CLINICAL ACCEPTABILITY OF ORTHODONTIC BRACKET BASE-CEMENT COMBINATIONS

by

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A thesis submitted in conformity with the requirements for the degree of Masters of Science Graduate Department of Orthodontics University of Toronto

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0-612-63003-X
ABSTRACT

CLINICAL ACCEPTABILITY OF ORTHODONTIC BRACKET BASE-CEMENT COMBINATIONS  Z. HASSANLOO, Faculty of Dentistry, Graduate Department of Orthodontics, University of Toronto, Canada. 2001

The aim was to identify bracket base-cement combinations that are clinically practical, provide adequate shear bond strengths (SBS), and result in the least damage to enamel. The SBS and the nature of bond failure using the Adhesive Remnant Index (ARI) were examined after 1 and 180-days for 28 combinations. SBS in 8±3 MPa range and ARI scores ≥ 2 were deemed clinically acceptable. Transbond and Fuji Ortho LC (FOL) (conditioned) were compatible with the four brackets (2 metal: Time, Speed; and 2 ceramic: Clarity, Transcend). Panavia21 was compatible with ceramic brackets. FOL (not-conditioned) yielded poor SBS and ARI scores with all of the bracket bases. Time had no significant effect on clinical acceptability. Enamel conditioning had a significant effect on the ARI scores (p<0.05) and SBS (p<0.05). No consistent association was noted between the ARI scores and SBS. The ideal cement for bonding the four brackets was FOL (conditioned).
ACKNOWLEDGMENTS

I would like to express my appreciation and sincere gratitude to the following individuals for their invaluable assistance with the successful completion of this thesis:

Dr. K.C. Titley, my thesis supervisor, for his meticulous attention to detail, guidance and assistance with all the aspects of this project.

Dr. G.V. Kulkarni, for his statistical analysis, expertise and advice in preparation of this thesis.

Dr. P.E. Rossouw, for his advice and participation in my thesis advisory committee.

Mr. Robert Chernecky, for his technical assistance with the Scanning Electron Microscope and for his kind friendship.

Dr. J.T. Mayhall, for the generous use of the Morphometric Program and for his help with the digitizing of the bracket bases.

Thank you to my family for their unconditional love and support. Lastly I like to dedicate this thesis to my mother, Azam, for having made everything good in my life possible.
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INTRODUCTION AND STATEMENT OF THE PROBLEM

The conditioning of the enamel surface with phosphoric acid (Buonocore, 1955) and the development of composite resin cements (Bowen, 1962) revolutionized aesthetic dentistry and the practice of orthodontics. Today, the direct bonding of brackets to enamel has become routine in fixed orthodontic appliance therapy. Clinicians have an extensive selection of bracket bases and bonding cements at their disposal so that their choices can be tailored to the patients’ specific needs, their own clinical experience, product monographs and published research pertaining to the properties and endurance of these materials. Despite the numerous publications in the field of orthodontic bonding, the orthodontic literature lacks studies that identify the most suitable bracket base-cement combinations. Similarly, there is no information on the interaction between bracket base design and cement particle size. Furthermore, bracket base-cement bond failure still occurs and this is costly to both patients and clinicians and may prolong treatment time.

Given the wide variety of orthodontic bracket base designs and the myriad of bonding cements available today, it is important to identify bracket base-cement combinations that are:

- Clinically practical
- Provide adequate shear bond strengths
- Result in minimal or no damage to enamel during bonding, orthodontic treatment and debonding

Information on the interaction between bracket base design and cement particle size will add to orthodontic knowledge and help manufacturers to develop compatible systems.

Important variables, which affect the bond strength of bracket bases to enamel, are cement type, bracket material and base design, enamel surface treatment and storage time.

The choice of brackets is dependant on the clinician’s preference and the aesthetic requirements of the patient. There are currently three bracket materials available, and they are: metal, plastic and ceramic. Each of these bracket types employs different mechanisms of retention, that are incorporated into their base designs. In metal and plastic brackets, the
bond strength is primarily derived from mechanical mechanisms, which include the welding of a mesh pattern to the base (metal brackets) or the incorporation of micro-porosities (plastic brackets). However, ceramic brackets may rely on both mechanical and or chemical mechanisms for bond strength enhancement. Consequently, during debonding of ceramic brackets, enamel may be damaged because of increased bond strengths. It is thus of clinical significance to identify cement types for ceramic bracket bases, which result in lower yet clinically acceptable bond strengths and favourable bond failure locations.

