough edges of glass fibers created during manufacturing of the dowels can be seen.

With all the FibreKor specimens, the weakest areas appear to be the stepped/indented areas on the surface. The stepped areas revealed abrupt fractures of the glass fibers even on intact, untested dowels (Fig 7).

The fibers in the two dowel systems in this study were also different, as shown by the EDS X-ray microanalysis. Even though both systems contained glass fibers, composed mainly of silica (Si), the glass fibers in the ParaPost Fiber Lux dowels were coated with zirconia (Zr) whereas the fibers of FibreKor dowels were not. EDS analysis of the FibreKor specimens revealed filler particles in the resin matrix, indicated by the presence of barium (Ba) and silica (Si), whereas there was no additional particulate filler in the ParaPost Fiber Lux dowels.

## Discussion

The results of this study indicate that aqueous storage over time resulted in a reduced flexural strength and modulus for both dowel systems tested. Therefore, the null hypothesis that there will be no statistically significant differences in the flexural strength and the flexural modulus of dowels stored in dry versus moist environments in combination with or without airborne-particle abrasion of the dowels was rejected. Previous studies have also reported decreased flexural strength of fiber-reinforced dowels after water storage.[6,7,30] Although the previous investigations evaluated different dowel systems than the two evaluated in the current study, their results support the flexural strength outcomes of this study.

While previous fiber-reinforced dowel studies have concentrated on evaluating flexural strength,[13,30] flexural modulus, which is related to stiffness and rigidity, is another important characteristic to consider.[31] In the current investigation, the dowels' flexural modulus was also tested to evaluate potential bending/flexing of the dowels, especially over time. Fiber-reinforced dowels are manufactured to have a modulus of elasticity similar to the modulus of elasticity of dentin (i.e., comparable flexure/bending characteristics).[3,4] Nevertheless, mechanical testing to measure elastic properties of dentin has resulted in different reported values. Early studies reported a mean elastic modulus of dentin in the range of 15 to 17.3 GPa,[32] whereas more recent investigations reported values of 25 to 30 GPa.[5] In this study, the highest mean flexural modulus values were recorded for the dry, non-abraded dowels (31.8 ± 0.9 GPa for the ParaPost Fiber Lux and 26.9 ± 1.35 MPa for the FibreKor), similar to the most recently reported values of the elastic modulus of dentin; however, the flexural modulus of both dowel systems decreased significantly over time with aqueous storage. The lowest recorded values of the flexural modulus values were 26 ± 2.1 GPa for the ParaPost Fiber Lux dowels and 24.7 ± 1.3 GPa for the FibreKor dowels. These decreases occurred over 30 days and even at that point, the lowest recorded flexural modulus of the dowels would be lower than the elastic modulus of dentin in some instances. This trend of decreasing modulus of elasticity over time may explain some clinical findings of debonding of fiber-reinforced dowels from endodontically treated teeth.[2,14] The decrease of the flexural modulus will result in increased flexibility of the dowel, which clinically may result in debonding. Interestingly, the flexural modulus reduction was detected only after the longer storage period (30 days), whereas reduction in flexural strength was noted even after 24-hour storage in aqueous solution. This may explain the wide range of success rates, from 100% to as low as 68%, that has been reported in different clinical studies of fiber-reinforced dowels.[2,14] In some clinical studies the results may have been calculated after relatively short periods in which reduction of flexural modulus of fiber-reinforced dowels has not yet occurred.

Based on the current results as well as previous studies, it appears that fiber-reinforced dowels are sensitive to aqueous exposure. The results of this study showed that with increasing storage time, flexural properties continue to decrease. Thus, it is important that residual moisture that might remain in a root canal system following endodontic treatment procedures and/or cementation procedures is removed prior to dowel placement.[33,34] Besides potential residual moisture considerations, previous investigations of fiber-reinforced dowels suggest that these dowels should be used only in situations where ample tooth structure remains. Poor clinical results have been reported in cases where the remaining coronal tooth structure is minimal.[2,14] These findings imply that the natural tooth structure encasing the dowel would be a support mechanism for these dowels. The results of this study tend to corroborate these findings. A gradual decrease in the flexural modulus of fiber-reinforced dowels may render them too flexible to withstand occlusal loads.

