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Stress relaxation and recovery behaviour of composite orthodontic archwires in bending

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SUMMARY The viscoelastic behaviour of prototype composite orthodontic archwires was evaluated using a bend stress relaxation test. Archwires having 10 different volume fractions of reinforcement were subjected to constant bending radii in a water bath at 37°C for time periods of up to 90 days. The wires were subsequently released and left unconstrained for the same testing conditions. Creep-induced changes in the unconstrained bending radii of the wires were measured at specific times during both phases (stress relaxation and recovery) of the test. The statistical analysis showed that stress relaxation behaviour was strongly correlated with the archwire reinforcement level. The final relaxation varied, with decreasing reinforcement, from 2 to 8 per cent. Archwire recovery was not correlated with reinforcement level, and revealed a final viscous loss of only 1 per cent. The relaxed elastic moduli in bending of the composite wires were similar to the elastic moduli in bending of several conventional orthodontic archwire materials. Losses that were associated with the viscoelastic behaviour varied with decreasing reinforcement level from 1.2 to 1.7 GPa. Because these modulus losses were minimal, each archwire retained sufficient resilience to be applicable to the early and intermediate stages of orthodontic treatment.

Introduction

Polymer composites are routinely used as dental restorative materials because of perceived problems with mercury toxicity from dental amalgam (Eley, 1997) and because of their aesthetic qualities. Increasingly, polymer composites are also being considered as materials for orthopaedic applications. The ability to specifically tailor stiffness properties to match those of cortical bone makes these materials attractive candidates for devices such as joint prosthesis (Skinner, 1988; Chang *et al*., 1990; Volz and Benjamin, 1990) and bone plates (Ali *et al*., 1990; Brown *et al*., 1990). This combination of aesthetics and favourable mechanical properties has prompted several investigators to consider the feasibility of fabricating an orthodontic archwire from a unidirectional fibre-reinforced polymer (UFRP; Goldberg and Burstone, 1992; Jancar and DiBenedetto, 1993; Jancar *et al*., 1993, 1994; Goldberg *et al*., 1994; Kennedy *et al*., 1994, 1998a, 1998b; Kennedy and Kusy, 1995; Kusy, 1997; Zufall *et al*., 1998). Such an archwire could be made with a tooth-coloured appearance and with stiffness properties similar to metallic archwires. In addition, the stiffness of a composite archwire could be varied by controlling the reinforcement and matrix composition, without changing the wire size or shape. Thus, uniform engagement between the archwire and the bracket slot could be maintained throughout treatment using variable modulus orthodontic techniques (Burstone, 1981).

In the typical implementation of an orthodontic archwire, elastic deformation of the wire produces a force that is used to move a tooth into a more desirable position. As the tooth slowly moves, the wire springs back towards a relaxed configuration and the force applied to the tooth decreases. This ‘springback’ stops at the point where the force on the tooth is less than the threshold that is required to stimulate the necessary biological responses, which ultimately govern tooth movement. For most contemporary archwires (the exception being certain nickel-titanium alloys), the relationship between the force (or stress) and the flexural displacement (or strain) of the wire is linear within the elastic limit of the constituent material. However, polymer-containing composites are often characterized by viscoelastic or time-dependent stress-strain behaviour. A highly viscoelastic composite archwire would experience a decrease in force over time in excess of that predicted by the elastic modulus of the composite material. From a clinical perspective, this behaviour would cause a decrease in the amount of springback that would be available for tooth movement.

Previous investigations of prototype composite archwires suggested that the wires could function well during the initial and intermediate stages of orthodontic treatment (Kennedy *et al*., 1994, 1998a, 1998b; Kennedy and Kusy, 1995; Kusy, 1997; Zufall *et al*., 1998). In this study, the viscoelastic behaviour of these wires was measured using a bend stress relaxation test. Composite archwires, with 10 different volume fractions of reinforcement, were tested in a simulated oral environment for relaxation and recovery periods of up to 90 days. The results showed that the final relaxation was negatively correlated with composite reinforcement level and varied from 2 to 8 per cent. A comparison with conventional archwire materials indicated that the relaxed archwire stiffness would be sufficient for clinical viability.

