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Effect of flexural strength of orthodontic resin cement on bond strength of metal brackets to enamel surfaces

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SUMMARY Three types of experimental resin cements with different curing systems, dual, light, and chemical, were designed. The relationship between the flexural strengths of the three experimental and five commercial (Beauty Ortho Bond, Transbond™ XT, Light Cure Bond, Kurasper® F, and Super Bond) orthodontic resin cements on the tensile bond strength (TBS) and shear bond strength (SBS) of metal brackets to enamel was determined.

Seven specimen bars of each resin were prepared for measuring the flexural strengths of the resins. Bonded specimens of each resin were prepared, seven for measuring TBS and seven SBS for after bonding of a metal bracket to a maxillary central human labial anterior tooth using experimental and commercial resin cements. The results were analysed by one-way analysis of variance and Scheffé's multiple comparison tests. The level of statistical significance was set at 0.05.

Increases in the flexural strength of the resin cements were related to increases in the TBS and SBS of the metal bracket. While the light-curing cements exhibited a strong linear correlation between flexural strengths and TBS or SBS, the dual- and chemical-curing cements exhibited a different flexural strength effect on both TBS and SBS. This was a result of the adhesive layer under the metal bracket, which could be chemically cured, in contrast to the light-curing cement.

To control setting time and to obtain higher initial TBS and SBS by polymerizing the resin cement under the bracket, a dual-curing system, that combines both light- and chemical-curing systems, is essential.

Introduction

For direct bonding of an orthodontic bracket (Linn *et al.*, 2006; Deahl *et al.*, 2007), the setting time of the orthodontic resin cement and the initial bond strength of the orthodontic bracket bonded to the enamel surface are important since orthodontic appliances are activated immediately after bonding the bracket to the enamel surface (Liu *et al.*, 2004; Yamamoto *et al.*, 2006).

In order to directly control the setting time of the resin cement and to obtain high initial bracket bond strength immediately after bonding, light-curing type resin cements have been developed (Greenlaw *et al.*, 1989; Eliades *et al.*, 1995; Armas Galindo *et al.*, 1998). However, when a metal bracket is placed onto the enamel surface, the bracket inhibits the transmittance of the visible light that is necessary for activating the polymerization reaction of light-curing type resin cements, which exists as an adhesive layer. The drawbacks with light-curing type resins can be associated with the amount of time required to cure the resin cement under the metal bracket and the fact that, whatever curing time is used, complete polymerization of the resin cement cannot be ensured (Smith and Shivapuja, 1993). To overcome these drawbacks, Li *et al.* (2009) developed an experimental dual-curing type resin cement (EXD) that combines both light- and chemical-curing systems.

In this study, in order to understand the effectiveness of the EXD, an experimental light-curing type resin cement (EXL) and an experimental chemical-curing type resin cement (EXC) were also designed. The relationship between the flexural strengths of the three experimental cements and five commercial resin cements and the tensile bond strength (TBS) and shear bond strength (SBS) of metal brackets to the enamel surface was examined. The efficacy of the EXD was then compared with the flexural strength and TBS and SBS of the light- and chemical-curing resin cements. The null hypotheses tested were: (1) the flexural strength of orthodontic resin cements is not related to the TBS and SBS of metal brackets to the enamel surface and (2) the EXD has no effect in enhancing TBS and SBS.

Materials and methods

This study was conducted according to established protocol and reviewed by the ethics committee of Nihon University School of Dentistry at Matsudo (EC 08-018).

Materials

The experimental resin cements consisted of two pastes (Li *et al.*, 2009). The components and compositions of the base monomers for pastes A and B are shown in Table 1.

Camphorquinone (CQ) as a photoinitiator and *p*-tolyldiethanolamine (*p*-TDEA) as an accelerator were utilized for the light-curing system. *p*-TDEA and sodium *p*-toluenesulfinate (*p*-TSNa) were used as accelerators for the chemical-curing system.

