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# Creep and dynamic viscoelastic behavior of endodontic fiber-reinforced composite posts

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## Abstract

*Purpose:* Fiber-reinforced composite (FRC) posts have gained much interest recently and understanding of their viscoelastic properties is important as they can be used in stress-bearing posterior restorations. The aim of this study was to evaluate the creep behavior and the viscoelastic properties of four commercial FRC posts under different temperatures and different storage conditions.
*Methods:* The FRC posts tested were Glassix, C-Post, Carbonite and Snowlight. For the creep measurements a constant load below the proportional limit of the posts was applied and the angular deformation of the specimens was recorded. The viscoelastic parameters were determined by using dynamic torsional loading under four different conditions.
*Results:* All materials were susceptible to creep and exhibited linear viscoelastic behavior. Residual strain was observed in all FRC posts. The viscoelastic properties were affected by the increase of temperature and water storage ($p < 0.001$) resulting in their decline. Carbon fiber posts exhibited better performance than glass fiber posts.
*Conclusions:* FRC posts exhibit permanent strains under regular masticatory stresses that can be generated in the oral cavity. Their properties are susceptible to changes in temperature, while direct contact with water also affects them deleteriously.


*Keywords:* Fiber post; Loss tangent; Creep; Temperature

## 1. Introduction

Restoration of endodontically treated teeth is a complicated procedure because of the various factors that need to be considered. These factors include retention of the restoration, the amount of remaining sound tooth structure, masticatory forces, prevention of microleakage and also the aesthetic performance in the case of anterior teeth. While for many years the insertion of a post was considered as a standard process in order to improve the strength of the tooth, it is now accepted that preservation of as much tooth substance as possible is of primary importance [1–3]. Endodontically treated teeth are weakened because of dental caries, removal of older restorations and because of the endodontic procedure. Placement of a root canal post causes further loss of tooth substance, therefore making their use favorable only in cases with adequate tooth volume.

Until recently, metal posts were the only material available in the restoration of endodontically treated teeth and exhibited satisfactory clinical results [4,5]. However, the increased contemporary aesthetic demands led to the introduction of composite posts as a more aesthetic alternative to metal posts. These posts are fiber-reinforced composites (FRC) and consist of unidirectional fibers impregnated in a polymer matrix. The polymer matrix is usually made of a highly cross-linked epoxy resin with a high degree of conversion [6] which protects and supports the fibers while distributing the stresses inside the composite. The polymer matrix retains the orientation of the fibers and determines the shear strength and temperature limitations of the composite material. The fibers can be made of carbon, glass or quartz and they increase the elastic modulus,

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**Table 1**
The materials used in the study.

| Post | Fiber type | Ø (mm) | Fiber vol. (%) | Matrix | Manufacturer |
|---|---|---|---|---|---|
| Carbonite (CB) | HTA/HTS carbon fiber braided plate | 1.2 | 65% | Epoxy resin | Harald Nordin SA, Montreux, Switzerland |
| C-Post (CP) | Pyrolitic carbon fiber | 1.2 | 64% | Epoxy resin | Bisco Dental Products, Schaumburg, IL, USA |
| Glassix (GL) | Glass fiber braided plate | 1.4 | 65% | Epoxy resin | Harald Nordin SA, Montreux, Switzerland |
| Snowlight (SN) | Zircon-rich glass fiber | 1.2 | 65% | Polyester methacrylate resin | Carbotech, Ganges, France |

the tensile and fatigue strength and the volumetric stability of the composite.

Although FRC posts were introduced as an aesthetic alternative, their use is based on the mechanical notion that materials restoring endodontically treated teeth should have similar mechanical properties with that of tooth substance [7]. Composite posts possess an elastic modulus close to that of dentin, thus creating a more homogenous restorative system consisting of the post, resin cement, core material along with the tooth substance. In this way, distribution of stresses to the root is more even and there is less risk of a root fracture, in contrast to what occurs in the case of metal posts [8].

It is obvious that knowledge of the physical properties of the FRC posts is very important in order to predict their performance in the oral environment. Posts are inserted into the root canals of weakened non-vital teeth that suffer from loss of tooth substance and therefore their behavior under the forces generated in the mouth is important for the longevity of the restoration. While there is a significant number of *in vitro* research studies regarding the fracture strength of the composite posts [9–11], there is not much data regarding their behavior under smaller stresses and the deformations that they may exhibit because of their polymer matrix.