Materials and methods

Constituent materials

Composite archwires were fabricated using a photo-pultrusion manufacturing process, the details of which have been described elsewhere (Kusy and Kennedy, 1994; Kennedy and Kusy, 1995). The wires were reinforced with S2-glass® continuous fibre yarns (Owens Corning Corp., Toledo, OH, USA) that had been treated by the manufacturer with an epoxy-compatible binding agent. The matrix material was a network copolymer, which consisted of 61 per cent weight (wt) bisphenol-A diglycidyl methacrylate (Nupol 046-4005, Cook Composites and Polymers Co., North Kansas City, MO, USA) and 39 per cent wt triethylene glycol dimethacrylate (TEGDMA, Polysciences Inc., Warrington, PA, USA). Benzoin Ethyl Ether (BEE, Aldrich Chemical Co. Inc., Milwaukee, WI, USA; 0.4 per cent wt of total weight) was added as the ultraviolet initiator for polymerization.

Composite wire fabrication

Composite samples, having round cross-sectional profiles, were pultruded continuously with a nominal diameter of 0.55 mm. The volume fraction of reinforcement (V_f; cf. Appendix A) and, hence the stiffness of the wires, was adjusted by changing the number of S2-glass® yarns that were pultruded into each composite profile. The actual V_f was calculated using the cross-sectional area of each composite as determined from the mean of eight diameter measurements (Sony μ-mate® Digital Micrometer, Sony Magnescale America, Inc., Orange, CA, USA). Archwires were manufactured with 10 different reinforcement levels, which varied between $V_f = 0.35$ and 0.70 (Table 1). The finished materials were wound onto a 0.5-m diameter spool immediately after processing. At the end of each manufacturing run, the materials were cut into samples of manageable lengths and stored in the dark until testing.

Table 1 Composite archwire materials.

Archwire code	Volume fraction of reinforcement, V_f
C70	0.70 ± 0.01
C65	0.65 ± 0.01
C60	0.60 ± 0.02
C58	0.58 ± 0.03
C54	0.54 ± 0.01
C51	0.51 ± 0.02
C46	0.46 ± 0.02
C40	0.40 ± 0.01
C38	0.38 ± 0.01
C35	0.35 ± 0.01

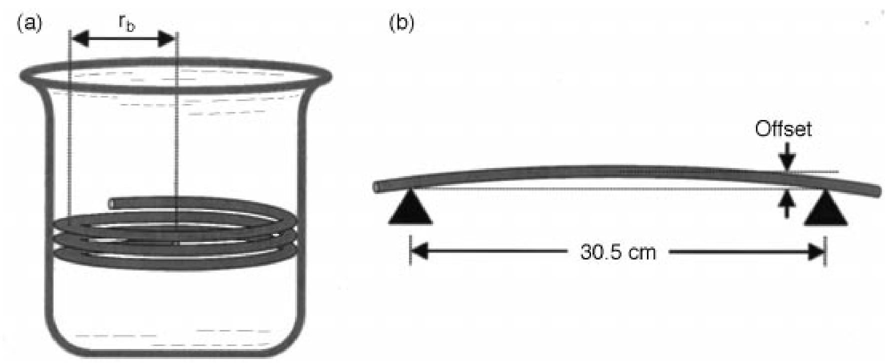

Figure 1 Composite orthodontic archwires were wrapped along the inside of a glass vessel into loops having known bending radii (r_b) for the relaxation phase of the bend stress relaxation (BSR) test (a). At specific time intervals, the archwires were released and the offsets from the centre of a 30.5-cm span were measured (b). These data were used to calculate the unconstrained bending radii, $r_u(t)$, via trigonometric identities.

Bend stress relaxation (BSR) test

The viscoelastic behaviour of the composite archwires was evaluated using a bend stress relaxation (BSR) test (DiCarlo, 1976; Morscher *et al.*, 1991; Morscher and DiCarlo, 1992). In this test, stress relaxation was measured by first applying a constant bending strain to the archwires. After specific treatment times, *t*, the bending strain was temporarily removed and changes in the curvatures of the wires (in the direction of the bending strain) were observed. In the same way, recovery was measured by removing the bending strain from the archwires and observing changes in the wire curvatures as a function of *t*.

For the relaxation phase of this test, a constant bending strain was applied by wrapping archwire samples along the inside circumference of a glass cylinder (Figure 1a). The walls of this cylinder constrained the wires into a circle with a specific bending radius, r_b. At designated *t* intervals the bending strain was released by removing the archwires from the cylinder, and the wire curvatures were determined by measuring the offset (cm) of each sample from the centre of a 30.5 cm long straight edge (Figure 1b). Since the curvature of a wire sample formed a circular arc, the offset was used to calculate the unconstrained bending radii, $r_u(t)$, of the wires by applying the relationship:

$$r_u(t) = [(30.5)^2 + (\text{offset})^2]/(8 \times \text{offset}) \quad (1)$$

that was derived using basic trigonometric identities (Zwillinger, 1996). The archwires were returned to the glass cylinder immediately after each measurement. At the end of the relaxation phase all samples were removed from the glass cylinder and left unconstrained for the recovery phase. During this latter phase, $r_u(t)$ was also measured after specific *t* intervals. For convenience, the completion of each phase was determined at the point where no further systematic change of $r_u(t)$ was observed.

