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Orthodontic bonding with glass ionomer cement—a review

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SUMMARY Orthodontic bonding with glass ionomer cement is comparatively new. The purpose of this article is to review the current literature covering both *in vitro* and *in vivo* studies of various glass ionomer cements that have been used for orthodontic bonding. The review indicates that there is little support in the literature to suggest that the currently available conventional glass ionomer cements are suitable for routine clinical use in orthodontics. Dual- or tri-cured hybrid materials, however, comprising both glass ionomer and resin components, appear to have greater potential with regard to clinical performance.

Introduction

Following the introduction of acid etching of enamel by Buonocore in 1955, composites have become widely accepted for cementing orthodontic brackets to teeth (Newman, 1965; Bernstein, 1965; Retief *et al.*, 1970). However, the use of composites for bracket attachment has a number of disadvantages. Enamel may be lost during prophylaxis, acid etching and at the time of clean up of residual resin at debond, as well as during rebonding procedures (Thompson and Way, 1981; Silverston, 1974; Pus and Way, 1980). The concentration of fluoride is greatest at the enamel surface (Thompson and Way, 1981) and the loss of this surface material is therefore of concern. In addition, decalcification may develop within a month of bracket placement due to prolonged accumulation and retention of plaque next to the bracket base (O'Reilly and Featherstone, 1987).

In view of these significant disadvantages with composite bonding, there has been considerable interest in developing a bonding material that could render the tooth surface less susceptible to decalcification yet retain the bond strength of composites without loss of enamel. Glass ionomer cements offer a potential means of achieving this.

Wilson and Kent (1972) were the first to describe glass ionomer cements. Their physical properties were an amalgamation of those of silicate and polycarboxylate cements, but their handling characteristics were not ideal. Also, the long setting times resulting from the poor reactivity of the aluminosilicate glasses in the early cements produced poor durability and high water absorption and solubility (McLean *et al.*, 1984; Atkinson and Pearson, 1985). The current glass ionomer cements were introduced following the development of ion-leachable glasses (Wilson and Kent, 1972) and have better physical and clinical handling properties (Knibbs *et al.*, 1986a, b). These have been reviewed very comprehensively by Walls (1986).

Glass ionomer cements possess a unique combination of properties that make them potentially useful in clinical orthodontics. Firstly, they adhere to both enamel and metal (Hotz *et al.*, 1977). Secondly, they release fluoride and thereby may prevent enamel decalcification (Hallgren *et al.*, 1994). Finally, they can be removed more easily than composite resin at the time of debond (Norevall *et al.*, 1995) as the cement which remains on the tooth surface can be dessicated by simply air drying it (White, 1986) thereby rendering it more friable. Enamel loss from bonding and debonding is therefore likely to be less than that with composites and there is the added bonus of increasing the fluoride content of the enamel surface adjacent to the bracket by fluoride uptake (David, 1994).

Glass ionomer cements have been investigated for cementation of orthodontic bands and have superior tensile and compressive strengths and a lower failure rate clinically compared with other cements (Norris *et al.*, 1986; Durning, 1989; Stirrups, 1991). More recently they have been used for direct bonding of orthodontic brackets in both laboratory and clinical studies (Cook and Youngson, 1988; Fricker, 1992) and are marketed in a variety of forms. They may be conventional (cement setting), dual-cured (cement setting or light-activated), or tri-cured (chemical or light-activated polymerization, as well as by a cement setting reaction). The new generation glass ionomer materials which are dual- or tri-cured are hybrid materials containing resin and glass ionomer components and therefore differ considerably in their properties from the conventional glass ionomer materials.

Although the use of glass ionomer for bonding may seem a restricted area of the dental literature for review, there have been a considerable number of reports over the past few years relating to orthodontic bonding with these materials. The purpose of this article, therefore, is to review the studies which have been performed and to attempt to reach a concensus of the current position.

In vitro studies

To date there have been 37 *in vitro* studies on bond strength testing of orthodontic brackets with glass ionomer cement (Table 1). They have attempted to isolate and study variables which are thought to be of clinical significance.

Effect of tooth preparation on bond strength

There would appear to be no clear guidelines as to the best method of enamel treatment prior to bonding with conventional glass ionomer cements. Simple prophylaxis and drying the tooth with a cotton wool pledget has been shown to produce a better bond than treating the enamel surface with an enamel cleanser (40 per cent polyacrylic acid) while the effect of etching the enamel with phosphoric acid is disputed, some workers finding it produced a significantly poorer bond (Cook and Youngson, 1988) while another found an increase in mean bond strength although this was not significantly greater than to unetched enamel (Wiltshire, 1994). Other workers have found that pre-treatment of the enamel with acids, e.g. polyacrylic acid or tannic acid improved bond strength to the extent of attaining about 60 per cent of the values achieved using an acid etch enamel/composite technique (Fischer-Brandies and Tragner-Born, 1989). These findings relate to bonding with conventional glass ionomer cements.

