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Influence of fibre and filler reinforcement of plastic brackets: an *in vitro* study

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SUMMARY In spite of their popularity in fulfilling aesthetic requirements, plastic brackets still present some disadvantages because of their low elastic modulus, decreased fracture toughness, and reduced wear resistance. Fibre-reinforced composites are well established in dentistry and consist of a polymer matrix in which reinforcing fibres are embedded. Stress is transferred from the polymer matrix to the fibres which present a high tensile strength. Hence, the mechanical properties of polymers could be improved.

The purpose of this study was to compare fracture strength, fracture toughness and flexural strength of an experimental fibre-reinforced bracket material, an SiO_2 filler-reinforced bracket and an unfilled plastic bracket material (control group). Experimental brackets and specialized bars were manufactured. Tests were performed after thermal cycling (5°C/55°C) the samples in an artificial oral environment of a device to simulate mastication. Statistical evaluation was undertaken. The median, 25th and 75th percentiles were calculated and a Mann–Whitney *U*-test was performed.

In this study two findings were obvious. (1) Filler reinforcement of plastic brackets improved fracture strength and fracture toughness in comparison with the unfilled bracket material. (2) Glass fibre reinforcement of orthodontic bracket materials resulted in the greatest enhancement of the mechanical properties in comparison with the other test groups. Therefore, the application of glass fibres in plastic brackets is a successful method to enhance fracture strength.

Introduction

Orthodontic brackets bonded to enamel are responsible for transferring the force applied by the activated archwire to the tooth. Stainless steel is the material commonly used for manufacturing brackets. Nevertheless, the period of appliance wear is long and the demand for more aesthetic appliances has increased. Therefore, consequent research has resulted in the introduction of ceramic and plastic brackets which have an improved aesthetic appearance (Brantley and Eliades, 2001).

Polymer brackets were also established in response to reports of enamel damage during de-bonding of ceramic brackets and excessive wear of enamel surfaces on opposing teeth (Brantley and Eliades, 2001). However, in spite of their popularity in fulfilling aesthetic requirements, plastic brackets still present some disadvantages because of their low elastic modulus, decreased fracture toughness, and inability to withstand the torquing forces generated by rectangular wires (Arici and Regan, 1997). In addition, a plasticizing effect caused by water sorption of the polymeric structures has been described (Rantala *et al.*, 2003; Göhring *et al.*, 2005). Therefore, current research on reinforcement methods of plastic brackets has encompassed several areas, including reinforcement of the polymer by fillers (so-called 'composites') or fibres, or the use of metallic inserts on the bracket slot (Brantley and Eliades, 2001).

Fibre reinforcement is well established in dentistry and its use is gaining popularity (Behr *et al.*, 2000; Bae *et al.*, 2001; Grandini *et al.*, 2005; Tirapelli *et al.*, 2005). Fibre-reinforced composites (FRCs) consist of a polymer matrix in which reinforcing fibres are embedded. The reinforcing effect of fibres on polymers, due to stress transferring from the polymer matrix to the fibres has been confirmed (Hamza *et al.*, 2004). Factors which influence the mechanical properties of FRCs include type and quantity of fibres, and orientation and impregnation of the fibres within the resin matrix. Different types of fibres such as carbon, polyethylene, and glass are available. In spite of the fact that carbon fibres raise the flexural strength of polymers, their unsightly black colour restricts their use (Yazdanie and Mahood, 1985; Hamza *et al.*, 2004). The reinforcing effect of glass fibres is reported to be more effective than that of polyethylene fibres (Kolbeck *et al.*, 2002). This could be attributed to adhesion problems between ultra-high modulus polyethylene fibres and the resin matrix (Vallittu, 1997; Hamza *et al.*, 2004). In dentistry, FRCs are commonly used for denture reinforcement, periodontal splinting, resin-bonded metal-free prosthesis, and intracoronal pins and cores (Pereira *et al.*, 2003). Uni-, bi-, and multidirectional fibre orientation is applied for reinforcement. Only when the direction of the highest strain is known can unidirectional fibre orientation be chosen.

Hence, it was decided to investigate the influence of a bidirectional glass fibre weave reinforcement with a Vectris Frame (Ivoclar-Vivadent, Schaan, Liechtenstein), which was embedded in an experimental polymeric bracket material in comparison with filler reinforcement.

The purpose of this study was to compare fracture strength, fracture toughness, and flexural strength of an experimental fibre-reinforced bracket material, an SiO_2 filler-reinforced bracket material, and an unfilled plastic bracket material (control group). To simulate temperature changes and the moisture of saliva in the oral environment, all bracket materials were exposed to thermocycling (6000 × 5°C/55°C) in a device to simulate mastication before testing.