Resin containing luting cements (RCLCs) and the resin reinforced glass ionomer cements (RRGICs) are the two major adhesive systems, which are used in direct bonding of orthodontic attachments. RRGICs have received special attention as bonding agents in orthodontics, because of their ability to release fluoride with its beneficial cariostatic effect. An added benefit is the claim that RRGICs do not require any acid conditioning so that it may be concluded that enamel loss due to acid conditioning and subsequent decalcification can be prevented. RRGICs can also be bonded on to a moist enamel surface. The current view on the use of enamel conditioner with RRGICs is equivocal some investigators have reported success with RRGICs even when enamel surface is not conditioned (Fricker, 1994 and Silverman et al., 1995). However, more studies are concluding that RRGICs do not provide adequate bond strength without the use of an enamel conditioner (Beress et al., 1998; Bishara et al., 1998b; Flores et al., 1999; Lippitz et al., 1998; Meehan et al., 1999; Millett et al., 1999). It is of clinical significance that RCLCs and RRGICs, with and without enamel conditioning, are tested to evaluate and compare their shear bond strengths (SBS) when used to bond different types of bracket bases.

New products are formulated with the object of both saving time and providing cost effective materials. The self-etching acidic primer, a combination of an acid and a primer, is advertised as a product, which combines both acid conditioning and primer application into one step. Acid conditioning and unfilled resin primer (sealant) application are the steps required in bonding bracket bases when using resin cements. A study by Bishara et al. (1998a) showed that the use of acidic primers to bond orthodontic brackets to the enamel surface provided clinically acceptable SBS when used with a highly filled RCLC
(Panavia21). However, more research is needed to test the compatibility of this bonding system (Acidic primer + Panavia21) using metal, and ceramic brackets.

The aim of this study was to identify combinations of orthodontic bracket bases and bonding cements that can provide clinically acceptable SBS at 1 and 180-days following bonding while resulting in minimal or no damage to the enamel. The effects of bracket base material and design, cement type, enamel surface treatment and storage time on the shear bond strength and bond failure pattern were assessed. Furthermore, the compatibility of four bracket base designs with three different cement particle sizes was determined.
REVIEW OF THE LITERATURE

Orthodontic bracket bond failure and the need for rebonding is a time consuming process which results in frustration for both the orthodontist and the patient, additional costs in materials and personnel, increased treatment time and possible damage to tooth structure. The variables affecting the bracket base bond strength are: 1) the bracket material and more particularly the base design, 2) the type of cement, 3) the mode of enamel surface treatment prior to bonding, and 4) storage time. The following is a brief literature review of these variables and the results of the pertinent studies. This review will also explore the types of bond failure and discuss the suitability of bovine enamel as a substitute for human enamel in bonding studies.

BRACKET MATERIAL

The choice of brackets is dependent upon the clinician’s preference and the aesthetic requirements of the patient. There are three bracket materials available: metal, polycarbonate, and ceramic.

Metal Brackets

Metal brackets, which are composed of stainless steel, were the first brackets to be introduced following the advent of enamel bonding. The major drawback of metal brackets is their associated poor aesthetics. In metal brackets the bond strength to the bracket base and tooth surface is primarily achieved by mechanical mechanisms. Although resin type cements bond well to a conditioned dry enamel surface, they do not adhere to stainless steel. Therefore, retention of these resin cements to metal bracket bases is primarily mechanical so that any bracket base design must incorporate a mechanical locking device for the cement to permeate prior to polymerisation. Following is a brief review of the different base designs that impart mechanical retentive properties to metal bracket bases.

Perforated Bases

When first introduced metal brackets had perforated bases in order to mechanically attach to cements (Thanos et al., 1979). When bonding these brackets the cement was free to flow through the holes, that were not obliterated by the bracket. The major problem associated
with this type of base was plaque retention and poor aesthetics. Brackets with perforated bases are no longer used in orthodontics.