Dual- or tri-cured resin modified products may require a different method of enamel pre-treatment; this has yet to be clarified with respect to each product, although some reports indicate that enamel pre-treatment with either phosphoric acid or polyacrylic acid appears to be required to improve their bond strength (Shin and Lee, 1995; Carter and McCabe, 1995; Scott *et al.*, 1995; Jaochakarasiri *et al.*, 1995). Interestingly, Shin and Lee (1995) found no significant difference in shear bond strength of a light-cured glass ionomer (product not specified) to enamel treated with 10 per cent polyacrylic acid and that of composite resin to enamel etched with 38 per cent phosphoric acid. Ewoldsen *et al.* (1995) indicated that the bond strength of the resin-modified glass ionomer cement (Fuji II LC; GC International, Tokyo, Japan) was not dependent on phosphoric acid etching and was only marginally enhanced by polyacrylic acid enamel preconditioning. In that study, all specimens were stored for 7 days in a humid environment prior to thermocycling and shear bond strength measurement. The differences in products tested in these recent studies on resin modified materials, time prior to testing and pre-test conditions make it difficult to evaluate independently the effect of enamel pre-treatment on the bond strength.

Since it will be shown later that one potential clinical drawback of some brands of glass ionomer cement is a higher bond failure rate than with composites, it is obviously important with these materials to consider any means of optimizing the bond strength of the material. However, as the site of failure for brackets bonded with conventional glass ionomer cements appears to be predominantly at the bracket/cement interface there would appear to be little merit in further work being directed at methods of enamel preparation in an attempt to improve their bond strength.

Effect of material proportioning (powder:liquid ratio)

The various glass ionomer cements that have been used for orthodontic bonding are given

Table 1 *In vitro* studies of glass ionomer cement (GIC) for orthodontic bonding.

Author	Teeth used	Bracket type	Cement mix	Cement tested	Specimen/ test	Test mode	Bond strength
Cook and Youngson (1988)	pm	s. steel	'st'	A E	20	T	49.5–60.9 N 73.9 N
*Davis *et al.* (1988)	pm	ng	mi	A B E	24	S	E > AB
Rezich *et al.* (1988)	m	s. steel	mi	A E F	10	S	1 MPa 16.6 MPa 6.0 MPa
*Davis *et al.* (1989)	pm	s. steel ceramic	mi	A E	24	S	E > AB
*Klockowski *et al.* *(1989)*	pm	s. steel	mi	A B E	24	S	2.9–3.9 N 3.8–4.2 N 5.9–10.4 N
*Miller *et al.* (1989)	pm	s. steel	ng	A E	22	T	2.7–3.4 MPa 10.3 Mpa (at 7 days)
*Fischer-Brandies and Tragner-Born (1989)	pm	s. steel	ng	A E	9–10	T	3.5–6.4 MPa 14.5 MPa
*Kao *et al.* (1989)	m	s. steel	ng	A E F	7	S	92–116 N 218–257 N 183–231 N (at 48 h)
Kluge *et al.* (1990)	bovine	s. steel	ng	A	107	T	34–62 N
Norevall *et al.* (1990)	pm	s. steel	mi	A E	ng	T S	37.9 N 33 N 69 N 103 N
Jähnig and Henkel (1990)	bovine	s. steel	ng	A E	20	T	E 50% stronger than A
Tavas and Salem (1990)	pm	s. steel	c	A	14	S	16.4–42.4 N
Fajen *et al.* (1990)	pm	s. steel	mi	A E	10	T	1.7–11.9 lbs (pumice pre-treatment) 32.7 lbs
Evans and Oliver (1991)	pm	s. steel eyelets	mi	A E	8	T/Peel	18.7–37.1 N 108 N
Fox *et al.* (1991)	pm	s. steel	mi	A E F	30	S	33.1 N 55.1 N 44 N
Øen *et al.* (1991)	pm	s. steel	mi	A C E	ng	S	40–47 N 35 N 95 N (at 20 mins)
Rezk-Lega and Øgaard (1991)	pm	s. steel	'st'	A except for C E	10 C	T	6–18 N 28 N 153 N
McCourt *et al.* (1991)	pm	s. steel	mi	C F G	10	S	11.6 MPa 6.0 MPa 11.4 MPa
Compton *et al.* (1992)	pm	s. steel buttons	mi	A C	13	S	17.2 MPa 11.8 MPa
Kimmins (1992)	pm	ng	ng	A E	ng	S	E > A
Dasch *et al.* (1993)	ng	s. steel ceramic	mi	C E	ng	T	s. steel 2.2 MPa 6.9 MPa ceramic 6.8 MPa 7.5 MPa
Millett *et al.* (1993)	pm	s. steel	mi	A E	30	S	38.7–47.1 N 83.6 N

Table 1 (*continued*)