Three types of experimental resin cements with different curing systems, specifically for dual-, light- and chemical curing, were designed. For the EXD, 0.5 mass% of CQ was added to base monomer A and 0.25 mass% of *p*-TDEA and *p*-TSNa to base monomer B. 4-Methacryloyloxyethyl dihydrogentrimellitate (4-MET) and β-methacryloyloxyethyl hydrogen phthalate (CB-1) utilized in the base monomer A act as an initiator for the chemical-curing system when the 4-MET and CB-1 are in contact with the *p*-TDEA and *p*-TSNa (Li *et al.*, 2009). For the EXL, 0.5 mass% of CQ was added to base monomer A, while 0.25 mass% of *p*-TDEA only was utilized in base monomer B. For the EXC, CQ was not utilized in the base monomer A; however, 0.25 mass% of both *p*-TDEA and *p*-TSNa were added to base monomer B.

For preparation of the experimental cements, colloidal silica (Aerosil 130; Aerosil Nippon Co., Tokyo, Japan), whose surface was silanated with 6 mass% of γ-methacryloxypropyltrimethoxysilane, was utilized as an inorganic filler. The experimental cements were prepared by adding 10 or 8 g of the silanated colloidal silica to 10 g of base monomer A or base monomer B.

Beauty Ortho Bond (BO; Shofu Inc., Kyoto, Japan), Transbond™ XT (TX; 3M, Monrovia, California, USA), Light Cure Bond (LB; Reliance Orthodontic Products, Itasca, Illinois, USA), and Kurasper® F (KF; Kuraray Medical Inc., Tokyo, Japan) were used as the commercial light-curing type resin cements and Super Bond (SB; Sun Medical, Shiga, Japan) as the commercial chemical-curing type resin cement (Table 2).

Table 1 Components and compositions of base monomers A and B used in the experimental resin cement (Bis-GMA: bisphenol A glycidyl dimethacrylate; CB-1: β-methacryloyloxyethyl hydrogen phthalate; HEMA: 2-hydroxyethyl methacrylate; 4-MET: 4-methacryloyloxyethyl dihydrogen trimellitate; PEM-F: penta(methacryloxy-ethyl-oxy)-cyclophosphazene mono-fluoride; TEGDMA: triethylene glycol dimethacrylate).

Base monomer A	Mass%	Base monomer B	Mass%
Bis-GMA	6.7	Bis-GMA	64.3
HEMA	33.3	TEGDMA	35.7
4-MET	26.7		
PEM-F	13.3		
CB-1	20.0		

Methods

Measurement of flexural strength. Pastes A and B of the EXD, EXL and EXC were mixed at a ratio of 1:1 for 20 seconds. The pastes were then poured into a split metal mould that had been glued onto a glass slide. The split mould was then used to prepare the specimen bars, in which the experimental resin cements had hardened with a width of 4.2 mm, a thickness of 2.1 mm, and a length of 35 mm. A transparent thin film was placed on the top surface of the mixture. With the exception of the EXC, the EXD or EXL was then irradiated with visible light, first from the transparent film side for 30 seconds and then from the glass slide side for 30 seconds with a light-curing unit (α-light II; Morita, Tokyo, Japan). The setting time of the EXC was approximately

Table 2 Components and composition of the commercial light- and chemical-curing type resin cements (Bis-EMA: ethoxylated bisphenol A dimethacrylate; CQ: camphorquinone; DMAPE: 4-*n*, *n*-dimethylaminophenylethanol; 4-META: 4-methacryloyloxyethyl trimellitate anhydride; MMA: methyl methacrylate; PMMA: polymethyl methacrylate; TBB: tri-*n*-butyl borane).

Product	Code	Component	Composition
Light-curing type			
Beauty Ortho Bond	BO	Self-etching primer A	Acetone, water, photoinitiator
		Self-etching primer B	Ethanol, phosphonic acid monomer
		Paste	Bis-GMA, TEGMA, silica filler
Transbond™ XT	TX	Etching gel	35 mass% phosphoric acid
		Adhesive primer	TEGMA, DMAPE, CQ
		Paste	Bis-GMA, TEGDMA, Bis-EMA, silylated quartz, silylated filler and submicron silica
Light Cure Bond	LB	Etching liquid	39 mass% phosphoric acid
		Paste	Bis-GMA, TEGDMA
Kurasper® F	KF	K-etchant	40 mass% phosphoric acid
		F-bond	TEGDMA, HEMA, Sodium fluoride, silica filler, methacryloyl fluoride-MMA copolymer, dimethacrylate, CQ
		Kurasper F paste	Bis-GMA, methacrylic acid ester monomer, dimethacrylate, silica filler, CQ
Chemical-curing type			
Super Bond	SB	Etching agent	65 mass% phosphoric acid
		Polymer powder	PMMA
		Monomer liquid	4-META, MMA
		Catalyst	Partly oxidized TBB