**Foil-mesh Bases**

Foil-mesh bases replaced perforated bases. The foil-mesh is either welded or brazed on to the bracket base. Compared to a perforated base foil mesh provides a smoother, less plaque retentive and thus more hygienic surface (Maijer and Smith, 1981). It has also been shown that foil-mesh bases provide better retention than perforated metal bases (Reynolds and von Fraunhofer, 1976; Faust et al., 1978; Thanos et al., 1979; Lopez, 1980). Weld spots used to secure the foil mesh to the bracket are thought to reduce the retentive area and as a result reduce the bond strength by obliterating distinct areas of the foil-mesh (Dickinson and Powers, 1980). Maijer and Smith (1981) also suggest that these weld spots act as “stress concentrators” in composite resin, thus leading to a weakened bond between the base and the cement. However, using a laser for welding or mesh attachment by brazing yields better tensile and shear bond strengths (Dickinson and Powers, 1980; Lopez, 1980; Maijer and Smith, 1981).

The mesh size (gauge) which refers to the number of openings per linear inch (Thanos et al., 1979) is reported to affect bond strength (Thanos et al., 1979). Studies by Maijer and Smith (1981) have reported that a 60 to 70-gauge mesh bracket base in combination with lightly filled resin cement gives the best results. These observations are similar to those made by Thanos et al. (1979) who achieved the best bond strengths using 60-gauge mesh bracket bases. Reynolds and Von Fraunhofer (1976) specifically related their work to mesh size and bond strength and demonstrated that maximum bond strength occurred when mesh sizes of 50 to 70-gauge were used.

**Integral Bases**

Metal brackets with integral bases are fabricated in a manner that both the bracket and its base are cast as an integral unit. As a result, the bracket cannot be separated from its base (Mahal, 2000). The integral base brackets are divided to two types: machined integral brackets and cast integral brackets. In machined integral brackets a milling process is used
for imparting mechanical retention on to the bracket base, whereas for cast integral base brackets a casting process is used. The bases of integral brackets have horizontal undercut channels, which open at the mesial and distal extremities (Ferguson et al., 1984). The Time bracket (American Orthodontics) is an example of a machined integral, microetched base with mechanical undercuts. Sharma (1999) compared the shear bond strengths of different metal brackets and reported that the highest 24-hours bond strengths were achieved with the Time brackets (machined, integral, microetched base with mechanical undercuts) followed by Speed brackets (60-gauge, microetched foil-mesh base). When compared to foil-mesh bases, the cast integral bases show higher bond strengths, but the machined integral bases show lower bond strengths (Deidnch and Dicluneiss, 1983; Regan and Van Noort, 1989). The latter authors attribute this observation to the fact that the cast base has a much rougher surface thus increasing overall retention due to greater micro-mechanical retention.

**Sintered Bases**

Sintering is a process that is used to improve the mechanical retention of the cement on metal base brackets and it involves fusion of metal or ceramic particles onto the bracket base. This process creates a porous layer with increased surface area into which the cement material can penetrate. These bases are shown to yield higher tensile bond strengths than conventional foil-mesh bases (Hanson et al., 1983; Smith and Majier, 1983).

**Photo-etched Bases**

An alternative to foil-mesh metal bracket bases is photo-etching. Photo-etched bracket bases are retained through small indentations in the base, that are microscopically roughened by an etching process (Lopez, 1980; Maijer and Smith, 1981). The bond strength achieved by using this type of base design is greater than perforated bracket bases but less than the foil-mesh bases (Lopez, 1980; Ferguson et al., 1984). The inferior bond strength compared to foil-mesh bases is attributed to poor penetration of resin cements which results in air inclusions that inhibit polymerization of uncured resin (Maijer and Smith, 1981).
**Sandblasting (microetching)**
Sandblasting uses a high-speed stream of aluminum oxide particles propelled by compressed air (Black 1950, Goldstein 1994). Sandblasting of bracket bases leads to micro-roughness and subsequent increases in the surface area to enhance bond strength (Willems et al., 1997). Dietrich and Dickmeiss (1983) reported that sandblasting increases bond strengths by 34% when compared to untreated brackets. MacColl (1995) found that sandblasting of foil-mesh bases of brackets with four different base sizes significantly increased bond strengths as compared to untreated foil-mesh base. Simoka and Powers (1985) reported a 56% increase in bond strengths when sandblasting integral grooved bases. In this study sandblasting foil-mesh bases was shown to have no effect on bond strength. In a study by Millet et al. (1993), 60-micon alumina was used to sandblast foil-mesh bases that were to be bonded with glass ionomer cements. Their results showed that sandblasting for 3 seconds significantly increased bond strength whereas sandblasting for 9 seconds damaged and distorted the wire mesh. Newman et al. (1995), using auto-polymerizing resin containing luting cements, showed that sandblasting increased bond strengths by almost 20%.