Author	Teeth used	Bracket type	Cement mix	Cement tested	Specimen/ test	Test mode	Bond strength
Eberhard *et al.* (1993)	bovine incisors	s. steel	ng	C E H	50	T	15.8–17.7 N 87.9 118.8 N 73.7–130.6 N (time to test not given)
*Fischer-Brandies *et al.* (1993a)	bovine	ng	ng	A E	ng	S	E>A (time to test not given)
*Fisher-Brandies *et al.* (1993b)	bovine	ng	ng	A B C	10	S	3.6 MPa 8.5 MPa 9.0 MPa
Wiltshire (1994)	pm	s. steel buttons	mi	A E	15	S	4.4–5.5 MPa 26 MPa
*Supak and Burgess (1994)	ng	ng	mi	A C E	10	S	54 N (32 N) 96–103 N (52–62 N) 91 N (103 N) (values in parentheses are after thermocycling)
Kao *et al.* (1994)	human incisors	s. steel ceramic	ng	A C	5	S	14.6 kg 8.3–21.1 kg (at 7 days)
Joseph *et al.* (1994)	human incisor	s. steel	ng	D E	15	S	9.9–14.2 MPa 19 MPa Bond strength of D increased with time (tested at 10 min–7 days)
Moseley *et al.* (1995)	pm	s. steel	P/L ratio 7:1	A E	15	S	Cyclic mechanical stressing reduced bond strength for both A and E. Both A and E displayed different fatigue behaviour
Blight and Lynch (1995)	pm	ceramic	mi	I C K	20	T	20.2 MPa 9 MPa 11.4 MPa
Shin and Lee (1995)	pm	s. steel	ng	A C E	ng	S	C>A No significant difference between C with 10% polyacrylic acid enamel pre-treatment and D with 38% phosphoric acid enamel pre-treatment.
Mitchell *et al.* (1995)	pm	s. steel	mi	A D E	25	T/S	E>A or D at 10 min D had greater probability survival than A at 24 h
Carter and McCabe (1995)	pm	s. steel	ng	C E	20	S	E>C
*Scott *et al.* (1995)	m	s. steel	ng	A C D	5	S	A>C or D

Table 1 (*continued*)

Author	Teeth used	Bracket type	Cement mix	Cement tested	Specimen/ test	Test mode	Bond strength
*Jaochakarasiri *et al.* (1995)	ng	s. steel	ng	J C D	10	S	J > C or D Etching increased shear bond strength of C and D
*Ewoldsen *et al.* (1995)	human incisors	s. steel	mi	C E	20	S	4.5–7.9 MPa 10.4 MPa (specimens stored for 7 days prior to thermocycling)

*Indicates studies where specimens were thermally cycled before testing. Bond strength results given at 24 h unless otherwise stated. All values rounded to nearest decimal place. No SD given for the sake of clarity. pm = premolar. E = composite resin. 'st' = slightly thicker. F = fluoride-releasing composite. m = molar. G = non-fluoride releasing light-cured composite. s. steel = stainless steel. H = fluoride-releasing light-cured composite. ng = not given. I = light-cured composite. mi = manufacturers' instructions. J = dual-cured composite. A = conventional GIC. K = resin-modified GIC. B = metal-reinforced GIC. S = shear. C = dual-cured GIC. T = tensile. D = tri-cured GIC.

in Table 2. The powder/liquid ratio of glass ionomer cement is critical for successful bonding but has varied between studies, some workers following manufacturers' instructions (Klockowski *et al.*, 1989; Norevall *et al.*, 1990; Øen *et al.*, 1991), others using a slightly thicker mix (Cook and Youngson, 1988; Rezk-Lega and Øgaard, 1991) while others have tested encapsulated glass ionomers (Evans and Oliver, 1991; Øen *et al.*, 1991; Rezk-Lega and Øgaard, 1991). There is a tendency for all encapsulated cements to have higher powder/liquid ratios than hand mixed cements, and the consistency of encapsulated cements would appear to be clinically acceptable (Øen *et al.*, 1991).

However, the manufacturers' instructions for mixing of all these cements relate to their application in restorative dentistry e.g. as filling materials, bases or liners. There are generally no manufacturers' guidelines for material proportioning for orthodontic bonding. It would seem essential and desirable that for non-encapsulated cements, the manufacturers provide a scoop for this purpose and for the encapsulated cements, a powder-liquid ratio should be developed that will provide adequate flow properties of the material while optimizing bond strength.

Choice of bond test system

Human premolars have been used in most bonding studies but human molar teeth (Rezich *et al.*, 1988) and bovine teeth have been used also (Kluge *et al.*, 1990; Jähnig and Henkel, 1990; Fischer-Brandies *et al.*, 1993a, b), although the exact type of bovine tooth has only been given by Eberhard *et al.* (1993). The variation in enamel structure between human tooth type (Whitaker, 1982) and between human and bovine enamel is likely to lead to variation in bond strength values.

In the authors' opinion, bond strength testing should be standardized using human premolar teeth extracted less than 6 months previously, stored for a short time (1 week) in chloramine solution (0.5 per cent) and then transferred to water in a fridge. These recommendations in relation to storage are advised by the International Standards Organization (1994).

The type of bracket and the bracket base treatment, if any, has also varied with a resulting variation in size of base area. Mini brackets have been used by some workers (Cook and Youngson, 1988) and preangulated (contour-fitted form) brackets by others (Øen *et al.*, 1991; McCourt *et al.*, 1991; Millett *et al.*, 1993). Mesh welded to lingual buttons (Compton *et al.*, 1992), orthodontic eyelets (Evans and Oliver, 1991) and ceramic brackets (Blight and Lynch, 1995) have also been used, while other workers have ultrasonically cleaned or sandblasted the metal brackets base prior to bonding (Evans and Oliver, 1991; Millett *et al.*, 1993).