Polymers cannot be classified as a specific type of material such as a glassy solid or a viscous liquid. They can show all the features of a glassy, brittle solid or an elastic rubber or a viscous liquid depending on different conditions [12], a combined solid/fluid behavior which is defined by viscoelasticity. Purely elastic materials recover completely after removal of the load, while purely viscous materials remain fully deformed. Their response to an applied stress depends on both temperature and time. Temperature dependence is influenced by the thermal properties of the material, while time dependence is influenced by the stress rate and the duration of the applied stress. In polymer matrix composites, the viscoelastic behavior of the composite as a whole depends on the stress experienced by the matrix.

The viscoelastic behavior of a material has a profound influence on its performance. Creep is the deformation generated in a material while it is under the influence of a constant stress. When stress is no longer applied, the material enters into the recovery phase. Static tests can give important information about the viscoelastic properties of the materials tested like shear modulus $G$, compliance $J$ and the residual deformation without catastrophic failure of the specimens. Creep has potential clinical relevance in that parts of the restored tooth may undergo progressive motion under the static component of masticatory force.

Dynamic tests can also be used to evaluate the viscoelastic properties of materials. In these tests values of storage and loss moduli are calculated. The storage modulus defines the amount of recoverable energy stored within the material (solid-like behavior), while the loss modulus defines the amount of unrecoverable energy lost within a deformed material (fluid-like behavior). Analogous to the creep and stress relaxation experiments, which determine the time- and temperature-dependent functions, are the dynamic mechanical experiments, which define the frequency and temperature-dependent functions characteristic of viscoelastic materials such as plastics.

The aim of this study was to evaluate the creep behavior and the viscoelastic properties under different temperatures of both glass fiber and carbon fiber endodontic posts. The null hypothesis was that the different fiber materials do not have differences in their properties and they are not affected by environmental changes.

## 2. Materials and methods

In this study four types of fiber-reinforced posts were used. Two of them were glass fiber posts (Glassix, Snowlight) and the other two carbon fiber posts (C-Post, Carbonite). The materials used are listed in Table 1. The posts were tested under creep at 21 °C. Measurement in dynamic testing took place with the materials dry at 21 °C and wet at 21 °C, 37 °C and 50 °C. Specimens tested wet were stored in beakers with distilled water for 24 h.

### 2.1. Creep measurements

From each type of FRC post four specimens were tested under different stresses. The specimens were mounted using a jig for centering, between a Plexiglas disk and a rod by means of a self-cured composite material, after being silanized at their ends (2 mm at each end). The specimens were tested in a torsional creep apparatus that is described by Lakes [13] and is capable of torsion or bending tests upon cylindrical specimens, following static or dynamic methods (Fig. 1). A permanent, high-intensity, samarium cobalt magnet was attached to the end of the specimen and placed at the center of a Helmholtz coil.

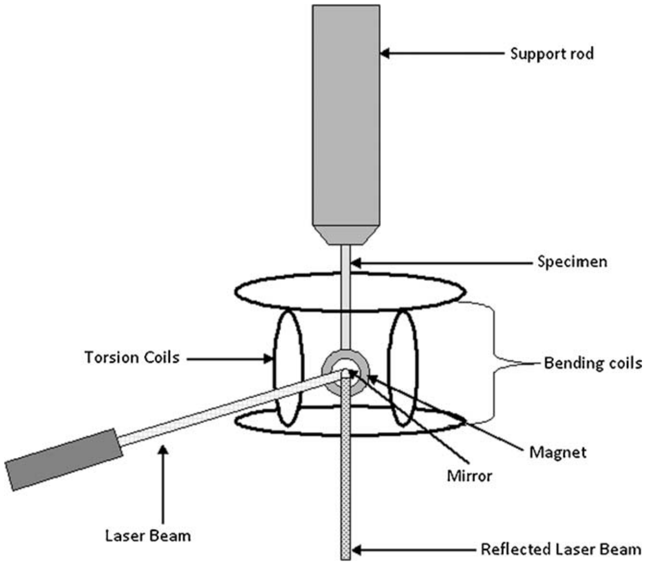


**Fig. 1.** Apparatus used in the study.

This cylindrical magnet ($M = 1.01 \times 10^{-2}$ N m/A) was able to produce torque on the specimen, controlled by the current in the coil. A thin mirror ($d$ = 1 mm) was cemented onto the magnet to reflect the laser beam spot of a low power helium neon laser on a calibrated chart at a distance $D$ = 944 cm.