Materials and methods

Fracture strength of experimental brackets

Three different experimental bracket groups were produced. The first consisted of urethane dimethacrylate (UDMA) and the second was constructed of a bidirectional glass fibre weave of Vectris Frame (Ivoclar-Vivadent). Vectris Frame consists of pre-impregnated (prepreg) fibreglass/composite components with a fibre orientation of 90 degrees. The fibres were silica coated and embedded in a resin matrix. Frame prepregs with the dimensions of 2 × 2 × 0.3 mm were cut and embedded in an UDMA matrix in the bracket centre before polymerization. The third bracket group was manufactured of UDMA as a monomer matrix and functionally silane-treated SiO_2 fillers. The filler level was 30 vol%. To obtain a homogenous mixture, the composite blend was mixed in a mixer device (Speed Mixer DAC 150FVZ, Hauschild Engineering, Hamm, Germany) for 60 seconds (1800 r.p.m.).

After preparation, the bracket polymers were carefully placed in a mould which was made of a silicone impression of an upper central incisor Brillant bracket (Forestadent, Pforzheim, Germany). The polymerization was carried out using a polymerization device (Targis-Power-Lichtofen, Ivoclar-Vivadent) for 25 minutes. After polymerization the brackets were taken out of the silicone mould and the surplus was removed with a scalpel. Ten brackets per group were produced.

After thermocycling (5°C/55°C) the brackets were fractured with a Zwick universal testing machine 1446 (Zwick, Ulm, Germany). The load was axially applied at the bottom centre of the bracket pad. The crosshead speed chosen was v = 1 mm/minute.

Fracture toughness

For determination of fracture toughness, rectangular specimens (10 per group) with the dimensions of 36 × 8 × 4 mm (length × width × thickness) were manufactured. According to the bracket groups, three different bar groups were manufactured: the first consisted of UDMA; the second UDMA and a glass fibre weave [36 × 8 × 0.3 mm (length × width × thickness) Vectris Frame (Ivoclar-Vivadent)], embedded in the middle of the specimens (Figure 1); and the third group UDMA, reinforced with SiO_2 fillers (filler level: 30 vol%). The Targis-Power-Lichtofen device (Ivoclar-Vivadent) was used for polymerization.

The surface of the bars was ground with sand paper (grit 800). At the midspan of the specimens a 3-mm-deep and 0.5-mm-wide notch was prepared. This cut was extended to a notch of 0.2–0.5 mm in length using a razor blade device (Ivoclar-Vivadent). Before the tests were performed, all bars were thermocycled in a mastication device (5°C/55°C).

After preparation of the bars, a three-point bending test (Figure 2, support distance: 32 mm) was performed with the Zwick universal testing machine. The load was applied axially in the centre of the bars directly above the notch (v = 1 mm/minute).

The fracture toughness (K_{1c}) was determined according to the following formula (Williams and Cawood, 1990):

$$K_{1c(\max)} = \frac{\left(P_{\max} \times S\right)}{B \times H^{\frac{3}{2}}} f\left(x\right),$$

$$f\left(x\right) = \frac{3x^{\frac{1}{2}}\left[1.99 - x\left(1-x\right)\left(2.15 - 3.93x + 2.7x^2\right)\right]}{2\left(1+2x\right)\left(1-x\right)^{3/2}},$$

$$x = \frac{a}{H},$$

where S is the support distance, P the fracture load, B the width, H the height, and a the notch length.

Flexural strength

A silicone mould was manufactured with an inner dimension of 2 × 2 × 25 mm and three different groups of bars were produced: the first group consisted of UDMA; the second

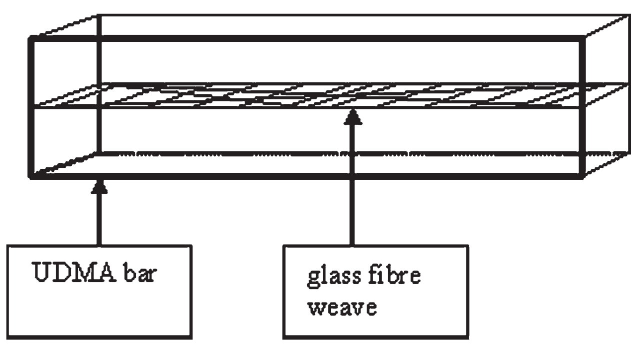

Figure 1 Urethane dimethacrylate (UDMA) bars reinforced with a glass fibre weave in the centre.

