The fabrication and properties of aesthetic FRP wires for use in orthodontics

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Transparent or translucent fibre-reinforced polymeric wires have been produced in an attempt to reproduce the mechanical properties of the metallic wires in current use in orthodontics. Two methods were employed: mould polymerization, and hot-drawing. Both methods produced wires of 0.5 mm diameter. Two polymers were investigated, poly(methyl methacrylate) and epoxy resin, and these were filled with either long silane-coated alumina fibres or fibres made from CPSA glass. Whilst mould-polymerized wires showed a linear increase in Young's modulus with fibre content, they did not obey the rule of mixtures. However, the hot-drawn wires did, and they also demonstrated the rigidity, strength and good elastic recovery needed for use in orthodontics.

1. Introduction
Orthodontic wires are used in dentistry to align irregularly arranged teeth. Brackets are bonded to the teeth and the wires are fastened to them. Until recently, both brackets and wires were made of metals, and as such were clearly visible to observers. To make these fixed orthodontic appliances more aesthetically acceptable, brackets made from either polymer [1] or ceramics [2], which includes transparent, monocrystalline alumina and white, polycrystalline alumina, have been introduced. However, the wires have remained metallic.

The wires for these applications require an unusual combination of properties and experience has shown that those made of stainless steel [3], nickel–titanium [4] or cobalt–chromium alloys [5] have the flexibility, strength and chemical resistance needed for use in the mouth. Patients would prefer that such wires were not so apparent as opaque, shiny metals are, and any alternative should be transparent or translucent.

This paper reports an investigation into the mechanical and optical properties of fibre-reinforced polymer (FRP) wires.

2. Methods and materials
Wires were made in two different ways, by moulding and by drawing, and from two different polymers, poly(methyl methacrylate) (PMMA) and epoxy resin. Moulded wires of these polymers were made in a cylindrical groove, 0.5 mm diameter, formed in a silicone rubber mould. Both monomers were mixed with activator and the moulds were filled and tightly covered before being allowed to cure at room temperature for 24 h [6].

MMA and epoxy resins were also used to create the matrices of fibre-reinforced wires. The fibres used were of either alumina (Al_2O_3) or of biocompatible glass fibres formed from CaO, P_2O_5, SiO_2 and Al_2O_3 (CPSA) [7]. In each case, the long and straight fibres were silane-coated to improve the bond between themselves and the polymer matrix and all fibres were orientated parallel to the long axis of the wires.

FRP wires containing 10 μm diameter alumina were made by the matrix polymerization process described above, by dipping the fibres in the monomer which filled the mould. Wires containing between 13% and 26% by volume of fibres were produced in this way. However, wires made from PMMA containing CPSA glass fibres, 20 μm diameter, were made by drawing through a glass die at 250 °C, and this produced wires containing between 28% and 60% by volume of CPSA glass fibre [8].

Optical and scanning electron microscopy were used to assess both longitudinal and transverse cross-sections of the wires, and three-point transverse tests were carried out on sections from each wire to assess its mechanical properties. These tests were carried out on a 14 mm gauge length of wire which was deformed at 1 mm min^{-1} up to a deflection of 2 mm, and then unloaded at the same rate. The hysteresis curves thus produced on the chart recorder were compared.

In the results presented below, the wires are described by their fibre content and its type, together with the nature of the matrix. Hence FRP ($13Al_2O_3$/epoxy) refers to a wire with an epoxy matrix containing 13% by volume of alumina fibres.