**POLYCARBONATE BRACKETS**
The current trend in orthodontics includes an ever-increasing interest of adult patients in orthodontic therapy and their insistence on the use of aesthetic appliances. Attempts to develop inconspicuous attachments lead to the introduction of polycarbonate brackets in the early 1970s. These brackets had limited success due to their water absorption and plastic deformation under load. They also stained very easily which resulted in the elimination of any aesthetic advantage (Britton et al., 1992; Reynolds, 1975). To compensate for the lack of rigidity and strength, these brackets were reinforced with metal bracket slots and ceramic fillers (Britton et al., 1992). However, the problem of slot distortion and staining remained thus restricting their clinical use. To address these problems ceramic brackets were introduced in 1986 and they have been gaining popularity ever since.
CERAMIC BRACKETS

Ceramic is the third hardest material known to humans (Swartz, 1988a). Ceramic brackets resist staining, discoloration, and are chemically inert to oral fluids, but they are susceptible to fracture due to brittleness and low fracture toughness. The fracture toughness of ceramics (the total energy loading required to cause failure) is 20-40 times less than that of stainless steel (Phillips, 1988; Viazis, 1990). The brittleness of ceramics can result in their fracture during debonding and this will prolong the time for cleanup and increase possibility of damage to the enamel. Ceramic brackets can also cause nicks in the arch wires, resulting in more friction between the bracket and the arch wire. The increased friction can decrease the efficiency of tooth movement (Pratten et al., 1990; Bishara et al., 1993). In addition, when using ceramic brackets care should be taken to prevent contact of the ceramic bracket with opposing enamel surfaces to prevent wearing of enamel as it contacts ceramic.

Ceramic brackets are composed of either aluminum oxide or partially stabilized zirconium. The composition of most currently available ceramics is aluminum oxide. Based on the manufacturing process ceramic brackets can be divided into two basic types, namely: Polycrystalline and Monocrystalline (Swartz, 1988a).

Polycrystalline Brackets

The polycrystalline ceramic brackets are fabricated by sintering aluminum oxide particles. The process is initiated by blending the particles with a binder. The resulting mixture is then molded into a shape from which the critical parts of the brackets can be cut. The molded part is then fired at 1800° C to burn out the binder and fuse, but not melt the aluminum oxide particles (Swartz, 1988a). This firing process is called sintering (Bishara and Fehr, 1997). The process of molding and sintering is a popular ceramic bracket manufacturing technique owing to its relative inexpensiveness. However, this process results in not only structural imperfections at the grain boundaries but also the incorporation of trace amounts of impurities. These imperfections and impurities can serve as foci for crack propagation under stress and thus lead to fracturing of the bracket. Moreover, the grain boundaries and impurities associated with polycrystalline ceramic brackets also reflect light, which results in some degree of opacity and reduces the aesthetic effect (Swartz, 1988a).
Monocrystalline Brackets
Monocrystalline ceramic brackets are manufactured by melting aluminum oxide particles at temperatures above 2100° C and allowing them to cool slowly thus permitting complete crystallization. The process minimizes the impurities and imperfections found in the polycrystalline brackets, with the result that the probability for crack propagation under stress is reduced (Bishara and Fehr, 1997). A ceramic bracket is then milled from a single crystal of aluminum oxide. This technique of manufacturing is more difficult and costly because of the hardness of the material. The process of milling and the presence of sharp corners will introduce stresses on the material and predispose ceramic brackets to fracture (Swartz, 1988a; Bordeaux et al., 1994). Milled crystal ceramic brackets are, therefore heat treated to eliminate stress inducing surface imperfections and material impurities (Swartz, 1988a). Monocrystalline brackets are essentially clear as a result of two factors: reduction in grain boundaries and fewer impurities introduced during the manufacturing process (Swartz, 1988a).