A stress ratio, $m(t)$, quantified the level of relaxation in the archwires at a specific temperature. Assuming a linear relationship between relaxation and the bending strain, this parameter was equal to the stress within an archwire at any *t*, $\sigma(t)$, divided by the initial bending stress at r_b, σ_b, such that:

$$m(t) = \sigma(t)/\sigma_b. \quad (2)$$

Thus, $m(t)$ varied from 0 to 1 for viscoelastic behaviour that ranged from being completely viscous [where $\sigma(t)$ approached 0] to being completely elastic [where $\sigma(t) = \sigma_b$]. Assuming hydrolytic stability of the elastic modulus in bending (E), $m(t)$ was determined for the composite archwires by:

$$m(t) = 1 - \left[\left(\frac{r_0}{r_u(t)} - 1 \right) \Big/ \left(\frac{r_0}{r_b} - 1 \right) \right], \tag{3}$$

where r_0 was the initial unconstrained bending radii of the wires (cf. Appendix B). This initial curvature was characteristic of all archwire samples and was an artefact of the manufacturing technique, which resulted from post-curing of the composite material while being stored on the take-up spool. The relaxed (m_{rel}) and recovered (m_{rec}) stress ratios were determined at the completion of the relaxation and recovery phases, respectively.

All BSR tests were conducted in a circulating water bath that was maintained at 37°C. A linear relationship between relaxation and bending strain was established by preliminary tests of the relaxation phase. Ten samples each of the C60, C54, and C38 composite archwires were tested with r_b = 45, 30, and 17 mm. Measurements of $r_u(t)$ were taken at t = 0, 30, 60, and 90 days, the last t representing the typical maximum duration of clinically used archwires. Subsequent tests of both the relaxation and recovery phases were conducted on five samples each of the C70, C65, C60, C58, C51, C46, C40, and C35 composite archwires with r_b = 51 mm. The number of samples per V_f was reduced in these later tests because of the high level of statistical significance ascribed to the preliminary BSR test results. For the C70, C58, C46, and C35 archwires, $r_u(t)$ measurements were taken at several times from t = 0 to t = 45 days during the relaxation phase and from t = 0–38 days during the recovery phase. The remaining archwires were tested from t = 0–18 and from t = 0–17 days for the relaxation and the recovery phases, respectively.

Hydrolytic stability of E was verified by testing, in three-point bending, each of the samples used in the preliminary BSR tests. Moduli were calculated for each of the samples following the same procedure used in previous studies (Kennedy *et al.*, 1994, 1998b).

Statistical analysis

Hydrolytic stability of E was evaluated using a fully factorial, multiple analysis of variance (MANOVA) (Systat Version 5, Systat, Inc., Evanston, IL, USA). Differences in moduli with respect to r_b and t were examined in terms of the main effects and two-way interaction. In addition, a least-squares linear regression was performed on the modulus data. Since the rule of mixtures for composite materials defines a linear relationship between V_f and E, this allowed moduli to be predicted for reinforcement levels not tested in three-point bending.

A linear relationship between relaxation and bending strain was defined, where $r_u(t)$ was linearly proportional to r_b or, equivalently, where m_{rel} was independent of r_b. A MANOVA was performed on the preliminary BSR test data to determine significant differences in $m(t)$ with respect to r_b, V_f, and t in terms of the main effects and two-way interactions. The correlation between m_{rel} and V_f, and m_{rec} and V_f for the remaining BSR data was also investigated with MANOVA and with least-squares linear regression techniques. Tukey pairwise comparison of the means was used to elucidate significant differences in the m_{rec} data. The significance of all regressions were determined using the probabilities (P) based on the correlation coefficients and the sample size (n).

Results

No significant change in E was observed with respect to r_b or t (Table 2), which verified that the modulus was hydrolytically stable for t = 0–90 days. A linear regression through the E versus V_f data had a slope of 118.4 and a y-intercept of –20.5.

Statistical analysis of the preliminary BSR test results verified a linear relationship between relaxation and bending strain (Table 3). The MANOVA showed no significant difference in $m(t)$ with respect to r_b for the C60, C54, or C38 composite archwires. The MANOVA also showed that $m(t)$ was unchanged for t = 30, 60, and 90 days. This observation implied that no significant relaxation of the archwire occurred

Table 2 Hydrolytic stability of the elastic modulus in bending.