The bracket base area should be quoted in all publications on bond strength testing to allow effective comparison between studies. Moreover studies using brackets that are not well adapted to the tooth surface are likely to

Table 2 Glass ionomer cements reported for orthodontic bonding *in vitro*.

Cement	Manufacturer	Form in which supplied	Means of setting
Ketac-Cem	Espe	NE	C
Ketac-Fil	Espe	NE/E	C
Chelon	Espe	NE	C
Fuji I	GC International	NE	C
Fuji II	GC International	NE	C
Aqua-Cem	Dentsply	NE	C
Chemfil II	Dentsply	NE	C
Intact	Orthocare (UK) Ltd	NE	C
Ortho-Cem	PSP Dental Co Ltd	NE	C
Vitrabond	3M	NE	D
Base-Line	Dentsply	NE	C
Zionomer	Den Mat	NE	D
Ketac-Bond	Espe	NE/E	C
Photac-Bond	Espe	E	D
Chelon-Silver	Espe	E	C
Alpha-Silver	Schottlander	NE	C
Shofu-Giz	Shofu	NE	C
Vitremer	3M	NE	T

NE = Non-encapsulated; E = Encapsulated; C = Chemical cure; D = Dual cure; T = Tri cure.

ADDRESSES OF MANUFACTURERS/SUPPLIERS

ESPE Gmbh, Seefeld/Oberbay, Germany
GC International Corporation, Tokyo, Japan
Dentsply Ltd., Weybridge, Surrey, UK
Ortho-care (UK) Ltd., Bradford, UK
PSP Dental Col. Ltd., Belevedere, Kent, UK
3M, Indianapolis, USA
Den-Mat Corporation, Santa Maria, California, USA
Davis, Schottlander & Davis, Letchworth, Herts., UK
Shofu, UK, Tonbridge, Kent, UK

produce a reduction in bond strength. As preadjusted edgewise systems are now the predominant fixed appliance type in use, it would seem sensible to bond premolar brackets with contour fitted form to extracted premolar teeth, ensuring the best possible adaptation of the bracket base to the tooth surface. This would also mimic more closely the clinical situation and perhaps indicate the lower end of the bond strength scale, as premolar brackets seem to debond more often than brackets bonded to other teeth (Millett and Gordon, 1994).

The application of varnish to the surface of conventional glass ionomer cements after bonding has been shown to be of limited value in improving the bond strength of orthodontic brackets (Evans and Oliver, 1991; Fischer-Brandies *et al.*, 1993a). This is because the cement producing the bond is well away from the exposed areas and cement solubility is not as critical for this short term application. The time from bonding to bond strength testing has usually been 24 h but has varied from 15 (Norevall *et al.*, 1990) to 20 min (Øen *et al.*, 1991) to 30 min (Kimmins, 1992) to 1 h (Compton *et al.*, 1992) to 48 h (Kao *et al.*, 1989) to 7 days (Miller *et al.*, 1989; Kao *et al.*, 1994) and up to 4 weeks (Kimmins, 1992). The bond strength of glass ionomer cements has been shown to increase more than 50 per cent between 10 and 20 min after the setting time (Øen *et al.*, 1991) but achieves its optimal bond strength at 24 h (Tavas and Salem, 1990). Kimmins (1992), however, found that the bond strength of glass ionomer cement, although initially high, reduced at 24 h then increased again up to 4 weeks.

For the sake of standardization, a common test time of 24 h to indicate short-term bond strength is probably adequate. However in order to mimic the clinical situation, the bracket should be attached in a humid environment and should be subjected to a small stress at about the time the wire would be tied in (approximately 10–15 min after bonding). The stress could perhaps be applied by placing the specimens in a ball mill (Abu-Kasim *et al.*, 1996) or by subjecting them to some form of cyclic stressing (Moseley *et al.*, 1995) for a short period.

The mode of testing has also varied between studies. It has been either shear, tensile, shear and tensile, tensile/torsion or tensile/peel. The number of studies using each of these particular modes is given in Table 3 with shear testing being predominant. Ideally both shear and tensile modes of testing should be used but if one test mode is preferable it is shear, as this is the most likely mode to be experienced clinically. Application of pure shear stress depends on applying a force consistently in the plane of the interfaces. This is difficult in testing bracket bonding since the exact location of the interface is difficult to determine and effectively there are two interfaces under consideration. In practice all shear tests involve a combination of shear and peel.

The number of specimens per test has also shown great variation and these are summarized in Table 4. Test groups of less than 10 are probably meaningless. For rigorous statistical analysis at least 15 specimens per test group (and preferably more) should be used (McCabe and Carrick, 1986; Fox *et al.*, 1994). Bond strength (force per unit area) values should be quoted in MegaPascals (MPa) and not as Newtons (N) which is a measure of force.

Table 3 Number of studies per each mode of testing.