Bracket Retention Mechanisms and Base Surface Characteristics
Ceramic brackets can adhere to the luting cement through three different mechanisms: (1) chemical, (2) mechanical, and (3) combination of mechanical and chemical (Swartz, 1988b, Karamouzos et al., 1997). Aluminum oxide, the main constituent of ceramic brackets, is an inert material, so that it cannot chemically adhere directly to any of the currently available resin containing luting cements (RCLCs) (Bishara and Fehr, 1997). As a result both mechanical and chemical modes of retention have been developed to aid in the bonding of ceramic brackets to RCLCs. Mechanical retention is achieved by producing indentations or recesses in the bracket base and these provide a mechanical interlocking with the luting cement. A chemical bond is achieved by introducing an intermediate layer of glass on the bracket base with a silane coupler thus producing a chemical bond between the bracket and the resin of the luting cement.

Ceramic bracket bases are available in four different designs (Karamouzos et al., 1997). The first design is a flat base covered with a silane layer for chemical bonding of the cement and undercuts or grooves for mechanical interlocking of the cement (Viazis et al., 1990). The
second design includes a smooth base surface coated with a silane layer for chemical bonding with the cement (Viazis et al., 1990). The third ceramic bracket base design has a rough polycrystalline alumina base comprised of either randomly oriented sharp crystals or spherical glass particles (Eliades et al., 1994). This type of bracket base provides only micro-mechanical interlocking with the bracket bonding cement. Transcend\(^2\) and Clarity\(^1\) brackets (3M/Unitek, CA) are both examples of this type and were tested in this investigation. The fourth design involves placement of a plastic (polycarbonate) wafer between the adhesive and the bracket base in order to facilitate debonding and avoid causing potential damage to enamel (Bordeaux et al., 1994).

**Ceramic Bracket Bond Strength and Fracture Mode**

The silane coupling agent enhances the bond of the luting cement to the ceramic bracket base to such a degree that it can approach the cohesive strength of enamel with the result that enamel cracks or fracture can occur during bracket debonding (Odegaard, 1989; Carter, 1989; Storm, 1990; Machen, 1990). A number of studies have demonstrated that ceramic bracket bases which have been treated with silane coupler produce significantly stronger bond strengths when compared to conventional metal brackets (Iwamoto et al., 1987; Odegaard and Segner, 1988; Gwinnett, 1988; Ripley, 1988; Hyer, 1989; Joseph and Rossouw, 1990). An increase in the strength of the bond between ceramic bracket bases and the cement, results in bond failure at the enamel-cement interface. Bond failure at the enamel-cement interface, however, results in an increased incidence of enamel fractures and this is undesirable (Swartz, 1988b; AAO 1989; Harris et al., 1990; Joseph and Rossouw, 1990; Storm, 1990; Viazis et al., 1990). The high bond strengths between the cement and the silane coated ceramic bracket bases are of particular concern when ceramic brackets are cemented to and subsequently debonded from heavily restored teeth or non-vital teeth with brittle enamel. To reduce iatrogenic enamel fracture during debonding, some alternatives have been proposed. Guess et al. (1988) suggested that the mechanical interlocking in the bracket base provides adequate bond strength so that the additional chemical bond provided by silane treatment is not necessary. Bishara et al. (1993) showed that shear loading of mechanically retained ceramic brackets results in a cohesive failure of the cement which results in materials being left on both the enamel and bracket bases with less risk of enamel...
fracture. A further alternative to reduce bond strength between enamel and a ceramic bracket is the placement of a plastic wafer between the adhesive and the bracket base. In this situation the bond between the bracket and the wafer is the weakest so that on debonding, the bracket comes away leaving the plastic wafer and the bonding cement on the tooth surface (Fox et al., 1992; Franklin et al., 1993; Bordeaux et al., 1994).