Only a small constant axial tensile stress was created on the specimen by the weight of the magnet and there was no constraint on the specimen for either torsion or extension. The torsional load generates an axial deformation on the specimen which in the case of a small torque is negligible. The weight of the magnet used also causes a small axial deformation which is considered negligible. In addition, the measurement of torsional angular displacement is insensitive to any axial deformation which may occur [14].

The distribution of shear strain, $\gamma$, in a circular cylinder in torsion is $\gamma = r\varphi/L$, where $r$ is the radial distance from the centerline and $L$ is the length of the cylinder. The distribution of shear stress $\sigma$ depends on the material properties of the specimen and in the case of linearly elastic or linearly viscoelastic materials it is given by $\sigma = MR/(\pi R^4/2)$, where $R$ is the specimen radius and $M$ is the torque. When small stresses are being used, the specimens are linearly viscoelastic and torsion results can be interpreted.

The shear modulus $G = \sigma/\gamma$ is calculated from the equation $G = 2ML/\pi R^4\varphi$, after a constant torque was applied to the specimen for 10 s. The angular displacement was recorded and the torque was 'instantaneously' released. The shear stress and shear modulus at 10 s reflect the instantaneous elastic response of the material. Compliance $J$ is the reciprocal of the shear modulus. The experiment consisted of applying a constant torque and recording the angular displacement of the specimen for duration of 3 h. The stress was then released and the recovery was recorded for 50 h. The specimens were tested at four different torques $5.07 \times 10^{-4}$, $7.06 \times 10^{-4}$, $9.63 \times 10^{-4}$ and $12.37 \times 10^{-4}$ N m/A which resulted to stresses from 2.23 to 11.64 MPa.

### 2.2. Dynamic viscoelastic measurements

In the case of the dynamic method the storage modulus $G_1$ (the real part of the complex modulus $G^*$) is in phase with the strain, while the loss modulus $G_2$ (the imaginary part of the complex modulus $G^*$) is 90° out of phase with the strain. Loss modulus is related to the dissipation of energy. Both stress and strain vary sinusoidally. The complex modulus $G^*$ is approximately equal to the storage modulus $G_1$ because in most cases of stiff solids $G_2$ is small compared to $G_1$. The ratio of the imaginary part to the real part ($G_2/G_1$) of the complex modulus $G^*$ is called the loss tangent (tan $\delta$) and represents the phase angle between stress and strain sinusoids. The loss tangent is proportional to the energy loss per cycle while in the framework of linear viscoelasticity.

In the present study frequencies that ranged from 1 to 100 Hz were used for the dynamic torsional vibration of the specimens tested. The displacement of amplitude was measured for on the chart for each frequency. The viscoelastic parameters were calculated by using the resonance frequency $\nu_o$, which corresponds to the peak amplitude and the resonance full width $\Delta\nu$, which is the difference between the two frequencies at which the amplitude is half of the maximum. The loss tangent is calculated from the following equation: $\tan\delta = (1/\sqrt{3})(\Delta\nu/\nu_o)$ and the storage modulus from: $\nu_o = (1/2\pi)\sqrt{G_1\pi r^4/2LI}$ where $L$ is the length of the specimen, $r$ the radius of the specimen and $I$ is the moment of inertia of the magnet which was measured to be $4.4 \times 10^{-7}$ kg m$^2$.

### 2.3. Statistical analysis

The mean values and standard deviation of initial strain, % of residual strain and shear modulus were measured and statistical significant differences were found using two-way ANOVA and Bonferroni post-tests (independent parameters: torque and materials) $\alpha = 0.05$. Mean values and standard deviation of shear storage modulus, loss tangent, quality factor, coefficient of decay and dynamic viscosity were calculated. The effect of wet and dry testing at 21 °C (independent parameters: material, testing condition) and also the effect of temperature for the materials tested wet (independent parameters: material, temperature) on loss tangent, storage modulus and quality factor were calculated with two-way ANOVA and Bonferroni post-tests.