8 minutes (Li *et al.*, 2009). The hardened specimen bars were then removed from the split mould and immersed in water at 37°C for 1 day prior to testing since polymerization of orthodontic resin cements may continue for up to 24 hours (Yamamoto *et al.*, 2006). After 24 hours, the bars were polished with a sequence of 600- and 1000-grit carbide papers under a stream of water. The width and thickness of the bars were reduced to either 4.0 or 2.0 mm. The bars were then placed on a three-point bending fixture (span distance: 10 mm) mounted on a universal testing machine (TG-5KN; Minebea, Kanagawa, Japan). Loading was applied to the bars under a crosshead speed of 1 mm/minute. Concurrently, the load-deflection curve was recorded on a computer. The flexural strength was derived from the maximum load and the elastic modulus from the deflection when a load of 0.4 kN was applied.

Bars of the commercial adhesives were prepared, and the flexural strengths and elastic moduli of the BO, TX, LB, and KF were measured using the same procedures. The irradiation time of the visible light to the resin paste was 30 seconds from the transparent film side and 30 seconds from the glass slide side. In addition, the flexural strength and elastic modulus of SB was measured after preparing the specimen bars by the brush dip method, as per the manufacturer's instruction.

Seven specimen bars for each resin were prepared for flexural testing. The flexural strength was measured once per specimen. The mean values of the flexural strength and elastic modulus and their standard deviation (SD) were calculated for each experimental group. The results were analysed by one-way analysis of variance (ANOVA) and Scheffé's multiple comparison tests. The level of statistical significance was set at 0.05.

Adhesion test. One hundred and twelve maxillary central human labial anterior teeth, which had been extracted from patients with periodontal disease and immediately stored in water at 4°C after extraction, were used for the adhesion test.

The labial enamel surface was cleaned, rinsed, and dried using generally accepted procedures and then etched with 31 per cent phosphoric acid (Etching Gel for Xeno Ortho; Dentsply-Sankin, Tokyo, Japan) for 30 seconds, rinsed with running water for 20 seconds and then air-dried for 30 seconds. EXD or EXL was then applied to the base of the bracket (standard number: 105–1100; Dentsply-Sankin) and the bracket was pressed onto the etched enamel surface. Excess resin cement was carefully removed from around the bracket base using a scaler. Visible light was used at an angle of 45 degrees to the mesial side of the bracket for 5 seconds and then to the distal side for 5 seconds with a light-curing unit (XL3000; 3M Espe, Grafenau, Germany). The specimens bonded with EXC were also prepared, but without visible light irradiation.

BO, TX, LB, or KF was applied to the brackets for bonding to the etched enamel surface, as recommended by the respective manufacturers (Table 3). The SB was applied to the bracket using the brush dip technique. After preparation, the specimens were then stored in water at 37°C. Fourteen bonded specimens for each resin were prepared for adhesion testing.

Measurement of bond strength. After immersion in water at 37°C for 1 day, the bonded specimens were embedded in a self-curing pour resin (Shofu Inc.). Fourteen bonded specimens were divided into two experimental groups for TBS and SBS testing.

When the TBS of the metal bracket to the enamel was measured, a cut stainless steel rectangular straight wire (0.457 × 0.558 mm; RMO Inc., Denver, Colorado, USA) was inserted into the bracket slot and coupled using a ligature wire (0.305 mm; RMO Inc.). The coupled specimens were then mounted on a universal testing machine (TG-5KN; Minebea, Nagano, Japan). After attaching both terminal sides of the rectangular straight wire with a metal device, the bracket was pulled vertically against the enamel surface under a crosshead speed of 1 mm/minute (Figure 1). The maximum load was then recorded on a computer. The TBS of the bracket to the enamel was calculated by dividing the

Table 3 Components of the etching agents, conditioning times for the enamel surface, and visible light irradiation times for each commercial resin cement.