In general, when comparing the types of cements used, the highly filled RCLCs provide a bond strength which is higher than that recorded with the lightly filled cements (Wood, 1982; Bishara et al., 1993). In the case of ceramic brackets, however, the unfilled RCLCs are reported to give comparable bond strengths to the highly filled RCLCs (Bishara et al., 1993). Alteration of enamel conditioning time was investigate by Olsen et al. (1994) as a means of subsequently reducing the force necessary to debond ceramic brackets. They showed that altering the conditioning time between 10 and 30 seconds had little influence on the bond strength or the ARI score. When the conditioning time was reduced to 5 seconds or less, the bond strength was too low to be considered clinically useful. Bishara et al. (1993) and Cacciafesta et al. (1998) also demonstrated that the use of polyacrylic acid as an enamel conditioner when cementing ceramic brackets resulted in location of bond failure that was mostly at the enamel-cement interface. According to Bishara and Fehr 1997, the use of polyacrylic acid as the enamel conditioner produces crystal growth so that neither the type of the cement nor the bracket base is critical, because the bond failure occurs within the crystals themselves. The result is that the stresses on enamel during debonding are minimized.

**Debonding of Ceramic Brackets**

During debonding stainless steel brackets can be “peeled” from the cement as a result of the stainless steel’s ability to elongate approximately 20% before failing. Ceramic bracket materials elongate less than 1% before fracturing and, therefore cannot be “peeled” off the cement (Merril et al., 1994). Ceramic brackets can fracture during debonding because ceramic is a brittle material. To address the problems associated with debonding ceramic brackets following completion of orthodontic treatment several mechanisms of removal and a number of modifications in the bracket base design (as mentioned earlier) have been
suggested in order to make debonding safer for the patients and less stressful and time consuming for the clinicians. Some manufacturers have developed especially designed pliers for each type of bracket, whereas some clinicians and researchers advocate their removal by electrothermal and ultrasonic methods (Bishara and Truelove, 1990). The use of a laser for debonding ceramic brackets has also been reported (Strobl et al., 1992). There are undesirable side effects to all of these methods. Mechanical debonding of ceramic brackets can cause enamel cracks, fractures, and flaking (AAO, 1989). Electrothermal or any other heat-producing devices have the potential to cause pulp irritation or possibly permanent damage. Thus, despite the employment of different methods for debonding, possible tooth or pulp tissue damage remains a concern to clinicians using ceramic brackets (Bishara and Fehr, 1997).

In summary, the superior aesthetics of ceramic brackets is their only advantage over stainless steel brackets, since their mechanical and chemical properties present a major problem in clinical use. However, the shortcomings that are associated with ceramic brackets should not detract from their use in orthodontic practice.

**BONDING CEMENTS**

**Resin Cements**

Direct bonding of orthodontic brackets became possible with the introduction of acid conditioning of enamel and the development of composite resin cements (Buonocore, 1955; Bowen, 1962). Currently, orthodontic bracket bonding is primarily accomplished with the use of composite resin cements. Almost all of these cements are based on the BIS-GMA formula that Bowen developed in 1962. He subsequently developed a Bisphenol A Glycidyl dimethacrylate (BIS-GMA) resin that proved to be considerably more stable than previous resins; it also had greater strength in the oral environment when filled with inert inorganic filler.

**Acrylic and Diacrylic Resin Cements**

Resin containing luting cements (RCLC) used for orthodontic bonding belong to two groups, acrylic and diacrylic resins (Reynolds, 1975). The constituents of acrylic resins are a
methylmethacrylate monomer and an ultra fine polymer powder. Activation of polymerization of the resin is usually accomplished by the use of a catalyst (Reynolds, 1975). The catalyst is either the tertiary amine-benzoyl peroxide curing system, or the tri-n-borane derivative (Reynolds, 1975). Acrylic resins form linear polymers. According to Gorelick et al. (1978) and Viazis et al. (1990) acrylic resin is a poor choice for luting cement for orthodontics because it lacks adequate strength. Diacrylic resins are based on an acrylic modified epoxy resin, which is referred to as BIS-GMA (Bowen, 1962). Diacrylic resins differ from acrylic resins because they may also be polymerized by cross-linking into a three dimensional network. This contributes to greater strength, low water absorption, and less polymerization shrinkage (Gorelick et al., 1978 and Phillips, 1982).