Archwire code	Bending radius, r_b (mm)	Elastic modulus in bending, E (GPa), at t =			
		0 days	30 days	60 days	90 days
C60	∞	48.5 ± 1.6*	49.0 ± 2.3	49.3 ± 2.4	48.7 ± 2.6
	45	48.5 ± 1.6	47.6 ± 3.1	48.8 ± 2.2	48.2 ± 1.6
	30	48.5 ± 1.6	47.6 ± 1.9	49.0 ± 1.8	47.8 ± 0.9
C54	∞	47.9 ± 3.2	46.0 ± 2.1	46.5 ± 1.3	46.9 ± 3.0
	45	47.9 ± 3.2	43.9 ± 3.3	47.9 ± 1.3	45.4 ± 3.2
	30	47.9 ± 3.2	44.9 ± 2.7	45.5 ± 2.2	46.2 ± 1.9
C38	∞	22.8 ± 1.9	24.1 ± 1.9	23.2 ± 1.5	24.1 ± 2.6
	45	22.8 ± 1.9	23.4 ± 2.2	24.1 ± 1.1	23.8 ± 2.9
	30	22.8 ± 1.9	24.8 ± 1.5	24.5 ± 1.6	24.3 ± 1.7
	17	22.8 ± 1.9	22.6 ± 2.4	21.4 ± 2.0	22.6 ± 2.2

*Results for a sample size, $n = 10$.

Table 3 Preliminary bend stress relaxation (BSR) test data.

Archwire code	Bending radius, r_b (mm)	Stress ratio, $m(t)$, at t =			
		0 days	30 days	60 days	90 days
C60	45	1.000 ± 0.000*	0.978 ± 0.008	0.974 ± 0.007	0.974 ± 0.007
	30	1.000 ± 0.000	0.974 ± 0.004	0.971 ± 0.003	0.973 ± 0.004
C54	45	1.000 ± 0.000	0.975 ± 0.003	0.974 ± 0.008	0.972 ± 0.007
	30	1.000 ± 0.000	0.975 ± 0.003	0.975 ± 0.005	0.975 ± 0.003
C38	45	1.000 ± 0.000	0.947 ± 0.008	0.949 ± 0.007	0.944 ± 0.005
	30	1.000 ± 0.000	0.947 ± 0.010	0.953 ± 0.005	0.950 ± 0.007
	17	1.000 ± 0.000	0.948 ± 0.003	0.950 ± 0.004	0.948 ± 0.006

*Results for $n = 10$.

after $t = 30$ days. Highly significant differences ($P < 0.001$) in $m(t)$ were observed with respect to V_f. When these results were averaged over all r_b and t, values of $m(t)$ were 0.98, 0.97, and 0.95 for the C60, C54, and C38 composite archwires, respectively.

Plots of the average $m(t)$ versus t for each archwire in the relaxation (Figure 2) and the recovery (Figure 3) phases revealed that most of the transient response occurred within the first day of testing. No further trend in the change of $m(t)$ was observed for $t \geq 17$ days in either phase. The m_{rel} and m_{rec} for each composite archwire were determined at $t = 18$ days and $t = 17$ days, respectively (Table 4, and Figures 2 and 3).

Highly significant ($P < 0.001$) differences in m_{rel} with respect to V_f were observed. A least-squares linear regression through a plot of this data revealed a highly significant ($P < 0.001$) positive correlation with a slope of 0.11 and a y-intercept of 0.91 (Figure 4). Values of m_{rel} ranged from a high of 0.98 for the C70 archwire to a low of 0.92 for the C40 archwire. Highly significant ($P < 0.001$) differences in m_{rec} with respect to V_f were also observed, however, a linear regression through this data was not significant. Pairwise comparisons showed that m_{rec} for the C58 archwire was significantly ($P < 0.05$) different than m_{rec} for the C51, C40, and C35 archwires, and that highly significant ($P < 0.001$)

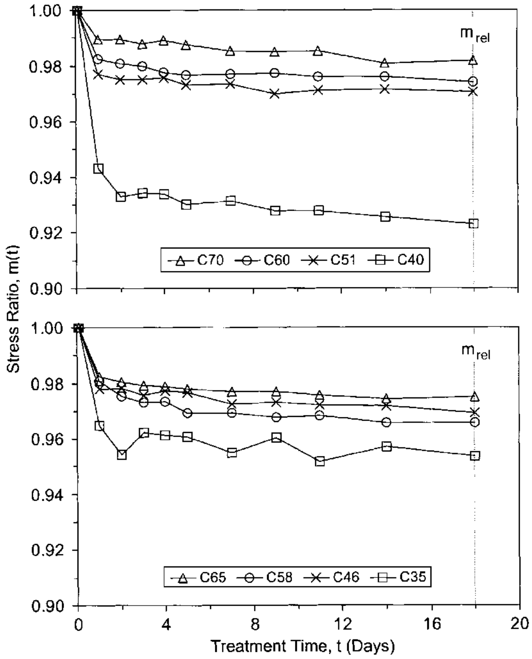

Figure 2 Relaxation phase plots of the average stress ratio, $m(t)$, as a function of ageing time, t, for composite archwires at eight volume fractions of reinforcement, V_f (cf. Table 1, archwire codes).