With every laboratory study, some assumptions have to be made that may not closely represent the clinical practice of dentistry. In this study, a limitation was the storage times of only 24 hours and 30 days. In clinical practice a dowel would be expected to withstand a longer passage of time; however, even though the evaluated storage times were relatively short, there was an observed trend of decreased flexural properties, and the decrease appeared to increase as the storage period increased. Another limitation of this study was that the dowels were stored in 100% aqueous solutions. It has been shown that moisture is present in teeth with endodontic treatments;[22] however, the degree of moisture would be less than 100%. A lower degree of moisture would likely result in less drastic reduction of mechanical properties or would require a longer period to demonstrate similar results. It is also important to note that to make definitive assumptions on the behavior of fiber-reinforced dowels, larger sample sizes and longer storage periods are needed.

Another observation is the amount of variability in the dowels as demonstrated by the flexural property standard deviation values. Even with the dry control group some variability likely reflected minor differences in the dowels related to the manufacturing process; however, with storage in moisture, the variability increased, suggesting individual differences in how the dowels responded to moisture.

The aim of this study was to test the fiber-reinforced dowels and directly evaluate their flexural properties to explain clinical performance reported in previous studies. The evidence from this preliminary study suggests that the clinical failure of these dowels could be linked to the reduction in the flexural properties over time, particularly the decrease in flexural modulus leading to increased flexibility. In previous investigations, fiber-reinforced dowels have been cemented in teeth and then stored in aqueous solutions prior to mechanical testing.[30,35–37] However, with such a testing configuration, flexural properties of the dowels cannot be directly measured. Instead, only dowel/tooth fracture strength can be measured.[35–37] In one of the previous studies,[30] the dowels were retrieved from the teeth to directly evaluate the dowel properties. Despite retrieving the dowels for direct evaluation, remnants of resin cement would likely remain and affect the mechanical properties of the dowels.[30]

SEM analyses performed in this study aimed to evaluate all the experimental groups of fiber-reinforced dowels tested and compare them to the untested, intact dowels. Micrographs were taken longitudinally and not transversely. Transverse viewing necessitates sectioning of the dowels, which may result in artifacts such as removal of resin matrix. An example of this artifact may be seen in a previously reported study,[36] where the transverse sections showed areas denuded of resin in the outer parts of the dowel. SEM results of this investigation showed that both dowel systems tested consisted of glass fibers (Si) and resin matrix surrounding the fibers; however, there were differences in the composition of the two dowels; the ParaPost Fiber Lux dowel fibers were coated with Zr, and the FibreKor matrix contained filler particles (indicated by the presence of Ba). These differences may have contributed to the different modes of failure between the two systems. The ParaPost Fiber Lux dowels failed mainly due to transverse fractures of fibers and resin on the surface of the dowels, suggesting a better bond between the fibers and the resin in that system as compared to FibreKor dowels.

It has been previously shown that degradation of resin matrices occurs in the presence of aqueous environment.[21] The dowel systems tested in this study have resin matrices surrounding glass fibers. In this investigation, under the procedures followed for SEM analyses, and for the storage periods tested, no degradation or sorption of the resinous matrix was observed, even in areas away from failure sites. Based on our analyses, it is the bond/interface between the glass fibers and the resin matrix that appeared to be the weak link. Separation of the fibers from the resin matrix occurred around the failure site and other sites on the dowels. This separation was more evident in the FibreKor dowels than in the ParaPost Fiber Lux. As mentioned above, there were differences in the composition of the two systems, and these differences may have contributed to the differences in the fiber–resin matrix bonds. As mentioned above, the results of this study on the failure behavior of the two-dowel system were based on the evaluation of a single random dowel from each experimental group. Further SEM and EDS investigations are necessary to validate these results.

The current results indicate that airborne-particle abrasion did not have a negative effect on the flexural strength nor on the flexural modulus of both fiber-reinforced dowel systems tested in this study. Previous investigations have shown that airborne-particle abrasion enhanced the bond strength of the dowel to the resin cement and the core material.[25-28] Therefore, based on these findings, airborne-particle abrasion would not be contraindicated as a mechanism for enhancing the adhesion between dowel and resin cement.