Resin cement	Etching agent	Conditioning time	Irradiation time
Light-curing type			
Beauty Ortho Bond	Phosphoric acid monomer	3 seconds	10 seconds
Transbond™ XT	35% phosphoric acid	30 seconds	10 seconds
Light Cure Bond	39% phosphoric acid	30 seconds	10 seconds
Kurasper® F	40% phosphoric acid	40 seconds	20 seconds
Chemical-curing type			
Super Bond	65% phosphoric acid	30 seconds	No irradiation

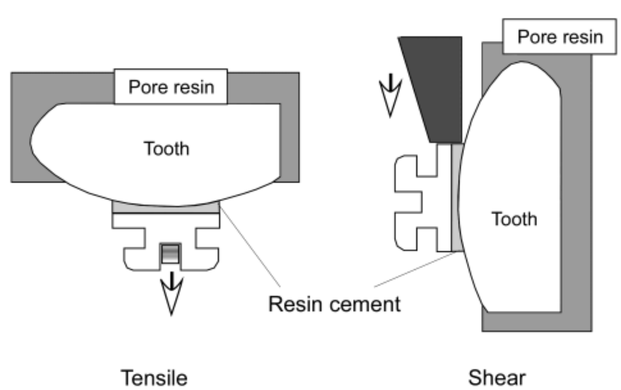

Figure 1 Diagram showing the loading direction applied for measuring the tensile or shear bond strength of metal brackets bonded to enamel surfaces.

maximum load by the area of the bracket base (9.97 mm^2 as reported by Dentsply-Sankin).

For determining SBS, the shear load was directly applied to the bracket using a chisel-edge plunger at a crosshead speed of 1 mm/minute (Figure 1). The SBS of the bracket was determined by dividing the maximum load by the area of the bracket base.

Fourteen bonded specimens for each resin were used, seven for TBS and seven for SBS testing. The mean values of the TBS and SBS and their SD were calculated for each experimental group. The results were analysed by one-way ANOVA and Scheffé's multiple comparison tests. The level of statistical significance was set at 0.05.

To clarify the relationship between the flexural strength of light- or dual- and chemical-curing cements on TBS or SBS, the analysis of covariance (ANCOVA) program, in the Statistical Package for Social Science Windows II (SPSS Inc., Chicago, Illinois, USA), was used. The ANCOVA consisted of two analysis stages. In the first stage, the interaction between the flexural strengths of the light- or the dual- and chemical-curing cements and TBS or SBS was analysed to determine whether the regression slopes for each of the two different curing systems were parallel. The level of statistical significance was set at 0.05. If the regression lines were parallel, a second stage analysis was applied to test the main effects of the flexural strength of the light- or the other curing cements on TBS or SBS. The difference between the y-intercept between the regression lines was evaluated. The level of significance was set at 0.05.

Adhesive remnant index. In order to classify the fracture mode into the four categories of the adhesive remnant index (ARI; Årtun and Bergland, 1984), the enamel surfaces and bracket/bases were observed under a light microscope (Eclipse E800M; Nikon Corp., Tokyo, Japan) at ×10 magnification. The four categories of the ARI were as follows: ARI = 0: no adhesive remained on the enamel surface; ARI = 1: less than half of the adhesive remained on the enamel surface; ARI = 2: more than half of the adhesive remained on the enamel surface; ARI = 3: all the adhesive remained on the enamel surface leaving a distinct impression of the bracket mesh.

The complex chi-square test (Bruning and Kintz, 1977) was used to determine any significant differences in ARI scores. Significance was set at 0.05.

Results

Comparison of flexural strength, elastic modulus, and filler content of the experimental and commercial resin cements

The flexural strengths, elastic moduli, and filler contents of the experimental and commercial resin cements are shown in Table 4. The filler content was determined using the ash technique (Nakaso and Yoshino, 1980).

The flexural strength and elastic modulus of the experimental resin cements were highly dependent on the type of curing system. The EXD exhibited higher flexural strength (114.6 MPa) and elastic modulus (4.7 GPa) than the EXL and EXC. EXL exhibited the lowest flexural strength and elastic modulus.

Conversely, the flexural strengths of the commercial light-curing type resin cements ranged from 93.9 to 176.2 MPa, with KF exhibiting the highest flexural strength. The commercial light-curing resin cements exhibited higher elastic modulus than the experimental resin cements, thus reflecting the greater mass amount of filler.

The flexural strength and elastic modulus of SB were 88.0 MPa and 1.7 GPa, respectively.