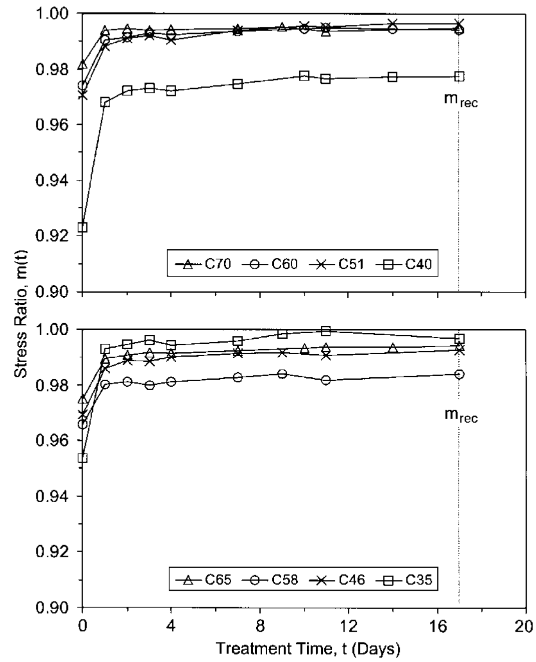

Figure 3 Recovery phase plots of the average $m(t)$ as a function of t for composite archwires at eight V_fs (cf. Table 1, archwire codes).

differences in m_{rec} existed between the C40 archwire and all of the other wires tested. Recovery was nearly complete for all but the C58 and C40 archwires with the overall average $m_{rec} = 0.99$ (Table 4).

Discussion

Application of the stress ratio, m(t)

The hydrolytic stability of E was assumed as a criterion for the derivation of $m(t)$ and was confirmed by the three-point bending test results (Table 2). In a previous study, however, E decreased slightly in water over a treatment period of 3 months (Kennedy *et al.*, 1998b). The difference between these results was attributed to improvements in the photo-pultrusion process. For example, early prototype UFRPs were polymerized using a relatively low power UV dental curing lamp (Duralux UV-300, Kultzer & Co GmbH, Bad Homburg, Germany) as compared with the present high intensity light source (Super Spot MKII, Lightwave Energy Systems Co., Inc., Torrance, CA, USA). The newer light source may have improved the degree of polymerization, which consequently reduced the

Table 4 BSR test data.*

Archwire code	Relaxed stress ratio, m_{rel}	Recovered stress ratio, m_{rec}
C70	0.982 ± 0.009	0.995 ± 0.005
C65	0.975 ± 0.004	0.994 ± 0.003
C60	0.974 ± 0.002	0.994 ± 0.002
C58	0.966 ± 0.006	0.984 ± 0.005
C51	0.970 ± 0.005	0.996 ± 0.006
C46	0.969 ± 0.010	0.993 ± 0.007
C40	0.923 ± 0.009	0.978 ± 0.007
C35	0.954 ± 0.012	0.997 ± 0.006

*Results for $n = 5$. For all tests, $r_b = 51$ mm. The m_{rel} and m_{rec} were measured after 18 and 17 days, respectively.

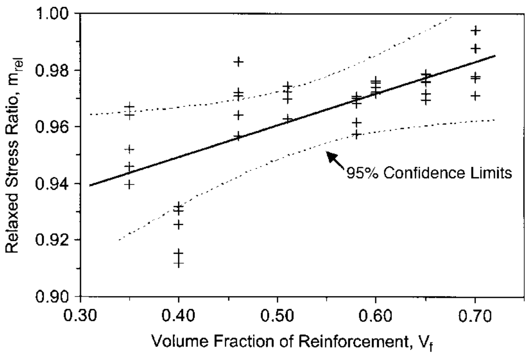

Figure 4 Least squares linear regression plot of the m_{rel} versus V_f. The 95 per cent confidence limits (denoted by the dotted lines) were calculated using the 6 degrees of freedom for the unexplained variances.

sorption and plasticizing effect of water on the composite material (Pearson and Longman, 1989).