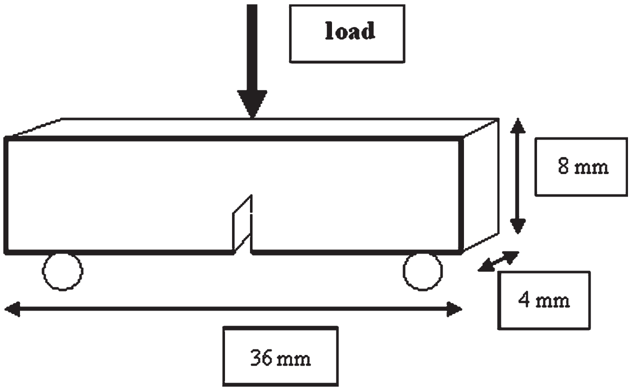

Figure 2 Three-point bending test for determining fracture toughness.

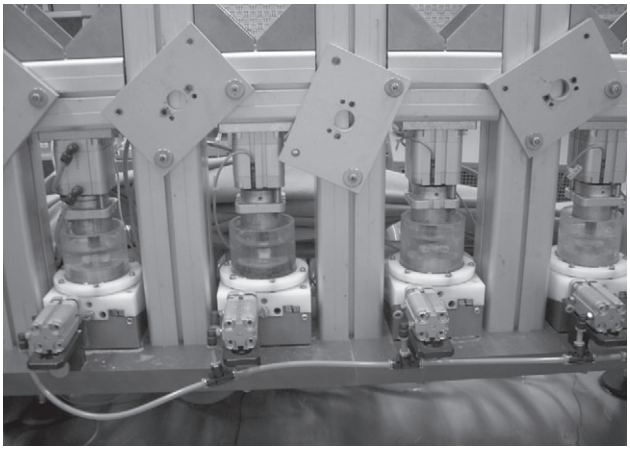

Figure 3 Artificial oral environment of a mastication device.

group of UDMA and a glass fibre weave of Vectris Frame (Ivoclar-Vivadent), which was embedded in the middle of the samples; and the third beam group was a composite, consisting of UDMA as a monomer matrix and SiO_2 fillers (filler level: 30 vol%). The polymers were placed carefully in the mould and the polymerization was carried out using the Targis-Power-Lichtofen polymerization device (Ivoclar-Vivadent) for 25 minutes. Ten samples per polymer group were manufactured. All specimens were thermocycled at 5°C/55°C in a mastication device prior to testing.

The test was performed with a Zwick universal testing machine 1446. All beams were loaded to fracture using a three-point bending test following DIN 53452 (Hellerich *et al.*, 1992). The support distance was 20 mm. The flexural strength (σ) of the bars was determined using the following formula (Hellerich *et al.*, 1992):

$$\sigma = \frac{3 \cdot F \cdot l}{2 \cdot b \cdot h^2},$$

where F is the force, l the length, b the width, and h the height of the bars.