Relationship between the flexural strength of the experimental and commercial resin cements on TBS and SBS of the metal bracket to the labial enamel

The TBS and SBS of the bracket to the enamel surface bonded using the experimental and commercial resin cements, as well

Table 4 Comparisons of the flexural strength, elastic modulus, and filler content of the experimental and commercial resin cements (ANOVA: analysis of variance).

Resin cement	Flexural strength (MPa)	Elastic modulus (GPa)	Filler content (mass%)
Light-curing type			
Experimental	34.3 (3.2)^{A}	1.1 (0.2)^{A}	47.4
Beauty Ortho Bond	93.9 (12.3)^{B}	8.6 (0.2)^{B}	67.2
Transbond™ XT	145.3 (9.2)^{C}	8.3 (0.4)^{B}	75.9
Light Cure Bond	145.8 (7.4)^{C}	7.3 (0.6)^{C}	83.5
Kurasper® F	176.2 (7.2)^{D}	8.3 (0.5)^{B}	78.1
Dual-curing type			
Experimental	114.6 (7.8)^{E}	4.7 (0.3)^{D}	47.4
Chemical-curing type			
Experimental	65.3 (1.0)^{F}	2.1 (0.2)^{E}	47.4
Super Bond	88.0 (1.8)^{B}	1.7 (0.1)^{E}	0.0

For each vertical column, the mean values of the flexural strengths and elastic moduli: different superscript letters indicate a statistically significant difference ($P < 0.05$), one-way ANOVA (Scheffé). Values in parentheses indicate standard deviation. Number of specimens per group = 7.

as the ARI scores after debonding are shown in Table 5. The relationship between the flexural strength of the experimental or commercial resin cements and the bond strength is summarized in Figure 2. After debonding the bracket from the enamel surface by applying tensile or shear loading, no cracking and/or fracturing of the enamel was observed.

When the flexural strengths of the resin cements were increased, the TBS of the bracket to the enamel surface increased (Figure 2A). The regression equations for the light- and dual- and chemical-curing cements were $y = 0.03x + 0.69$ and $y = 0.06x + 0.57$, respectively. The interaction between the flexural strengths of the resin cements after light- or dual and chemical curing and the TBS was statistically significant (ANCOVA, $P = 0.005$). Specifically, the slope of the regression line obtained from the light-curing cements, EXL, BO, TX, LB, and KF, was significantly different from that of the other curing cements, EXD, EXC, and SB.

Similar to TBS, the SBS of the bracket to the enamel surface increased when the flexural strengths of the cements were increased (Figure 2B). The regression equations for the light- and for the the dual- and chemical-cured cements

Table 5 Comparisons of the tensile and shear bond strengths of the stainless steel bracket to the labial enamel bonded by the experimental and commercial resin cements, as well as, the adhesive remnant index (ARI) scores (ANOVA: analysis of variance).

Resin cement	Bond strength			
	Tensile (MPa)	ARI score [0/1/2/3]	Shear (MPa)	ARI score [0/1/2/3]
Light-curing type				
Experimental	1.6 (0.3)^{A}	[0/6/1/0]^{a}	4.2 (0.8)^{A}	[2/3/2/0]^{a}
Beauty Ortho Bond	4.1 (0.9)^{B}	[4/2/1/0]^{a,b}	10.8 (1.5)^{B}	[3/3/1/0]^{a}
Transbond™ XT	4.2 (0.9)^{B}	[4/2/0/1]^{b}	15.8 (4.1)^{C}	[1/4/1/1]^{a}
Light Cure Bond	6.4 (1.5)^{C}	[0/1/5/1]^{a,c}	19.8 (4.8)^{D}	[1/1/5/0]^{a,b}
Kurasper® F	6.3 (2.0)^{C}	[2/0/3/2]^{b,c}	20.4 (3.0)^{D}	[3/3/0/1]^{a}
Dual-curing type				
Experimental	7.2 (0.8)^{C}	[0/0/6/1]^{c}	17.9 (3.6)^{D}	[0/0/6/1]^{b}
Chemical-curing type				
Experimental	4.3 (1.2)^{B}	[0/0/4/3]^{c}	12.9 (2.6)^{B}	[0/0/5/2]^{b}
Super Bond	5.9 (2.0)^{C}	[0/1/4/2]^{a,c}	16.9 (2.3)^{C,D}	[0/2/4/1]^{a,b}

Values in parentheses indicate standard deviation. For each vertical column, the mean values of the tensile and shear bond strengths: different superscript upper case letters indicate a statistically significant difference ($P < 0.05$), one-way ANOVA (Scheffé). Number of specimens per group = 7. For each vertical column, the type of fracture mode for the ARI scores: different superscript lower case letters (a–c) indicate a statistically significant difference ($P < 0.05$), complex chi-square test. Number of specimens per group = 7.