3. Results
The opacity of metallic orthodontic wires is compared with the transparency of the FRP wires in Fig. 1, in which straight FRP wires are seen resting on wires

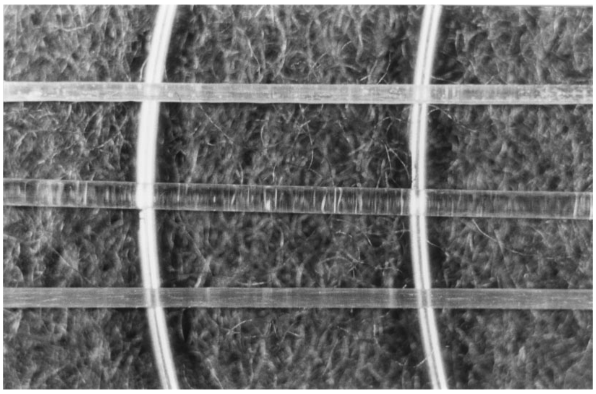

Figure 1 Various orthodontic wires. Arch form: left, Co–Cr; right, Ni–Ti. Straight form from top: FRP (Al_2O_3/epoxy); PMMA; FRP (glass/PMMA).

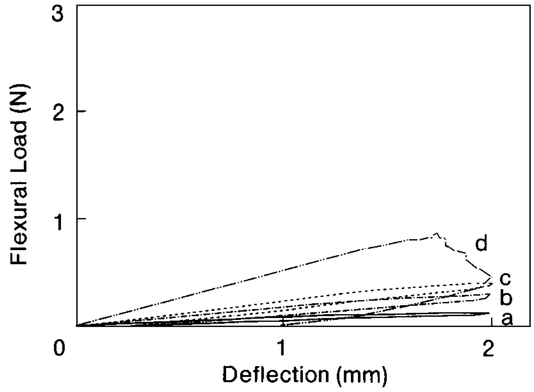

Figure 3 Flexural load–deflection curves of polymer wires and FRP wires with Al_2O_3 fibres made by the polymerization method: (a) PMMA, (b) epoxy, (c) FRP ($13Al_2O_3$/PMMA), (d) FRP ($13Al_2O_3$/epoxy).

of both cobalt–chromium (left) and nickel–titanium (right) which have been shaped to fit dental arches. The metallic wires are clearly visible through those of FRP. However, the FRP (Al_2O_3/epoxy) wire (shown at the top of Fig. 1) appears to contain small bubbles, and these make the wire more translucent than transparent. The unfilled PMMA wire in the middle shows the best transparency, followed by the FRP (CPSA glass/ PMMA) wire at the bottom.

The optical micrograph in Fig. 2 is the cross-section of a FRP (glass/ PMMA) wire. In this case, the external diameter of the wire was 0.5 mm and the volume percentage of the 20 μm glass fibres was 45. The glass fibres are distributed in a fairly uniform manner, and the interface between the polymeric matrix and the fibres appears to be free from discontinuities, suggesting that the fibres are bonded to the polymer.

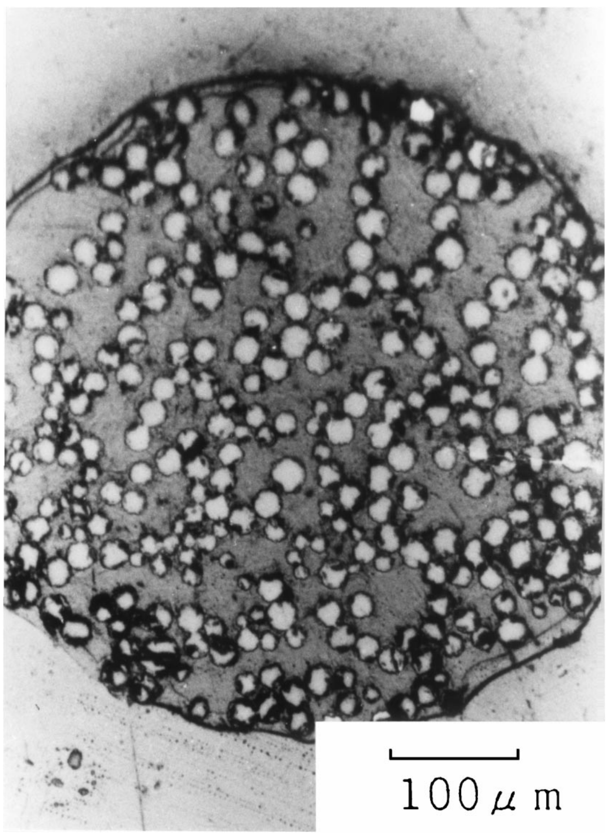

Figure 2 Cross-section of FRP (glass/PMMA) wire.