## 3. Results

The applied torque of each specimen, the initial strain, the percentage of residual strain and the initial shear modulus are shown in Table 2. The creep curves of the four FRC posts tested in 21 °C are given in Fig. 2. The curves were normalized by using the initial strains at 10 s. The creep compliance (stress/strain) curves of the materials tested are shown in Fig. 3. Instantaneous elastic strain was quickly recovered after the torque was removed at 3 h, however all the materials exhibited retarded strain which was not fully recovered at 50 h. The initial strains varied between the different materials and increased

**Table 2**
Creep results of the initial and residual strain and initial shear modulus (mean and S.D., $n = 4$).

| Materials | Applied torque ($\times 10^{-4}$ N m/A) | Initial strain ($\gamma_o$) ($\times 10^{-4}$ rad) | Residual strain ($\gamma_t/\gamma_o$), % | Initial shear modulus (GPa) |
|---|---|---|---|---|
| GL | 5.07 | 4.33 (0.51)[a] | 0.55 (0.32)[e] | 5.11 (0.43)[h] |
| | 7.06 | 5.55 (0.58) | 1.93 (0.41)[f] | |
| | 9.63 | 7.29 (0.62) | 4.95 (0.36) | |
| | 12.67 | 10.49 (0.43) | 10.34 (0.51) | |
| CB | 5.07 | 6.16 (0.69)[b] | 0.54 (0.28)[e] | 3.74 (0.16) |
| | 7.06 | 9.26 (0.82) | 0.6 (0.33)[g] | |
| | 9.63 | 10.74 (0.55)[c] | 0.86 (0.24) | |
| | 12.67 | 14.43 (0.23)[d] | 4.2 (0.39) | |
| CP | 5.07 | 6.94 (0.44)[b] | 0.6 (0.23)[e] | 6.78 (0.47) |
| | 7.06 | 10.64 (0.32) | 0.77 (0.32)[g] | |
| | 9.63 | 14.75 (0.34) | 4.01 (0.26) | |
| | 12.67 | 15.06 (0.19)[d] | 5.13 (0.41) | |
| SN | 5.07 | 4.75 (0.37)[a] | 0.57 (0.32)[e] | 5.72 (0.14)[h] |
| | 7.06 | 6.93 (0.51) | 1.51 (0.24)[f] | |
| | 9.63 | 11.63 (0.24)[c] | 1.86 (0.41) | |
| | 12.67 | 16.31 (0.51) | 7.23 (0.48) | |

Same superscript letters show values with no statistically significant difference ($p > 0.05$).

significantly with the increase of torque. Residual strain also increased with torque and at the highest torque ($12.67 \times 10^{-4}$ N m/A) it was found to be 10.34% for GL and 7.3% for SN, while CP had 5.13% and CB 4.02%, with all materials having statistical significant differences ($p < 0.001$) among them.

The material with the highest shear modulus was CP with 6.78 GPa. SN and GL followed with 5.72 and 5.11 GPa respectively and the lowest shear modulus was observed in CB with 3.74 GPa. Statistical analysis showed significant differences among all groups except between SN and GL ($p > 0.05$).

The mean values of loss tangent, quality factor, coefficient of decay and dynamic viscosity are shown in Table 3. Temperature had a significant effect ($p < 0.001$) on the properties of all the materials tested with the exception of the loss tangent of CP. Storage modulus $G_1$ (Fig. 4) and quality factor $Q$ (Fig. 5) decreased with the increase of temperature, while loss tangent and coefficient of decay increased. Statistically significant differences were found between all four types of posts tested at 21 °C dry and wet, with the materials tested wet possessing higher loss tangent and coefficient of decay and lower storage modulus and quality factor.

GL presented the highest loss tangent ($p < 0.001$) among the materials in all conditions tested. SN, CB and CP had loss tangents that were not significantly different ($p > 0.05$) in 21 °C dry and wet. With the increase of temperature however, SN possessed higher loss tangent than CB and CB when stored in water and tested wet in 37 and 50 °C.

CP was the material found to have the highest quality factor in all temperatures in both dry and wet conditions. GL and SN showed similar quality factors in all conditions tested ($p > 0.05$), while CB presented significantly higher quality factor than GL in 37 and 50 °C and than SN in 50 °C.

The shear storage moduli of SN and GL, like in the case of static measurements, did not exhibit statistically significant differences ($p > 0.05$). CB had the highest storage modulus, followed by SN and GL with CB presenting the lowest modulus. The storage modulus values calculated for specimens tested dry at 21 °C were higher than the static ones.

## 4. Discussion

Based on the results of this study, the null hypothesis has to be rejected. Differences were found among the different materials and their properties changed under the influence of different conditions.