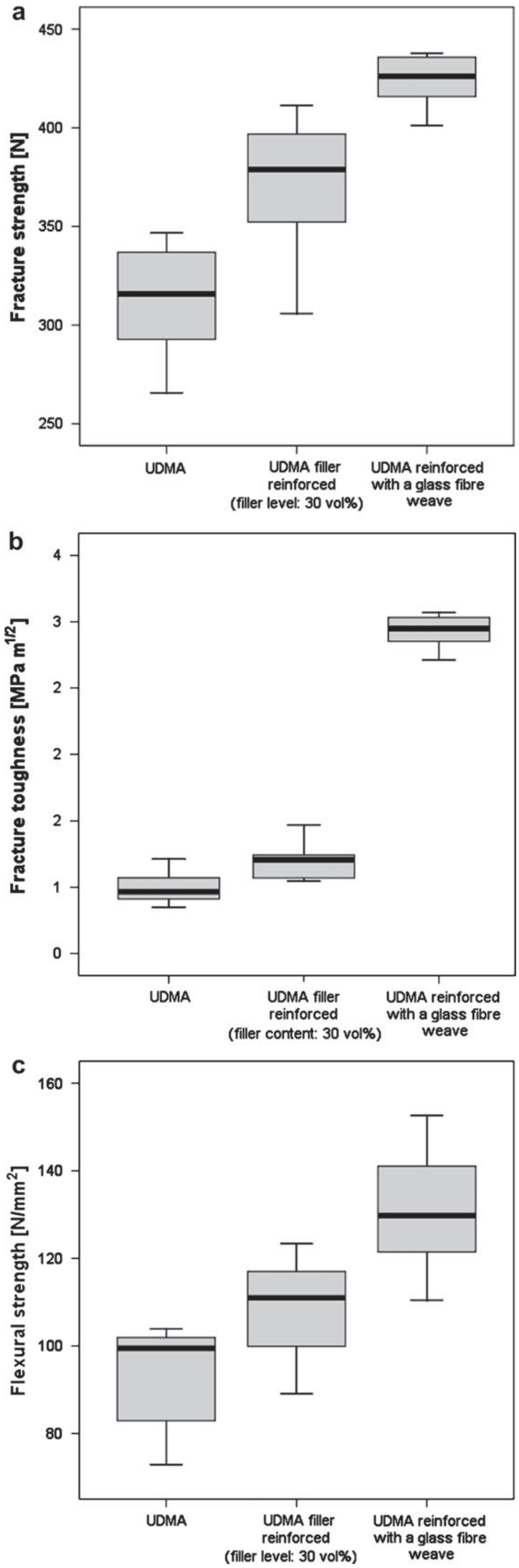

Figure 4 Fracture strength (a), fracture toughness (K_{1c}) (b), and flexural strength (c) of experimental polymer brackets (median, 25th and 75th percentiles, minimum, and maximum).

Table 1 Statistical analysis (Mann–Whitney *U*-test and *P* values) of mechanical properties of experimental brackets.

	Fracture strength	Fracture toughness (K_{1c})	Flexural strength
UDMA compared with UDMA filler reinforced	0.012	0.022	n.s.
UDMA compared with UDMA glass fibre reinforced	0.012	0.005	0.012
UDMA filler reinforced compared with UDMA glass fibre reinforced	0.012	0.005	0.012

UDMA, urethane dimethacrylate; n.s., not significant.

Table 2 Median values and standard deviations of the mechanical properties of the experimental brackets.

	Fracture strength	Fracture toughness (K_{1c})	Flexural strength
UDMA	317 ± 43	0.97 ± 0.11	99 ± 12
UDMA filler reinforced (filler content: 30 vol%)	369 ± 34	1.21 ± 0.14	111 ± 12
UDMA reinforced with a glass fibre weave	429 ± 14	2.95 ± 0.13	130 ± 14

UDMA, urethane dimethacrylate.

Artificial oral environment

Twenty-four hours after preparation, all brackets and bars were exposed to thermocycling to simulate the moisture of saliva and temperature changes in the oral environment. Therefore, all bracket groups were alternatively flooded every 2 minutes with warm (55°C) and cold (5°C) distilled water for 6000 cycles in a mastication device (Figure 3; Rosentritt *et al.*, 1997).

Statistics

Statistical analysis was undertaken using the Statistical Package for Social Sciences, version 12.0 (SPSS Inc., Chicago, Illinois, USA). Median, 25th and 75th percentiles were calculated. The Mann–Whitney *U*-test was performed. The level of significance was set to $\alpha = 0.05$.

Results

A significant increase of fracture strength ($P = 0.012$) was found when reinforcing UDMA brackets with a glass fibre weave (Figure 4a, Table 1). The glass fibre-reinforced brackets showed a distinct enhancement of fracture strength in comparison with the unfilled UDMA brackets. The unfilled UDMA brackets showed a median fracture strength value of 317 N (Table 2).

A small, but significant ($P = 0.022$), improvement in fracture toughness was observed when SiO_2 filler-reinforced brackets were compared with unfilled UDMA brackets (Figure 4b, Table 1). However, fracture toughness of the glass fibre-reinforced brackets almost tripled in comparison with the unfilled and filled polymer brackets.

A median value of 130 N/mm^2 was observed, when the flexural strength of glass fibre-reinforced brackets was examined (Table 2). No significant increase in flexural strength was found, when UDMA brackets were compared with filler-reinforced brackets. The flexural strength of glass fibre-reinforced brackets showed a significant improvement in comparison with the unfilled and filled brackets (Figure 4c, Table 1).

Discussion

Aesthetics should be one of the most central properties of dental materials. For that reason greater attention has been paid to tooth-coloured brackets, especially in adult treatment. Nevertheless, in the oral cavity orthodontic appliances are subjected to cyclic mechanical and thermal loading in a wet environment during treatment. Thus, in this study an artificial oral environment was chosen to simulate temperature changes in a damp milieu *in vitro*. Fracture toughness, fracture strength, and flexural strength were tested. Fracture toughness is described as the ability of a material to resist crack propagation, whereas fracture strength is the stress at which the material fractures. The flexural strength test is able to compare the load-bearing capacity of different materials under flexure. According to Pereira *et al.* (2003), the flexural strength test deserves particular attention, because it measures tension and compression acting together, simulating clinical conditions.