The flexural load–deflection curves for wires produced by polymerization in the silicone mould are shown in Fig. 3. Curves a and b are the loading/unloading hysterisis loops for wires made of unfilled PMMA and epoxy, respectively. They show the low loads that were needed to deflect these wires and their good elastic recovery. Curves c and d are the loops obtained for PMMA and epoxy wires which contained 13% by volume of alumina fibres. In each case the flexural load required to produce a deflection of 2 mm was more than double that for the unfilled wires. The effect of adding alumina fibres to the epoxy wire was to raise its stiffness, such that in Fig. 3, the force needed to cause a deflection of 1 mm was 0.5 N, considerably higher than in the case of the filled PMMA wire. However, whilst the FRP ($13Al_2O_3$/ PMMA) wire showed good elastic recovery, the filled epoxy wire did not. When the deflection reached 1.7 mm the recorded load started to fall and when the load was removed a permanent strain remained.

A comparison between the load–deflection curves for unfilled and fibre-filled wires produced by polymerization in a mould and fibre-filled wire produced by hot drawing is shown in Fig. 4. The fibre volume in each of the filled wires was similar at 26% and 30%. By comparing loop c in Fig. 3 for FRP ($13Al_2O_3$/ PMMA)

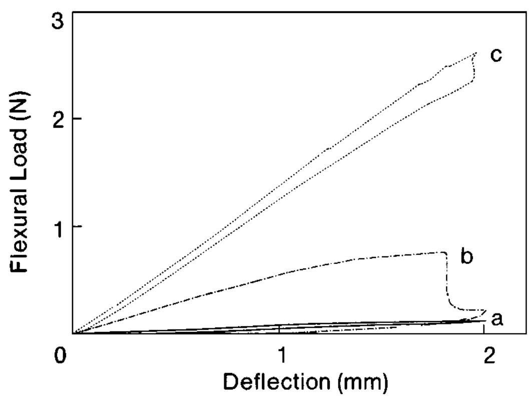

Figure 4 Flexural load–deflection curves of the wires with PMMA matrix: (a) PMMA, (b) FRP ($26Al_2O_3$/PMMA), (c) FRP (30glass/PMMA).

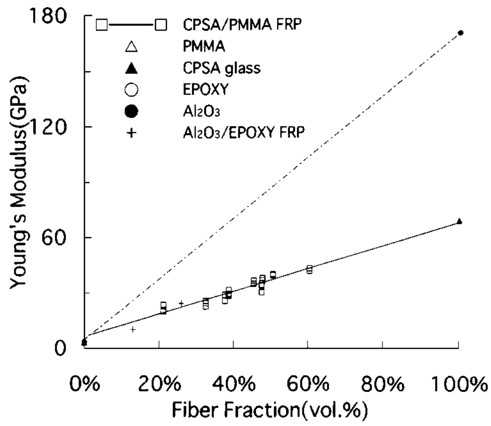

Figure 5 Dependence of Young's modulus of FRP wires on fibre fraction. (–□–) CPSA/PMMA FRP, (△) PMMA, (▲) CPSA glass, (○) epoxy, (●) Al_2O_3, (+) Al_2O_3/epoxy FRP.