The statistical analysis of the preliminary BSR test results showed that $m(t)$ was independent of the bending strain on the composite archwires (Table 3). This result was consistent with compressive creep studies of particulate composites that were made from the same constituent materials (Hirano and Hirasawa, 1989, 1992). The independence of $m(t)$ from r_b is important because orthodontic archwire applications do not typically involve isostrain conditions. Archwire deactivation is concurrent with tooth movement, which causes the wire to experience decreasing strain over time. Thus, strain independence is necessary for $m(t)$ to predict the viscoelastic behaviour of the wire during orthodontic treatment.

Influences on the relaxed stress ratio, m_{rel}

The linear regression analysis of Figure 4 showed a significant positive correlation ($P < 0.001$) between m_{rel} and V_f. A more rigorous analysis, using an unpooled ANOVA of the explained (due to the linear regression) and unexplained variances (Sokal and Rohlf, 1969), confirmed the statistical significance ($P < 0.05$) of this correlation. Extrapolating the regression coefficients to V_f = 1.00 gave m_{rel} = 1.02. Thus, at the temperature and over the time periods tested in this study, the influence of the viscoelastic behaviour of the glass reinforcement on the overall composite behaviour was negligible.

Values of m_{rel} indicated that the composite archwires retained between 92 and 98 per cent of their initial stress (Table 3 and Figure 2). Other investigators have found that UFRPs with similar V_fs and different thermoplastic matrix compositions retained from 67 to 90 per cent of their original bending moment after t = 56 days (Goldberg *et al.*, 1994). The present improvement was most likely associated with the use of a highly cross-linked, thermosetting matrix material (Tobolsky, 1971). The cross-links would have prevented the polymer molecules from slipping past one another and forming extended chains. The resulting macromechanical effects of this molecular interaction would be low relaxation, and almost no viscous or permanent deformation. From an orthodontic perspective, this behaviour would mean greater springback and, therefore, greater tooth movement following a particular wire placement.

Relaxation of the composite archwire was also influenced by non-homogeneity of the reinforcement fibre distribution. Previous work (Kennedy *et al.*, 1994) showed that the photo-pultrusion process preferentially positioned the reinforcement fibres toward the perimeter of each composite's cross-section. Here, as V_f was increased the concentration of reinforcement at the perimeter remained approximately the same as the additional reinforcement displaced the polymer-rich region that existed at the centre of the composite (Figure 5). Since the normal stress within the composite during bending was greatest at the perimeter and zero at the centre, the effect of V_f on the viscoelastic behaviour was minimized by this preferential distribution.

Influences on the recovered stress ratio, m_{rec}

Statistical analysis showed that m_{rec} did not correlate with V_f (Table 4). Additionally, the overall average m_{rec} of 0.99 indicated that viscous relaxation caused a 1 per cent decrease in the initial stress within the archwire. Composite restorations with highly cross-linked matrices

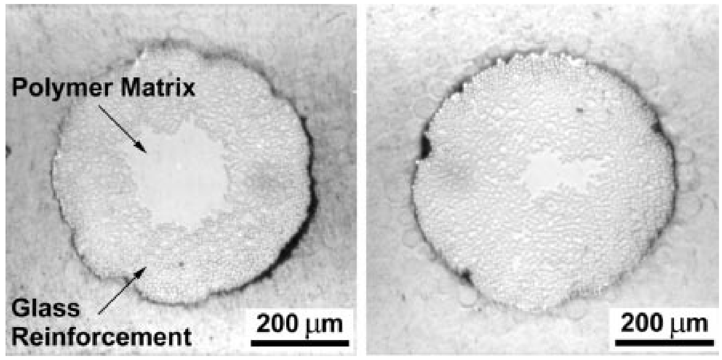

Figure 5 Cross-sectional morphology of the C54 (left) and C60 (right) composite archwires. Note that the reinforcement distribution is not homogeneous, but rather that the polymer-rich region at the centre of the cross-section is displaced by additional reinforcement as a result of the manufacturing process (Kennedy *et al.*, 1994).

have demonstrated a similarly low level of viscous relaxation (Hirano and Hirasawa, 1992, 1994; Papadogianis *et al*., 1985). However, if the polymer matrix was primarily responsible for viscous behaviour, m_{rec} should have correlated with V_f. One explanation for V_f independence was the preferential loading of the reinforcement fibres as discussed previously (cf. Figure 5). Although a correlation between m_{rec} and V_f could exist, the preferential loading may have decreased the effect to a level that was beyond the resolution of the BSR test method.