Unquestionably, fiber-reinforced dowels have better esthetic properties than metallic dowels, and there are clinical situations in which such dowels should be the preferred treatment;[1,2] however, the mechanical properties of these dowels still remain controversial. Clinical studies show a great range of success rates, ranging from 100% to as low as 68%,[15-20] which creates difficulty for making clinical decisions based on the evidence from the literature. A significant difference between fiber-reinforced dowels and metallic dowels is that, over time, the metallic dowels' structure and mechanical properties remain constant, whereas the fiber-reinforced dowels become weaker. Long-term clinical investigations would be most reliable to assess behavior and failure modes of fiber-reinforced dowels.

## Conclusions

Within the limitations of this in vitro study, the following conclusions can be drawn:

1. Aqueous storage of both fiber-reinforced dowels tested (ParaPost Fiber Lux and FibreKor) resulted in statistically significant reduction of flexural strength when the dowels were stored for 24 hours or 30 days.
2. Aqueous storage of the fiber-reinforced dowels tested resulted in statistically significant reduction of their flexural modulus only when the dowels were stored for 30 days.
3. Airborne-particle abrasion did not cause a significant adverse effect on the flexural properties of either fiber-reinforced dowel systems.
4. SEM analysis revealed that the failure mode of the two systems was different. The ParaPost Fiber Lux dowels failed mainly due to transverse fractures of the glass fibers and resin matrix, whereas the FibreKor dowels showed some transverse fractures along with longitudinal fractures of the fibers from the resin matrix. The fiber–resin interface was the weak structure for both systems tested, and it was weaker for the FibreKor dowels than for ParaPost Fiber Lux.

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## References

1. Bateman G, Ricketts DN, Saunders WP: Fibre-based post systems: a review. Br Dent J 2003;195:43-48 [discussion 37]
2. Baba NZ, Golden G, Goodacre CJ: Nonmetallic prefabricated dowels: a review of compositions, properties, laboratory, and clinical test results. J Prosthodont 2009;18:527-536
3. King PA, Setchell DJ: An in vitro evaluation of a prototype CFRC prefabricated post developed for the restoration of pulpless teeth. J Oral Rehabil 1990;17: 599-609
4. Asmussen E, Peutzfeldt A, Heitmann T: Stiffness, elastic limit, and strength of newer types of endodontic posts. J Dent 1999;27:275-278
5. Senawongse P, Otsuki M, Tagami J, et al: Age-related changes in hardness and modulus of elasticity of dentine. Arch Oral Biol 2006;51:457-463
6. Lassila LV, Nohrstrom T, Vallittu PK: The influence of short-term water storage on the flexural properties of unidirectional glass fiber-reinforced composites. Biomaterials 2002;23:2221-2229
7. Lassila LV, Tanner J, Le Bell AM, et al: Flexural properties of fiber reinforced root canal posts. Dent Mater 2004;20:29-36
8. Peutzfeldt A, Sahafi A, Asmussen E: A survey of failed post-retained restorations. Clin Oral Investig 2008;12:37-44
9. Martinez-Insua A, da Silva L, Rilo B, et al: Comparison of the fracture resistances of pulpless teeth restored with a cast post and core or carbon-fiber post with a composite core. J Prosthet Dent 1998;80:527-532
10. Ferrari M, Vichi A, Garcia-Godoy F: Clinical evaluation of fiber-reinforced epoxy resin posts and cast post and cores. Am J Dent 2000;13:15B-18B
11. Theodosopoulou JN, Chochlidakis KM: A systematic review of dowel (post) and core materials and systems. J Prosthodont 2009;18:464-472
12. Newman MP, Yaman P, Dennison J, et al: Fracture resistance of endodontically treated teeth restored with composite posts. J Prosthet Dent 2003;89:360-367
13. Galhano GA, Valandro LF, de Melo RM, et al: Evaluation of the flexural strength of carbon fiber-, quartz fiber-, and glass fiber-based posts. J Endod 2005;31:209-211
14. Cagidiaco MC, Goracci C, Garcia-Godoy F, et al: Clinical studies of fiber posts: a literature review. Int J Prosthodont 2008;21:328-336
15. Hedlund SO, Johansson NG, Sjogren G: A retrospective study of pre-fabricated carbon fibre root canal posts. J Oral Rehabil 2003;30:1036-1040
16. Ferrari M, Cagidiaco MC, Goracci C, et al: Long-term retrospective study of the clinical performance of fiber posts. Am J Dent 2007;20:287-291
17. Glazer B: Restoration of endodontically treated teeth with carbon fibre posts—a prospective study. J Can Dent Assoc 2000;66:613-618
18. Mannocci F, Qualtrough AJ, Worthington HV, et al: Randomized clinical comparison of endodontically treated teeth restored with amalgam or with fiber posts and resin composite: five-year results. Oper Dent 2005;30:9-15
19. Mannocci F, Bertelli E, Sherriff M, et al: Three-year clinical comparison of survival of endodontically treated teeth restored