In this investigation UDMA was chosen as the polymer matrix, because it reveals increased tensile properties, low viscosity, and faster and more complete conversion (Asmussen and Phillips, 1998; Göhring *et al.*, 2005). These factors may influence the mechanical properties of the experimental brackets and the embedding quality of the used bidirectional glass fibres and SiO_2 fillers. A large amount of literature is available concerning fibre reinforcement and fibre content of FRCs (Drummond *et al.*, 2004; Narva *et al.*, 2004; Kanie *et al.*, 2005; Lassila *et al.*, 2005). Nevertheless, Behr *et al.* (2000) demonstrated that a higher fibre content does not necessarily lead to higher flexural strength. They stated that not only the fibre content but also the bond between the polymer matrix and fibres and the composition of the matrix influence the mechanical properties of FRCs.

In orthodontics FRCs have been successfully used as fixed orthodontic retainers or for temporary tooth splinting in periodontally compromised patients (Karaman *et al.*, 2002). FRCs have also been used as experimental orthodontic wires (Huang *et al.*, 2003) and space maintainers (Kargul *et al.*, 2003). However, Kirzioglu and Erturk (2004) reported that FRC space maintainers could be accepted as successful appliances only for short periods. They stated that prolonged use of this material for retention in orthodontic patients must be evaluated in long-term studies.

In this investigation two findings were apparent. (1) Filler reinforcement of plastic brackets improved fracture toughness and fracture strength in comparison with unfilled brackets. (2) Glass fibre weave reinforcement of orthodontic brackets demonstrated the greatest mechanical properties of the tested samples. The explanation for these findings is that stress is transferred from the polymer matrix to the fibres which present a high tensile strength (Nohrstrom *et al.*, 2000; Hamza *et al.*, 2004).

In the present study the glass fibre weaves were positioned in the central part of the specimens. Göhring *et al.* (2005) found a significant reinforcing effect of flexural strength when the fibre weaves were located on the tension but not on the compression side of the samples. However, the direction of forces on brackets caused by the activated archwire, food, and opposing teeth during mastication is multidirectional. Because of the complex structure of orthodontic brackets and the unpredictable forces on brackets, the glass fibre weaves in this study were placed in the centre of the brackets and bars.

Several investigations have demonstrated that reinforcement of the polymeric structure with fibres and fillers is able to increase the mechanical properties (Jaarda *et al.*, 1996; Condon and Ferracane, 1997; Drummond *et al.*, 2004; Göhring *et al.*, 2005; Kanie *et al.*, 2005; Lassila *et al.*, 2005). However, during cyclic temperature loading, interfacial stress between polymer matrix and fillers or fibres can occur, because of different thermal expansion coefficients (Göhring *et al.*, 2005). Chai *et al.* (2005) found that water immersion affected the flexural strengths of different FRCs. In agreement with others (Vallittu *et al.*, 1998; Vallittu, 2000; Tanner *et al.*, 2001), Lassila *et al.* (2002) the decrease in flexural properties of FRCs after water immersion was mainly caused by the plasticizing effect of the water. Water molecules are able to penetrate into the spaces between polymer chains. As a result, water molecules push the polymer chains further apart and cause, after a sufficient period of time, an expansion in a wet environment. This results in a decline of the secondary chemical bonding forces (van der Waals forces) between the polymer chains (Rantala *et al.*, 2003). Therefore, the mechanical properties, e.g. flexural strength and fracture toughness of plastic brackets, are reduced. Exposed fibres and voids in the structure of the FRC lead to another problem during water exposure in the oral environment. By means of capillary forces water could be absorbed (Rantala *et al.*, 2003). As a result, water saturation of the brackets could be hastened. Poorly impregnated fibres could accelerate this progress. Nevertheless, Meric *et al.* (2005) reported that silica glass fibres showed sufficient qualities in aqueous environments, such as the oral environment. Consequently, fibreglass reinforcement, which is able to withstand the moisture of saliva in the oral cavity, seems to be a method to improve the mechanical properties of orthodontic brackets.

Conclusions

Reinforcement with fillers or fibres is able to improve the mechanical properties of polymeric brackets. The application of glass fibre weaves in plastic brackets has the podential to enhance fracture strength.

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