Hydrolytic degradation of covalent bonds in the fibre-matrix inter-phase could also cause viscous relaxation. Inter-phase bonds are responsible for the transfer of stress across the matrix and between adjacent reinforcement fibres. These bond failures were suggested as the mechanism by which E degrades in earlier prototype UFRPs (Kennedy *et al*., 1998b). Furthermore, since the inter-phase concentration was approximately the same in the greatest stress region of the composite cross-section for all reinforcement levels (due to preferential loading, cf. Figure 5), the viscous relaxation caused by this mechanism would be only marginally affected by V_f. Regardless of this, the stability of E, as shown by the three-point bending tests (Table 2), would suggest that degradation of covalent bonds was minimal. Only the C58 and C40 archwires had greater relaxation and less recovery than expected (Table 4, and Figures 2 and 3). Since each reinforcement level was fabricated separately, subtle differences in the manufacturing technique may have caused defects, which increased degradation of the inter-phase and which, consequently, resulted in poorer performance.

Comparison with traditional orthodontic materials

The isostrain behaviour of the composite archwires was characterized by an instantaneous elastic response that was followed by a retarded, time-dependent, viscoelastic response. This later response was further characterized by a rapid change in $m(t)$ that was followed by a slower transient period (Figures 2 and 3). Steady-state behaviour existed when, at a particular strain, the change in $m(t)$ was equal to zero (i.e. when no relaxation or recovery was occurring). Since most of the change occurred within the first day of testing and because orthodontic tooth movement is a relatively slow process (roughly 1 mm/month) (Kusy and Whitley, 1989), steady-state behaviour was assumed.

For comparing the composite archwires to metallic archwire materials, m_{rel} was related to a more conventional engineering property. The time-dependent elastic modulus, $E(t)$, has been defined for stress relaxation experiments by a ratio of $\sigma(t)$ to strain (Callister, 1994). This property is analogous to E and represents the slope of a linear relationship between stress and strain for a viscoelastic material at a specific t. Substituting $E(t)$, E, and the bending strain (ε_b) into equation (2),

$$m(t) = [\varepsilon_b E(t)]/(\varepsilon_b E). \quad (4)$$

Complete recovery (i.e. no viscous deformation) was required for $E(t)$ to be applicable to both activation and deactivation of the archwire, so $m_{rec} \approx 1$ was assumed. For steady-state behaviour, $m(t)$ equalled m_{rel} and

$$E_{rel} = Em_{rel} \quad (5)$$

where E_{rel} was the relaxed elastic modulus in bending of the composite archwires. This parameter was indicative of the archwire stiffness in actual clinical use and could be directly compared with the E of non-viscoelastic archwire materials.

Moduli calculated with the coefficients from the linear regression of the three-point bending data compared favourably with those from previous composite archwire studies (Kennedy *et al.*, 1994). Using these coefficients and equation (5), E_{rel} was calculated for composite archwires with four different levels of reinforcement (Figure 6). These results were compared with typical E values for nickel titanium (NiTi) and beta titanium (β-Ti) archwires (Kusy and Stush, 1987). Losses were minimal and varied from 1.2 to 1.7 GPa, which represented a decrease of only 2–8 per cent. Because these losses were so small, the composite archwires were still within the stiffness values that were outlined by the NiTi and β-Ti materials.

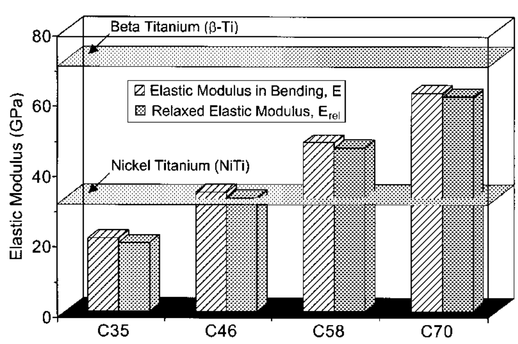

Figure 6 Similarity of the elastic modulus in bending (E) and the relaxed elastic modulus in bending (E_{rel}) for four composite archwires (cf. Table 1, archwire codes). The E values for nickel titanium (NiTi) and beta-titanium (β-Ti) archwire materials are superimposed for comparison (Kusy and Stush, 1987).