with either full cast coverage or with direct composite restoration. J Prosthet Dent 2002;88:297-301
20. King PA, Setchell DJ, Rees JS: Clinical evaluation of a carbon fibre reinforced carbon endodontic post. J Oral Rehabil 2003; 30:785-789
21. Ferracane JL: Hygroscopic and hydrolytic effects in dental polymer networks. Dent Mater 2006;22:211-222
22. Papa J, Cain C, Messer HH: Moisture content of vital vs endodontically treated teeth. Endod Dent Traumatol 1994;10: 91-93
23. Rathke A, Haj-Omer D, Muche R, et al: Effectiveness of bonding fiber posts to root canals and composite core build-ups. Eur J Oral Sci 2009;117:604-610
24. Bitter K, Neumann K, Kielbassa AM: Effects of pretreatment and thermocycling on bond strength of resin core materials to various fiber-reinforced composite posts. J Adhes Dent 2008;10: 481-489
25. Balbosh A, Kern M: Effect of surface treatment on retention of glass-fiber endodontic posts. J Prosthet Dent 2006;95:218-223
26. Sahafi A, Peutzfeld A, Asmussen E, et al: Effect of surface treatment of prefabricated posts on bonding of resin cement. Oper Dent 2004;29:60-68
27. Sahafi A, Peutzfeldt A, Asmussen E, et al: Bond strength of resin cement to dentin and to surface-treated posts of titanium alloy, glass fiber, and zirconia. J Adhes Dent 2003;5:153-162
28. Kelsey WP, 3rd, Latta MA, Kelsey MR: A comparison of the retention of three endodontic dowel systems following different surface treatments. J Prosthodont 2008;17:269-273
29. ASTM Standard D4476: Standard Test Method for Flexural Properties of Fiber Reinforced Pultruded Plastic Rods. American Society for Testing and Materials (ASTM) International, West Conshohocken, PA; 2009
30. Mannocci F, Sherriff M, Watson TF: Three-point bending test of fiber posts. J Endod 2001;27:758-761
31. Anusavice KJ: Mechanical properties of dental materials. In Anusavice KJ (ed): Phillips' Science of Dental Materials, vol 1 (ed 10). Philadelphia, Saunders, 2003, pp. 49-74
32. Craig RG, Peyton FA: Elastic and mechanical properties of human dentin. J Dent Res 1958;37:710-718
33. Chersoni S, Acquaviva GL, Prati C, et al: In vivo fluid movement through dentin adhesives in endodontically treated teeth. J Dent Res 2005;84:223-227
34. Mannocci F, Bertelli E, Watson TF, et al: Resin-dentin interfaces of endodontically-treated restored teeth. Am J Dent 2003;16:28-32
35. Cormier CJ, Burns DR, Moon P: In vitro comparison of the fracture resistance and failure mode of fiber, ceramic, and conventional post systems at various stages of restoration. J Prosthodont 2001;10:26-36
36. Vichi A, Vano M, Ferrari M: The effect of different storage conditions and duration on the fracture strength of three types of translucent fiber posts. Dent Mater 2008;24: 832-838
37. Vano M, Carvalho C, Sedda M, et al: The influence of storage condition and duration on the resistance to fracture of different fiber post systems. Am J Dent 2009;22:366-370