Linear viscoelastic behavior for all the materials is indicated by the superimposition of the creep curves from the four FRC posts tested. This means that creep compliance is a function of time alone and not of the magnitude of stress. In all the materials there was an initial elastic response to the initial loading. The elastic strain was followed by a time-dependent viscoelastic deformation which defines the creep stage. After the load was removed, the recovery period was characterized by an instantaneous elastic recovery and then by a slower recovery called the retarded elastic recovery. This behavior is generally observed in polymers and has been reported for composite resins in the past [15–17]. The FRC posts tested are made of a highly cross-linked resin polymer matrix and thus, their behavior was expected to be linear viscoelastic.

When tested in low stress levels (2–3 MPa) all materials exhibited similar creep behavior, presenting similar ($p > 0.05$) residual strain which was very small. With the increase of torque the materials differed in their residual strains. The carbon fiber based materials showed the least residual strain, while the glass fiber based materials exhibited significantly higher strains. Another issue that should be discussed is the distribution of these stresses *in vivo*. It has been found in 3D finite element analyses that in FRC posts maximum stresses are gathered at the cervical third of the root canal [18,19]. Thus, the FRC post should possess more strength at that area, something that could be achieved with more volume of FRC material placed at that part of the post or with careful choosing of the adhesive, as different adhesives provide different bond strengths [20]. As adhesion failure seems to be the most common type of failure of FRC posts [21], this problem is important.

Under dynamic testing the materials were directly affected by the influence of water and changes of temperature. GL, CB and SN exhibited a significant decline in their viscoelastic properties, while CP was affected more mildly. The degradation in the flexural properties of FRC posts has been observed in the past by other researchers [6,22–24]. The deleterious effect of water to the properties of the FRC posts has been attributed to the plasticizing effect of its molecule inside the polymer network of the resin matrix. The small water molecules can be dissolved in the polymer without forming any strong bonds with it. They provide more space for chain segment rotation

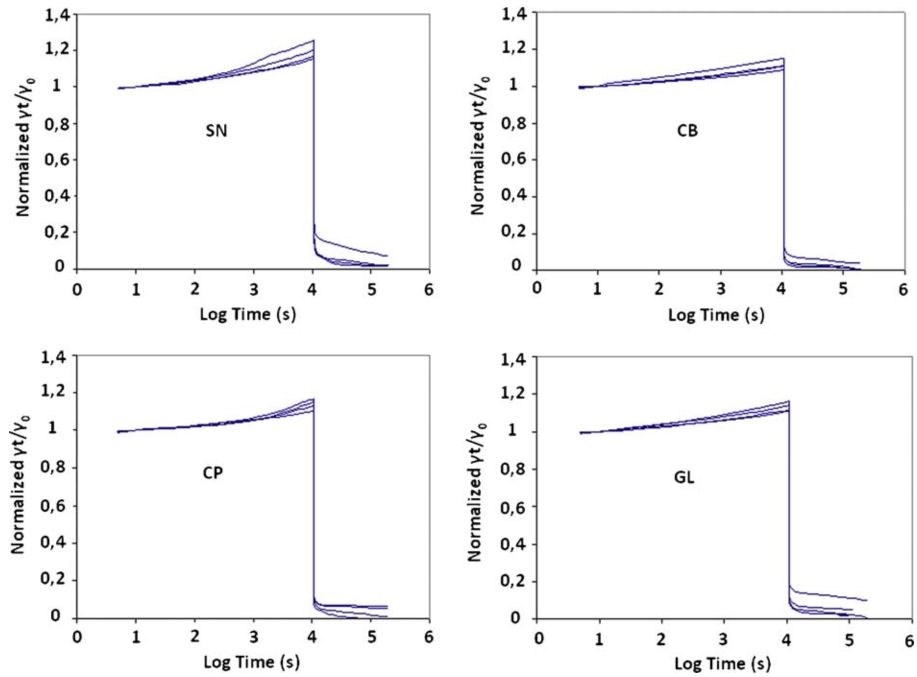


**Fig. 2.** Creep and recovery curves of the materials. The typical stages of deformation (instant elastic and viscoelastic) and recovery (instantaneous and retarded elastic) can be seen (materials tested at 21 °C under torques of: 5.07, 7.06, 9.63 and 12.67 × $10^{-4}$ N m/A).