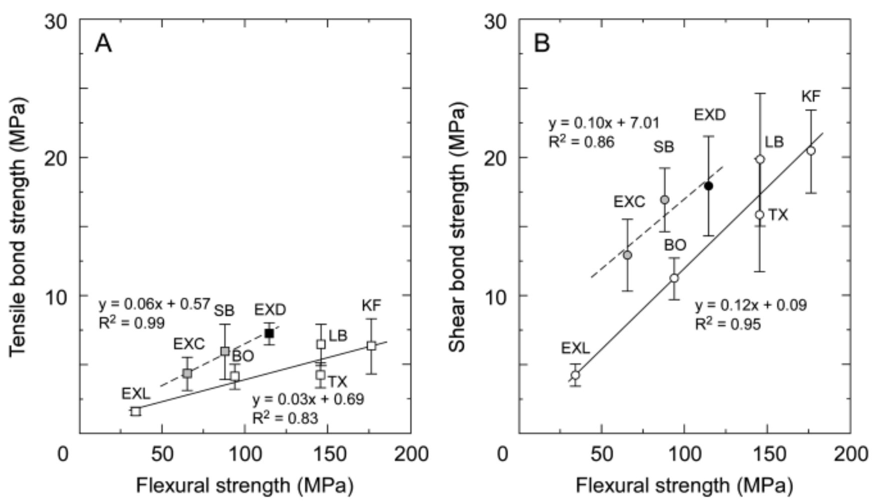

Figure 2 Relationship between the flexural strength of the experimental and commercial resin cements and the bond strength of metal brackets bonded to labial enamel. (A) Effect of flexural strength on tensile bond strength (TBS). (B) Effect of flexural strength on shear bond strength (SBS). The regression line between flexural strength and TBS or SBS was determined using the light-curing cements alone or the dual- and chemical-curing cements, respectively. White squares or circles show the TBS or SBS of the metal bracket bonded to the enamel surface using EXL, BO, TX, LB, and KF. The black square and circle are the TBS or SBS of the metal bracket bonded to the labial enamel with EXD. Grey squares or circles are the TBS or SBS of the metal brackets bonded to the labial enamel by EXC and SB.

were $y = 0.12x + 0.09$ and $y = 0.10x + 7.01$, respectively. The interaction between the flexural strengths of the resin cements after light or dual and chemical curing and the SBS was not statistically significant (ANCOVA, $P = 0.46$). Specifically, the slope of the regression line obtained from the light-curing cements was parallel to that of the other curing cements. However, when the y-intercept obtained from the regression line between the flexural strength of the light- or the dual- and chemically cured cements and SBS was analysed, a significantly different effect (ANCOVA, $P = 0.001$) was observed. The difference in the y-intercept implied that the light-cured group was significantly different from the dual- and chemically cured group.

When tensile force was applied to the bracket bonded to the enamel surface using light-curing cements, the type of fracture mode changed from failure at the interface (ARI score: predominately 0 or 1) to cohesive failure (ARI score: predominately 2 or 3) with increasing flexural strength. In contrast, when shear force was applied, with the exception of LB, failure occurred at the enamel–resin interface (ARI score: predominately 0 or 1), even though flexural strength of the light-cured cements was increased. However, when the EXD, EXC, or SB was used, most of the metal brackets were pulled or peeled away from the resin cement. A cohesive failure of the resin cement was observed at the resin–base interface (ARI score: predominately 2 or 3).

Discussion

Katona and Moore (1994) and Katona (1994, 1997) reported that when tensile or shear force is applied to a metal bracket, tensile or tensile and compressive stresses are generated within the resin cement that exists as an adhesive layer under the bracket. The mechanical properties of orthodontic resin cements are, therefore, important for resisting bond failure.

In this study, the flexural strength of experimental and commercial resin cements were examined to correlate the flexural strengths with the TBS and SBS of a bracket bonded to an enamel surface. This correlation was plausible since, when the resin cement bar is bent, the compression and tension forces are generated at the top and bottom of the bar, respectively, which was the same results observed during adhesion testing. Assuming that the fracture mechanism of the resin cement under the bracket observed during adhesion testing was similar to that during flexural testing, the relationship between the flexural strengths of the experimental and commercial resin cements on the TBS or SBS of a bracket to the enamel surface could be examined.