Mode of testing	Number of studies
Shear	24
Tensile	8
Shear and Tensile	3
Tensile/Torsion	1
Tensile/Peel	1
TOTAL	37

Table 4 Number of studies per each number of test specimens.

Number of test specimens	Number of studies
<10	4
10–19	13
20–29	10
>30	4
Not given	6
TOTAL	37

Relation of bond strength to conventional resin cements

Conventional glass ionomer cements have inferior bond strengths to composites. This finding was reported by all workers although Shin and Lee (1995) found the bond strength of a dual-cured glass ionomer with polyacrylic acid enamel pre-conditioning to be comparable with that of a composite resin. There is great 'interbrand' variation in bond strength amongst the glass ionomer cements. This is not easily related to the chemical nature of the cements used. The ranking order of bond strength varies amongst authors and research groups and no clear pattern emerges (Davis *et al.*, 1988; Miller *et al.*, 1989; Fajen *et al.*, 1990; Øen *et al.*, 1991; Rezk-Lega and Øgaard, 1991; Fischer-Brandies *et al.*, 1993b). Bond strength values recorded for glass ionomer cements have large SD, a factor which may give rise to some concern over the reliability of both the test system and the bond achieved. Great emphasis is often put on the mean bond strength value and this may not be wise as it indicates the level of force or stress at which about half of the test specimens will have broken if the data is normally distributed. A value corresponding to the first centile (10 per cent of specimens) may be more appropriate as a 10 per cent failure rate is just about acceptable clinically. This type of information is readily obtained using Weibull statistics which are valid whether or not the data are normally distributed (Fox *et al.*, 1994).

One factor often not considered in laboratory testing of bond strength is the effect of thermocycling. Only 12 studies (indicated by an asterisk in Table 1) have considered this and overall it appears that thermal stress leads to a reduction in bond strength for both composite and conventional glass ionomer cements (Davis *et al.*, 1988; Klockowski *et al.*, 1989; Fischer-Brandies *et al.*, 1993a) but the metal reinforced glass ionomer cement has been shown to be least affected by thermal stress in one study (Klockowski *et al.*, 1989). Scott *et al.* (1995) found no significant difference in the bond strength values obtained with a dual-cured or a tri-cured glass ionomer after thermocycling, while Supak and Burgess (1994) found that thermocycling decreased significantly the bond strength of the dual-cured cement Fuji II LC. It may be helpful to subject half of all test groups to mechanical and/or thermal stress prior to bond strength testing. It appears that so far only one study by Moseley *et al.* (1995) has examined the effect of cyclic mechanical loading on the bond strength of brackets bonded with either glass ionomer cement or composite resin. Cyclic loading reduced the bond strength for both materials but low stress levels led to a greater decrease in bond strength for composite-bonded compared with glass ionomer-bonded brackets. These results suggest that the two types of material display different fatigue behaviour when used for orthodontic bonding. Ideally, exposing the specimens to microbial attack as well as simulated environmental stress would allow more valid comparison with the clinical situation.

Fracture pattern observed in debonded bracket specimens

Most of the specimens bonded with conventional glass ionomer cements fracture adhesively between bracket and cement, i.e. most cement remains on the tooth after debonding (Cook and Youngson, 1988; Davis *et al.*, 1988). However, the opposite would appear to be the case with specimens bonded with Vitrabond, a light-cured hybrid-type glass ionomer cement (Rezk-Lega and Øgaard, 1991). A mixture of fracture at the bracket-resin and resin-enamel interfaces has been observed with more recently marketed dual-cured and tri-cured cements (Scott *et al.*, 1995), while Ewoldsen *et al.* (1995) found fracture at the tooth-adhesive interface for all specimens bonded with a tri-cured cement. Fracture mode should be recorded in all studies.

Overall, it would appear from the results of the laboratory trials that conventional glass ionomer cements are not recommended for clinical bonding of brackets and there is a consensus of opinion favouring the use of dual- or tri-cured cements for this purpose.

In vivo studies

Direct bonding of orthodontic brackets with glass ionomer cement was first described by White in 1986. He estimated that he obtained a similar number of bond failures with glass ionomer cement as with composites over a 9-month period. Apart from this anecdotal evidence and the bond strength study carried out *in vivo* by Voss *et al.* (1993), to date there have been only 11 other reports in the literature on the clinical performance of brackets bonded with glass ionomer cement (Table 5).

These will be considered under the following headings: tooth preparation, powder/liquid proportioning, failure rate relative to composites and pattern of bond fracture recorded.