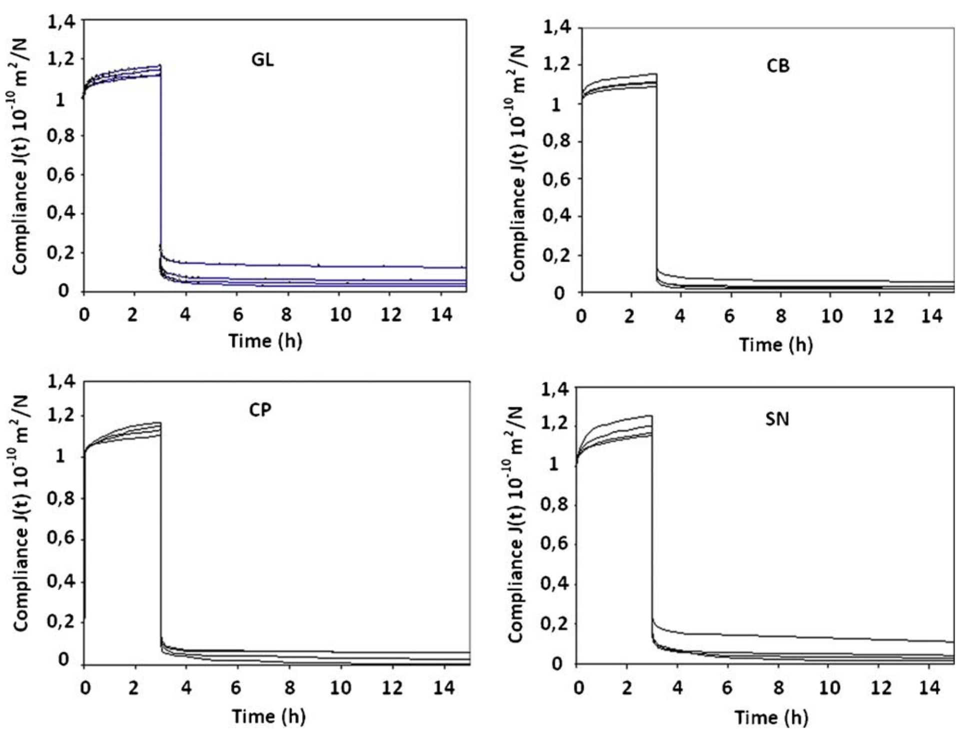


**Fig. 3.** Creep compliance curves (materials tested at 21 °C under four torques: 5.07, 7.06, 9.63 and 12.67 × $10^{-4}$ N m/A).

because they hold the chains apart and reduce the van der Waals forces operating between them, but also because they are much more mobile than the polymer chains themselves [25]. This causes an effect similar to the increase of the free volume of the polymer. The easier movement of the chains results in the lower modulus observed.

The change of temperature from 21 to 37 °C and then to 50 °C caused a decline in the storage modulus of the materials. In GL there was a 20% decrease of $G_1$, in SN a 17% decrease, 12% in CB and 9% in CP (Fig. 4). Significant decrease of the quality factor was also found with change of temperature (Fig. 5). Quality factor is indicative of the shape of the

**Table 3**
Viscoelastic properties at different storage conditions and temperatures (mean values and S.D., $n = 4$).

| Materials | Condition | Loss tangent (tan $\delta$) | Quality factor ($Q$) | Coefficient of decay ($a$) | Dynamic viscosity $n^*$ (MPa s) |
|---|---|---|---|---|---|
| GL | Dry 21 °C | 0.0508 (0.004) | 27.38 (1.1)$^{c}$ | 11.06 (0.84) | 17.04 (0.46) |
| | Wet 21 °C | 0.0586 (0.002) | 23.50 (1.58)$^{d}$ | 12.75 (1.03) | 16.87 (0.33) |
| | Wet 37 °C | 0.071 (0.003) | 18.53 (1.24)$^{e}$ | 15.46 (1.02) | 16.13 (0.51) |
| | Wet 50 °C | 0.0912 (0.001) | 13.51 (1.87)$^{f}$ | 19.85 (1.16) | 15.12 (0.67 |
| CB | Dry 21 °C | 0.0305 (0.007)$^{a}$ | 29.42 (1.6)$^{c}$ | 7.71 (0.95) | 16.90 (0.23) |
| | Wet 21 °C | 0.0391 (0.003)$^{b}$ | 24.25 (1.48)$^{d,i}$ | 9.20 (0.42) | 15.70 (0.38) |
| | Wet 37 °C | 0.0420 (0.004) | 22.07 (2.12)$^{g,i}$ | 9.82 (0.44) | 15.20 (0.41) |
| | Wet 50 °C | 0.0490 (0.004) | 20.28 (1.75) | 10.37 (0.32) | 14.80 (0.26) |
| CP | Dry 21 °C | 0.0299 (0.002)$^{a}$ | 33.35 (1.88) | 25.76 (1.88) | 8.03 (0.15) |
| | Wet 21 °C | 0.0365 (0.008)$^{b}$ | 27.35 (1.76)$^{h}$ | 31.29 (1.92) | 8.01 (0.22) |
| | Wet 37 °C | 0.0369 (0.004)$^{b}$ | 27.09 (1.44)$^{h}$ | 30.76 (2.01) | 7.79 (0.18) |
| | Wet 50 °C | 0.0375 (0.003)$^{b}$ | 26.67 (2.02)$^{h}$ | 30.60 (1.43) | 7.63 (0.24) |
| SN | Dry 21 °C | 0.0330 (0.007)$^{a}$ | 30.27 (1.83)$^{c}$ | 8.98 (1.02) | 20.01 (0.43) |
| | Wet 21 °C | 0.0443 (0.01)$^{b}$ | 22.55 (1.23)$^{d}$ | 11.66 (0.53) | 19.29 (0.37) |
| | Wet 37 °C | 0.0522 (0.009) | 19.16 (1.53)$^{e,g}$ | 13.45 (0.88) | 18.91 (0.52) |
| | Wet 50 °C | 0.0741 (0.01) | 13.50 (0.97)$^{f}$ | 17.72 (1.44) | 17.59 (0.62) |