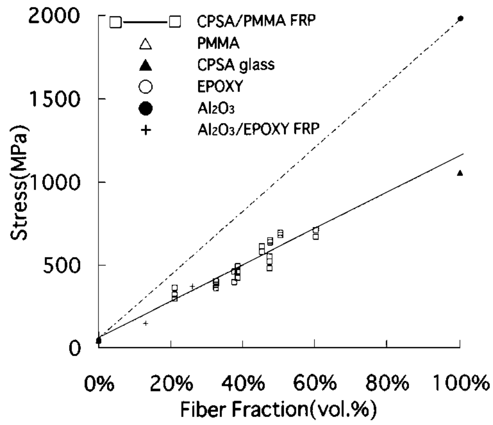

Figure 6 Dependence of flexural stress of FRP wires on fibre fraction. (–□–) CPSA/PMMA FRP, (△) PMMA, (▲) CPSA glass, (○) epoxy, (●) Al_2O_3, (+) Al_2O_3/epoxy FRP.

with that of loop b in Fig. 4 for FRP (26Al_2O_3/ PMMA), the effect of increasing fibre content becomes apparent. One effect is that when the fibre content was raised from 13% to 26% there was a reduction in the recorded load when the deflection reached 1.8%, and on unloading a large permanent strain was evident.

The flexural load required to bend the hot-drawn wire (loop c in Fig. 4) was considerably greater than those required for the mould-polymerized wires, and although it contained similar amounts of fibre, the hot-drawn wire showed no permanent strain when it was unloaded.

The effect of the volume fraction of fibres on the Young's modulus in wires produced by both mould polymerization and hot drawing is shown in Fig. 5. The points shown at zero are the moduli of the unfilled PMMA and epoxy, and those at 100% fibre fraction are values taken from references for alumina and CPSA glass. The values for FRP (glass/ PMMA) wires fit well the solid straight line drawn between the modulus for PMMA and for CPSA glass, and satisfy the rule of mixtures for composite systems. However, whilst the values for FRP (Al_2O_3/epoxy) show a similar linear dependence, they are much lower than the dot/dash line drawn between the modulus for the polymer and for alumina.

The flexural stress required to cause 1 mm deflection of the wires is shown as a function of the volume percentage of the fibre in Fig. 6. The values at zero are those for unfilled PMMA and epoxy, and those at 100% are the calculated values for alumina and CPSA glass. As with Young's modulus, the flexural stress values fitted well the straight lines, with the FRP (glass/ PMMA) again being the system that satisfied the rule of mixtures.

4. Discussion

The optimum force for moving teeth during orthodontic treatment is considered to be that which matches the blood pressure in the capillaries of the periodontal tissues. This can be generated by the elastic distortion of orthodontic wires attached to teeth via brackets. As the teeth move, the wire experiences stress relaxation and thus the useful load exerted by a wire is represented by the unloading curve of the hysterisis loop. Such a force should ideally be constant and in the range 0.6–6 N. In practice, the superelastic behaviour of nickel–titanium wires, used in the initial stage of orthodontic treatment, is often regarded as the closest to the ideal.

Of the polymeric and FRP wires tested, those composed only of polymer were neither stiff enough nor strong enough for clinical use. The addition of fibres increased the stiffness proportionally with their content. Although FRP wires produced by mould polymerization showed stiffness, the drop of stress often occurred at high stress level. As seen in FRP (Al_2O_3/epoxy) wire of Fig. 1, FRP wires made by polymerization method includes air bubbles and residual monomers. The highest fibre fraction in wires produced in this way was about 30%.

FRP wires fabricated by hot drawing not only had the stiffness and strength needed, but also showed excellent elastic recovery after deformation. It was possible to produce wires containing between 30% and 60% by volume by the hot-drawing process.

5. Conclusions

1. Polymeric or FRP wires with a diameter of 0.5 mm can be produced either by mould polymerization or by the hot-drawing of fibre–polymer composites.

2. Polymeric wires did not have the flexural rigidity needed for orthodontic applications, whereas FRP wires did.

3. FRP wires made by hot-drawing showed better mechanical properties than those made by mould polymerization.

4. Young's modulus and the flexural stresses needed to produce small deflections increase linearly with fibre fraction, and those wires made by hot drawing fitted well the rule of mixtures. Those made by mould polymerization did not.

5. FRP wires have improved aesthetics over alloy wires and can be produced such that they have the mechanical properties needed for use in orthodontics.

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