Tooth preparation

The means of enamel preparation is not reported in three studies (Miller *et al.*, 1989; Hallgren *et al.*, 1990; Lodter and Sarda, 1991). Fricker (1992, 1994), using a conventional and a dual-cured cement respectively, pre-treated the enamel with polyacrylic acid for 10 s prior to bonding while Miguel *et al.* (1995) etched the enamel with 37 per cent phosphoric acid for 60 s prior to bracket bonding with the conventional glass ionomer, Ketac-Cem. Both Cook (1990) and Millett (1992) also used Ketac-Cem for bonding but in each study the tooth surface was dried with a cotton wool roll and no enamel etching was carried out. The optimal means of enamel preparation is likely to vary for conventional and hybrid materials. Etching the enamel with 37 per cent phosphoric acid led to a failure rate of 50 per cent with the conventional cement, Ketac-Cem (Miguel *et al.*, 1995) while pretreatment of the enamel with polyacrylic acid led to both a 20 per cent failure rate with the conventional cement, Fuji I (Fricker, 1992) and a 3 per cent failure rate with the dual-cured material, Fuji II LC (Fricker, 1994). The cement mix and material type have varied in the two studies by Fricker so it is difficult to evaluate independently the effect of enamel preconditioning on the failure rate recorded. A similarly low failure rate to that of Fricker (1994) has been reported by Silverman *et al.* (1995) using a tri-cured cement, Fuji Ortho LC. Silverman *et al.* (1995) did not etch or dry the enamel surface prior to bracket bonding.

Powder/liquid ratio

No indication of powder/liquid ratio is given in the studies by Miller *et al.* (1989, 1995). Cook (1990) and Hallgren *et al.* (1990) used a 'somewhat thicker' mix of cement to that recommended by the manufacturer of the particular cement type. Millett (1992), Fricker (1994) and Miguel *et al.* (1995) followed the manufacturers' recommendations in relation to powder/liquid ratio while Fricker (1992) used a mix of cement

Table 5 Reports of the clinical failure rate of brackets bonded with glass ionomer cement (GIC).

Author	Cement	No. of brackets bonded with GIC	Time of observation (months)	Mechanics	Overall failure (%)
Miller *et al.* (1989)	Ketac-Fil	53	2.2	Edgewise	3.8
Cook (1990)	Ketac-Cem	402	17.1	Straight-wire	12.4
Hallgren *et al.* (1990)	Ketac-Cem	106	1	Not given	10.6
Lodter and Sarda (1991)	Ketac-Bond	42	6	Edgewise	13
	Ketac-Fil	37			4.4
Fricker (1992)	Fuji I	60	12	Light-wire (Begg)	20
Millett (1992)	Ketac-Cem	120	12	Straight-wire	17
Fricker (1994)	Fuji II LC	60	12	Light-wire	3.3
Miller *et al.* (1995)	Ketac-Fil	ng	36	Edgewise	34
Miguel *et al.* (1995)	Ketac-Cem	112	12	Edgewise	50.9
Silverman *et al.* (1995)	Fuji Ortho LC	3226	ng	Edgewise	3.2
Norevall *et al.* (1995)	Aqua-Cem	ng	ng	Edgewise	36

ng = not given

with twice the amount of powder per drop of liquid than recommended by the manufacturer.

As mentioned in the section on *in vitro* studies, manufacturers should provide a scoop that gives a powder/liquid ratio suitable for orthodontic bonding, thereby also ensuring a reproducible mix of cement.

Failure rate

The failure rate of brackets bonded with glass ionomer cement has varied from 3.2–50.9 per cent. The cause of the highest failure rates recorded is unclear as there were several variables which may have contributed to early failure. These include pre-conditioning of the enamel (Fricker, 1992; Miguel *et al.*, 1995), use of a higher than recommended powder/liquid ratio and the use of Begg mechanics (Fricker, 1992). The experience of the operators may also be an important factor in accounting for the differences in failure rate recorded between studies. The lowest failure rates have been with the resin-modified glass ionomer, Fuji II (Fricker, 1994; Silverman *et al.*, 1995). There are differences, however, between both of these studies. Fricker (1994) used Fuji II LC mixed according to the manufacturers' instructions with polyacrylic acid enamel preconditioning with an observation period of 1 year. In contrast, Silverman *et al.* (1995) used a brand of Fuji II LC specifically designed for orthodontic bonding, carried out no enamel preconditioning and the observation period, although unspecified, appears to be about 8 months. Nonetheless, the failure rate recorded in both of these trials is similar.

While the failure rate of a particular bracket/cement combination is useful to know, it is also interesting to consider the time to failure. Failure rate can be expressed as survival rate on a time scale and can be included easily in analysis of material performance (Millett and Gordon, 1994).