Same superscript letters show mean values with no statistically significant difference ($p > 0.05$).

resonance curve and when it is high, like in the case of CP, it shows a peaked resonance curve and little damping. The effect of temperature changes on the properties of fiber-reinforced composites can be explained by the differences between the thermal expansion coefficients of the composites' constituents [6,26,27]. The polymer matrix has a much higher coefficient than that of fibers either glass, quartz or carbon and this can lead to the generation of stresses. It is possible that these stresses can cause adhesive failure between the fibers and the matrix, resulting in the decrease of their viscoelastic properties.

In the present study four different commercial fiber-reinforced posts were tested. Two of them consisted of carbon fibers and two of them had glass fibers. The fiber content of the composite plays an important role on its elastic properties as it affects the modulus and the strength of the material. According to the manufacturers, the % volume fiber content of the materials used is similar ranging from 64 to 65%, so any differences between the materials tested in this study cannot be attributed to the differences between the fiber volume content.

CP was the material with the highest shear modulus calculated both under static and dynamic conditions. CP has a higher modulus than the other carbon fiber-reinforced material (CB) and this could be explained by the fact that CP consists of pyrolitic carbon fibers which have a higher modulus than HTA/HTS graphite fibers. What is more important though is that CP had the best behavior under the effect of water and temperature changes. It was the material with the smallest changes in its properties from 21 to 50 °C, resulting in a 9% decrease in storage modulus and a 2.5% increase of the loss tangent, which was found to be not statistically significant ($p > 0.05$). While pyrolitic carbon fibers have a slightly higher coefficient of thermal expansion compared to graphite and glass fibers, there is still an important difference with the polymer matrix coefficient and so its resistance to temperature changes cannot be justified by this fact. A possible reason for this finding could be that the sizing agent used in CP created a stronger bond between the fibers and the matrix, withstanding the stresses generated. This material also presented the lowest loss tangent and highest quality factor under all conditions. The loss tangent is a measure of the ratio of energy lost to energy stored, thus determining properties as damping of free vibrations, attenuation of propagated waves and the frequency width of a resonance response.

CB was the material with the least residual strain under the highest torque and along with the other carbon-reinforced post (CP) exhibited better resistance to creep than the glass fiber posts. It also had better resistance to the effects of water and temperature change than the glass fiber posts. Surprisingly, its shear modulus (both static and storage) was found to be lower than the moduli of GL and SN that consist of glass fibers.

The material with the highest residual strain was GL in the three out of four different torque levels the FRC posts were tested. It was also the material with the highest loss tangent in all conditions tested. It presented a similar static and storage shear modulus to SN, something that was largely expected due to the fact that they both consist of glass fibers in similar volume content. GL was affected by the different testing conditions, presenting the highest decline of storage modulus (20%) and the second highest increase of loss tangent.