Conclusions

The composite archwires satisfied the BSR test requirements of a stable elastic modulus and a linear relationship between relaxation behaviour and bending strain. Most of the relaxation and recovery responses occurred during the first day of testing. A strong positive correlation between the relaxed stress ratio and the reinforcement level verified that the polymer matrix was responsible for viscoelastic behaviour. From the recovered stress ratios, viscous losses were only 1 per cent of the initial stress and were unrelated to the reinforcement level. A preferential distribution of the reinforcement fibres and a highly cross-linked polymer matrix minimized the viscoelastic behaviour. The level of initial stress that was retained by the archwires varied from 92 to 98 per cent. Using the relaxed stress ratio, the relaxed elastic moduli in bending compared favourably with the elastic moduli in bending of NiTi and β-Ti archwire materials. Thus, considering their minimal viscoelastic behaviour, the prototype composite archwires retained sufficient resilience to function during the initial and intermediate stages of orthodontic treatment.

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Appendix A: nomenclature

BSR	bend stress relaxation
b	length of the neutral plane
E	elastic modulus in bending
E(t)	time-dependent elastic modulus
E_{rel}	relaxed elastic modulus in bending
l	strained length
l_0	initial length
MANOVA	multiple analysis of variance
$m(t)$	stress ratio
m_{rec}	recovered stress ratio
m_{rel}	relaxed stress ratio
n	number of samples
P	probability
r	radius
r_b	bending radius
$r_u(t)$	unconstrained bending radius
r_0	initial unconstrained bending radius
t	treatment time
UFRP	unidirectional fibre-reinforced polymer
V_f	volume fraction of reinforcement
z	distance from the neutral plane
$\varepsilon(t)$	normal bending strain
ε_b	normal bending strain at the bending radius, r_b
ε_{creep}	treatment-induced creep strain
$\sigma(t)$	normal bending stress
σ_b	normal bending stress at the bending radius, r_b
θ	central angle

Appendix B: stress ratio derivation*

Equation (2) defines a stress ratio, $m(t)$, for a member in bending as the stress after a treatment time, t, divided by the initial stress. If the elastic modulus remains constant for all t and if the initial strain and bending strain within the archwire at any t are linearly related, $m(t)$ can be expressed using Hooke's Law as,

$$m(t) = \varepsilon(t)/\varepsilon_b, \qquad \text{(B1)}$$

where $\varepsilon(t)$ and ε_b are the bending strain within the archwire at any t and the initial bending strain at the bending radius (r_b), respectively. The treatment-induced creep strain, $\varepsilon_{creep}(t)$, can be defined as the difference between ε_b and $\varepsilon(t)$ such that,

$$m(t) = [\varepsilon_b - \varepsilon_{creep}(t)]/\varepsilon_b. \qquad \text{(B2)}$$

Strain for a member in bending is defined along a plane, parallel to and at any perpendicular distance (z) from the neutral plane (Figure 7), as

$$\varepsilon = (l - l_0)/l_0, \qquad \text{(B3)}$$

where l_0 and l are the initial and strained lengths of the plane, respectively. Since the length of an arc can be determined from the product of the radius (r) and the central angle (θ) in radians, the length of the neutral plane (b) is,

$$b = r\theta, \qquad \text{(B4)}$$

and the length of l is,

$$l = (r + z)\theta. \qquad \text{(B5)}$$

Solving equation (B4) for θ and substituting into (B5) gives l in terms of b, r, and z. Thus, assuming that the neutral plane passes through the centre of the composite archwires, ε_b can be expressed by,

$$\varepsilon_b = \frac{r_0(r_b + z)}{r_b(r_0 + z)} - 1, \qquad \text{(B6)}$$

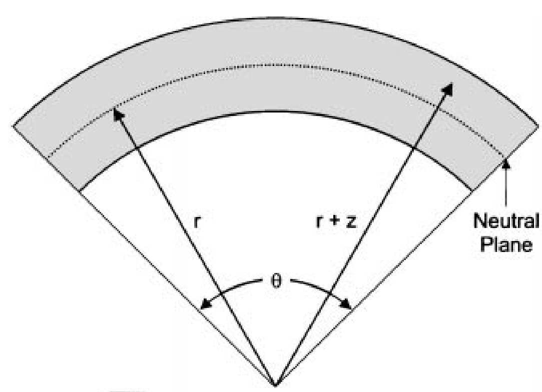

Figure 7 Diagram of a composite archwire being subjected to a bending angle θ. The radius (r) is given by the distance from the centre of bending curvature to the neutral plane. All other points in the composite are described in terms of their distance (z) from the neutral plane.

where r_0 is the initial unconstrained radius. Similarly,

$$\varepsilon_{creep}(t) = \frac{r_0[r_u(t) + z]}{r_u(t)(r_0 + z)} - 1, \qquad \text{(B7)}$$

where $r_u(t)$ is the unconstrained radius at t. Equations (B6) and (B7) can then be substituted into equation (B2) to obtain the relation given by equation (3).

*All stresses and strains are normal to the cross-section of the member in bending.