Relation of failure rate to that achieved with conventional resin cements

Seven studies have compared the failure rate of glass ionomer cement with that of a conventional adhesive resin (Lodter and Sarda, 1991; Fricker, 1992, 1994; Millett, 1992; Miller *et al.*, 1995, Miguel *et al.*, 1995, Norevall *et al.*, 1995). In the first of two clinical trials carried out by Lodter and Sarda (1991), 13 per cent of brackets bonded with Ketac-Bond failed while 3.7 per cent failed with composite. In the second trial 4.4 per cent of brackets bonded with Ketac-Fil failed whilst 3.5 per cent failed with composite. Although both materials were used in encapsulated form there was almost a three-fold difference in failure rate between Ketac-Fil and Ketac-Bond. In the study by Fricker (1992) 20 per cent of brackets bonded with Fuji I failed while 5 per cent failed with the composite resin and in the study by Millett (1992) 17 per cent of brackets bonded with Ketac-Cem failed while 4.2 per cent failed with composite resin. Both studies showed a four-fold increase in failure rate for glass ionomer compared with composite. Other studies have found a two-fold (Miller *et al.*, 1995), a two-to-three fold (Norevall *et al.*, 1995) and a seven-fold (Miguel *et al.*, 1995) increase in failure rate between brackets bonded with the glass ionomer cements Ketac-Fil, Aqua-Cem and Ketac-Cem compared with brackets bonded with composite resin. Brackets with a cut groove base had a greater failure rate (50 per cent) than meshed foil based brackets (22 per cent) when bonded with Aqua-Cem (Norevall *et al.*, 1995). Overall, the highest failure rate recorded has been with Ketac-Cem and enamel pretreatment for 60 s with 37 per cent phosphoric acid (Miguel *et al.*, 1995). However, Fricker (1994) found no significant difference in the failure rate of brackets bonded with Fuji II LC light-activated glass ionomer (3.3 per cent) compared with those bonded with a composite (1.6 per cent). There appears to be great interbrand variation in failure rate between materials with a tri-cured Fuji product (Fuji Ortho LC) being the most reliable material to date (Silverman *et al.*, 1995).

Pattern of bond fracture recorded

This has not been documented in any of the published studies, most probably because the failure has typically occurred some time before the patient attends for appliance repair or inspection.

Discussion

This review has attempted to analyse the published *in vitro* and *in vivo* studies on glass ionomer cements for orthodontic bonding. This is an area of continuing development and the authors are aware that we are in a sense reviewing a 'moving target'. Ideally a subject of this nature should be reviewed when there is a degree of stability in the literature related to it. However there is merit in reviewing the current situation in view of the considerable volume of published material on the use of glass ionomers in orthodontics over recent years.

From the results of the laboratory and clinical trials reported above, it is evident that the bond strength of conventional glass ionomer cements is less than ideal and not surprisingly debonding, both during and after treatment, is easier. From the limited evidence available, conventional glass ionomers have merit in preventing decalcification during treatment (Marcusson *et al.*, 1993) but such a benefit does not appear to be evident in the longer term at 1-year review post-debonding (Marcusson *et al.*, 1993; Millett *et al.*, 1994). Silverman *et al.* (1995) recorded no decalcification with the tri-cured cement, Fuji Ortho LC (GC International, Tokyo, Japan) but the observation period for that study appears to be less than 1 year and no objective assessment of decalcification was made. The limited potential of glass ionomer cements to prevent decalcification cannot therefore be considered to outweigh the problems of debonding. Conventional glass ionomer cements and resin-modified glass ionomer cements are quite different materials in terms of chemical structure and should ideally be treated separately although, for the purposes of this review, they have largely been considered together due to the small number of studies conducted so far on the resin-modified cements. In some respects light-activated resin-modified glass ionomers are more like composites. Overall, at present, conventional glass ionomer cements appear to have limited use as a bonding material but if further attempts are to be made to make them more reliable for bonding, it appears that the bond strength of the cement to the bracket must be improved.

Before considering possible solutions to this problem, it is important to identify the most common site of failure. The laboratory trials indicate that the site of failure with conventional materials is primarily adhesive at the bracket/cement interface (Cook and Youngson, 1988) with most of the cement remaining on the tooth surface after debonding. The site of failure has not been reported in the clinical trials. Matasa (1989) claims that the strongest bond with orthodontic adhesives is achieved when the failure is cohesive, i.e. the adhesive remains on both substances in almost equal proportions after debonding.

There would appear, therefore, to be two possible solutions to obtaining a more reliable bond strength with conventional glass ionomers; either improving the characteristics of the cement (most likely increasing the powder/liquid ratio or reinforcing with resin) or treating the bracket base to increase the surface area available for bonding, perhaps by sandblasting.

In relation to the first of these possible solutions, Fischer-Brandies *et al.* (1993b) measured the bond strength of 25 commercially available glass ionomer cements and found that the best results were obtained with Photac-Bond (Espe, Seefeld, Germany), Chelon Silver (Espe) and Alpha-Silver (DMG, Hamburg, Germany). Photac-Bond is a dual-cured encapsulated cement; Chelon Silver is a silver-containing conventional non-encapsulated cement, while Alpha-Silver is similar but encapsulated.

The powder/liquid ratio is greater and more reproducible with encapsulated cements than with hand mixed systems. This should increase the early strength and reduce solubility as well as giving a more consistent mix of cement. However, the innately brittle nature of glass ionomer cement when set may be aggravated by increasing the powder/liquid ratio. This modification would also tend to reduce wettability which is essential for bonding to enamel. Further work is required to determine the optimum powder/liquid ratio for orthodontic bonding and once this has been realised it can be reproduced in encapsulated form.