The creep compliance curves show that SN was the most susceptible material to creep by possessing the highest compliance among the materials on all four different stresses. SN also presented the second highest residual strain under the effect of the highest torque. While its loss tangent was similar to that of the carbon fiber posts when tested at 21 °C the effect of temperature caused a severe decline to its properties. With the increase of temperature its loss tangent increased by 67% at 50 °C, the highest among the materials, and its storage modulus decreased by 17% which was second highest. It also was the material that water storage had the biggest effect on, when tested at 21 °C. The most important difference between SN and the other materials was its resin matrix. SN was the only

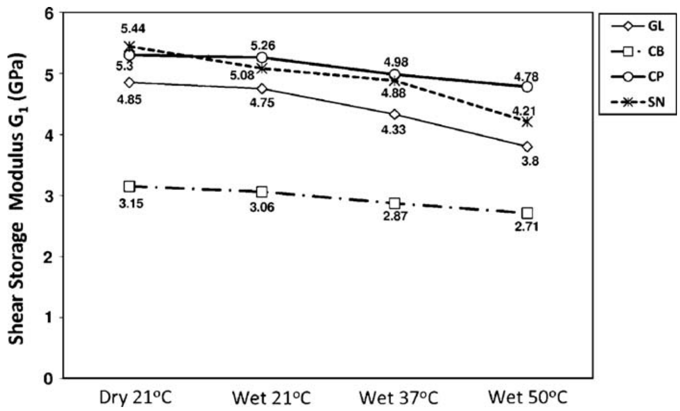


**Fig. 4.** The decrease of the shear storage modulus ($G_1$) of the materials under the different testing conditions: dry 21 °C, wet 21 °C, wet 37 °C, wet 50 °C.

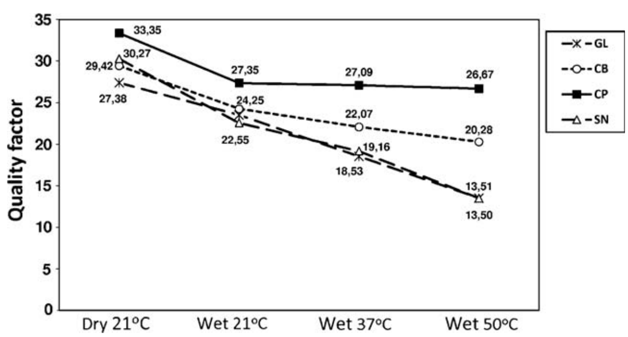


**Fig. 5.** The decrease of the quality factor ($Q$) of the materials under the different testing conditions: dry 21 °C, wet 21 °C, wet 37 °C, wet 50 °C.

material that was not based on an epoxy resin matrix, for reasons of light translucency the zircon-rich glass fibers are embedded in a polyester methacrylate matrix. Polyester resins exhibit high polymerization shrinkage that can weaken the glass–resin bond and can also place stresses other than tension on the glass fibers, while epoxy resins offer better adhesive properties [28]. It can be postulated that this is the main reason behind its behavior under the increase of temperature and the effect of water.

All the materials tested were susceptible to creep under the stresses used and did not exhibit full recovery. This could be a problem under clinical conditions where an endodontic post has to withstand many masticatory cycles. The stresses used in this study were at the range of physiological bite forces [29,30], however the maximum stresses generated in the oral cavity can be higher and the materials' performance could be hindered by the inelastic strain which they can exhibit under these stresses. It has been shown that composite resin materials with high creep strains have lower resistance to mechanical stress [17] and this could be the case with the FRC posts. It should be noted though that this study is an *in vitro* study and the results should be considered carefully. The FRC posts operate inside the canal root being bonded to its walls while usually supporting a crown. It is obvious that endodontic posts perform under a complex system consisting of different materials and are being subject to different kinds of stresses. This study is not a prediction of the FRC posts' behavior inside the oral cavity, but instead it is indicative of the properties of the materials themselves.

The results of this study are in agreement with previous studies regarding the mechanical stability of fiber-reinforced composite posts [6,31]. These materials are sensitive to both water and temperature changes. The decline of their properties might cause problems to their long term service when they are inserted into the root canal. Mannocci et al. [31] stored FRC posts inside root canals of bovine teeth immersed in water and found out that under this type of storage the flexural properties of the posts were not affected, while Vichi et al. [32] used human teeth and had the same results when testing post-fracture strength. It is obvious that the goal of the clinician should be to protect the FRC post from contact with water prior to and during the insertion of the post, but it is also important that the final restoration will provide a dry environment for the FRC posts. The latter may be proven to be difficult in some cases because it requires good adhesion between the composite core, the crown and the tooth. In the case that the dentist manages to keep the FRC posts safe from humidity and large variations of temperature, there is less risk that their long term performance will be affected.

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