Increases in the flexural strengths of the cements resulted in increases in TBS and SBS of the bracket to the enamel surface. Thus, the hypothesis that the flexural strength of the orthodontic resin cement is not related to the TBS and SBS of the bracket to the enamel surface was rejected. The observed increase in both TBS and SBS was probably due to the bonding of the resin cement to the etched enamel surface by micromechanical interlocking increasing the mechanical property, specifically the flexural strength of the cements.

When the light-curing type resin cements were used, a strong linear correlation between flexural strengths and TBS and SBS was observed. However, this flexural strength effect differed between TBS and SBS. The flexural strength effects on SBS were 4× greater than those on TBS (ratio of the slope of the regression lines of SBS/TBS: 0.12/0.03). These effects were due to differences in the maximum stress and stress distribution that had developed within the resin cement under the bracket during tensile or shear loading (Katona and Moore, 1994; Katona, 1994, 1997). The observed lower TBS than SBS was due to the maximum stress that had developed as a result of tensile loading being greater than that of shear loading (Katona, 1997). These results indicate that clinicians should pull the metal bracket away from the enamel surface using tension force, so as to reduce the amount of debonding force (Bordeaux *et al.*, 1994; Valletta *et al.*, 2007). This will then place significantly less stress on the enamel surface and thus reduce the risk of enamel fracture.

EXD, EXC, and SB exhibited a different flexural strength effect on TBS and SBS to that obtained from the experimental and commercial light-curing type resin cements. These cements exhibited higher TBS and SBS than expected, which was calculated by assigning the flexural strengths of the respective resin cements to the equations that were determined by the relationship between the flexural strength of the light-curing cement and the TBS and SBS of the bracket to the enamel surface. Thus, the hypothesis that the EXD has no effect on enhancing TBS and SBS was rejected. The observed different flexural strength effects on bond strength between the EXD and the light-curing resin can probably be attributed to differences in the type of curing systems utilized. The higher TBS and SBS of the EXD than that expected were due to the adhesive layer that existed under the bracket, being able to chemically cure equally and uniformly, the same as chemical-curing resins, such as the EXC and SB, in contrast to the light-curing type resin. This was possible since the EXD includes both a light- and chemical-curing system.

The value and reliability required for clinical applications of TBS have been discussed by Wright and Powers (1985), who cite a requirement for maximum tensile force exerted on a bracket of 5.9 MPa (0.6 kgf/mm^2). The EXD, LB, KF, and SB met this requirement. The EXD provided a noticeably higher TBS. A higher TBS and smaller SD are important during orthodontic treatment since a high and stable TBS could reduce the risk of bond failure of the bracket. However, the EXC, EXL, BO, and TX did not achieve this requirement. This may be due to the light-curing resin that existed as an adhesive layer under the bracket being unable to cure completely.

For the ideal orthodontic resin cement, safe debonding of the bracket from the enamel surface without fracturing of the enamel is also important (Meguro *et al.*, 2006a; Arhun and Arman, 2007). When considering safe debonding, most of the resin under the bracket should remain on the enamel surface (Meguro *et al.*, 2006b; Arhun and Arman 2007). In the present study, the EXD exhibited a cohesive failure of the resin cement (ARI score: predominately 2 or 3), even though a tensile or shear force was exerted on the bracket. This type of failure mode may reduce the risk of enamel fracture during debonding. In contrast, when the light-curing type resin cements were used, most of the specimens exhibited failure at the enamel–resin interface (ARI score: predominately 0 or 1). This type of fracture mode may cause the enamel to fracture (Valletta *et al.*, 2007).

Conclusions

In spite of the limitations of the present investigation, the following conclusion was established.

The designed EXD exhibited noticeably higher TBS and SBS of the bracket to the enamel than expected, due to the relationship between the flexural strengths of the light-curing cements and the TBS or SBS. With dual-curing system, which combines both light and chemical curing, it is essential to control the setting time to obtain higher initial TBS and SBS with the light-curing system and to polymerize the resin cement, which exists under the metal bracket as an adhesive layer, by the chemical-curing system.

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