The clinical studies by Cook (1990) and Fricker (1992) used conventional glass ionomers with a manual dispensing system but with an increased powder/liquid ratio, the former using a 'somewhat thicker' mix and the latter added 50 per cent more powder per drop of liquid than recommended by the manufacturer. This was to reduce the potential bracket 'float' problem with a thinner mix and give greater bond strength. The authors reported failure rates of 14 and 20 per cent respectively. It seems from these studies that increasing the powder/liquid ratio of glass ionomer cement did not bring the bond failure rate within the range reported for adhesive resins (Zachrisson, 1977; Kinch *et al.*, 1988) which is usually 6–12 per cent. Despite this, 86 and 80 per cent of the brackets survived during the observation periods in these two trials.

It seems that what is required with conventional glass ionomer cements, to make them more acceptable for direct bonding, is only a modest improvement in bond strength to give a more reliable bond whilst maintaining the ease of debond after treatment. At present, there have been only three reports on the clinical failure rate with encapsulated glass ionomers for orthodontic bonding (Miller *et al.*, 1989, 1995; Lodter and Sarda, 1991). The increased powder/liquid ratio which they offer appears to go some way towards achieving a more reliable bond in the short-term, i.e. over a 2–6 month trial period (Miller *et al.*, 1989; Lodter and Sarda, 1991). The failure rate recorded with Ketac-Fil over a longer trial period of 18–36 months has been about 30 per cent which is disappointingly high (Miller *et al.*, 1995). Over this time period, Miller *et al.* (1989) and Lodter and Sarda (1991) recorded failure rates of about 3 per cent with Ketac-Fil (Espe). However with Ketac-Bond (Lodter and Sarda, 1991) the failure rate was 13 per cent.

Light-activated encapsulated cements e.g. Photac-Bond, (Espe) and Dyract (DeTrey, Dentsply, Weybridge, UK) have been developed in the last couple of years. Dyract, however, is more akin to a composite than a glass ionomer cement. Encapsulated materials have advantages in terms of reproducible mixing (or no mixing in the case of Dyract) and also allow the cement to be 'command set' once final bracket positioning has been achieved. Tri-cured glass ionomer cements, e.g. Vitremer (3M, Indianapolis, USA) have also been marketed but as yet there have been few laboratory reports evaluating their suitability for orthodontic bonding.

A light-activated glass ionomer (Fuji II LC) mixed according to the manufacturers' instructions has recently been evaluated for clinical orthodontic bonding and its performance closely matched that of composites (Fricker, 1994). Some manufacturers have produced tri-cured glass ionomer materials specifically designed for orthodontic bonding, e.g. Fuji Ortho LC. Early reports on this material are promising, with a bracket failure rate of about 3 per cent recorded (Silverman *et al.*, 1995). Further controlled clinical trials over a 2-year period are required to evaluate objectively this material and other dual- or tri-cured cements.

The fact that these light-activated and dual-cured cements reportedly behave in a manner similar to that of resin cements is not surprising as the composition of some materials is closer to that of a composite than glass ionomer cement.

The second possible solution to improving the bond strength of conventional glass ionomer cements is by bracket base treatment or developing a modified bracket base (Voss *et al.*, 1993) These options have received very little attention. Increasing the bracket base area by sandblasting has been shown to improve the bond strength *in vitro* (Millett *et al.*, 1993) but has not yet been evaluated *in vivo*. It is, however, unlikely that such bracket base treatment will shift the site of failure to being entirely cohesive but may go partly in that direction.

In summary, the consensus of opinion appears to indicate that conventional glass ionomer cements are unreliable for clinical orthodontic bonding. Some resin modified materials have shown particular promise in this regard, and it would appear that at present the right combination of cement type and mix and/or bracket base treatment for orthodontic bonding with these materials is close to being developed. The relative ease of debonding of residual adhesive remaining after bracket removal with glass ionomer materials compared with resin adhesives and the possible benefits of fluoride release warrant further investment in this area of orthodontic research.

Conclusions

Firstly, with respect to the *in vitro* studies on glass ionomer cement for bonding, there is great variation in the teeth used, bracket type and mix of cement adopted as well as in the number of specimens per test, the mode of testing and values quoted for bond strength. To combat this problem the following are recommended: (i) As advised by the International Standards Organization (1994) bond strength testing should be standardized using human premolar teeth extracted less than 6 months previously, stored for 1 week in 0.5 per cent chloramine and then transferred to water in a fridge; (ii)The bracket base area and mix of cement used should be specified. At least 15 specimens per test should be used; specimens should be subjected to some form of mechanical/thermal stress prior to measuring bond strength. Shear bond strength is the preferred test mode and values should be quoted in MegaPascals.

Secondly, to date all laboratory trials have reported inferior bond strength for brackets bonded with conventional glass ionomer cements compared with those bonded with resin adhesives, but laboratory studies have varied in their opinion with regard to adopting these glass ionomer cements for more widespread clinical use as a bonding material.

Thirdly, from the clinical trials, the failure rate of brackets bonded with glass ionomer cement has ranged from 3.2–50.9 per cent with the observation period ranging from 2.2–36 months. The lowest failure rate with glass ionomer cement has been with a resin-modified tri-cured material.

Finally, conventional glass ionomer cements are not recommended for routine clinical orthodontic bonding, and further modifications to the bonding system with resin-modified glass ionomer cements may be required before they can be widely recommended in clinical orthodontic practice.

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