**Filler Content**

A composite material by definition consists of a mixture of two or more materials. Resin based composite materials have three major components: (Craig, 1997)

1. An organic resin matrix which is the chemically active component. The most commonly used monomer is BIS-GMA, which is derived from the reaction of Bisphenol-A and Glycidylmethacrylate.

2. An inorganic filler which is added to resin cements to increase their viscosity, reduce polymerization shrinkage, and allow for the thermal dimensional change of the set composite to approximate that of enamel.

3. A coupling agent, which bonds the filler and resin components to render acceptable mechanical properties to the composite.

It should also be noted that the inorganic filler increases the strength and wear resistance of resin cements (Craig 1977). The filler content of orthodontic resin cements, however, is lower than those used for restorative purposes. This is primarily to allow for easier removal of the remaining cement during debonding (Smith and Williams, 1982).

Acrylic and diacrylic resins exist as unfilled, low filler content, or high filler content resins. Filled resins are further subdivided based on the size of the particles, which can be large
(macrofilled resins), or small (microfilled resins) (Sharma, 1999). Highly filled restorative composite resins contain 60% to 80% by weight of silica (glass filler), whereas the lightly filled composite resins contain about 28% by weight of silica. The orthodontic composite resins consist of 24% to 72% inorganic fillers (Smith and Williams, 1982). The two RCLCs tested in this investigation were Panavia21 and Transbond. Panavia21 is a BIS-GMA two-paste low viscosity restorative composite resin with a filler content of over 70% by weight. This cement is auto-polymerized in the absence of oxygen (Rux et al., 1991). Panavia21 contains the adhesive monomer MDP (10-Methacyloyloxydecyl dihydrogen phosphate) which provides long-term bond strength between tooth structure and metal or silanated porcelain. (Rux et al., 1991). Transbond is a BIS-GMA based, no mix photo-polymerized microfilled orthodontic RCLC and is 80% filled by weight. Mechanically retentive bracket bases depend on the filler content of RCLCs to provide adequate bond strength. Highly filled resin composites appear to bond better to metal brackets (Dickinson and Powers, 1980; Powers, 1997). In addition, an increase in filler content increases its viscosity, which prevents slippage of the bracket on enamel surface before setting of the bonding material. It should be noted, however, that a RCLC with a very high filler content interferes with the wetting of the conditioned enamel which adversely affects the mechanical retention of the cement on to the tooth.

Composite filled resins are available in auto-polymerizing, photo-polymerizing, and dual cure systems. The following is a detailed description of each system.

**Auto-polymerizing and Photo-polymerizing Resin Containing Luting Cements (RCLCs)**

Auto-polymerizing (chemically activated) RCLCs are divided to no-mix systems and two-paste systems (Zachrisson, 1994). The two-paste auto-polymerizing RCLCs require mixing of the two pastes for the initiation of polymerization reaction (setting reaction). These cements set in 30 to 60 seconds which limits their working time and necessitates quick removal of excess cement from the bracket periphery. Separate mixes are required for each bracket (Proffit, 1986). These two-paste composite resin cements also have a thicker viscosity, which reduces slippage of a bracket placed on a tooth.
The no-mix auto-polymerizing composite resins consist of a composite paste and a liquid primer. A thin coat of primer is painted onto the bracket base and the conditioned enamel surface, after which the bracket base is coated with composite resin paste. As the bracket is pressed onto the enamel surface, the resin is activated from both the bracket and enamel surfaces. Excess flash is essentially un-reacted paste and it can be easily removed since it does not set. The no mix systems are less viscous and allow bracket slippage prior to polymerization of the cement.

The auto-polymerized RCLCs were the first system developed for orthodontic bracket cementation (Newman, 1968). Subsequently ultraviolet (UV) light sensitive resins with more rapid polymerization times were introduced as an alternative. The greatest advantage of the photo-polymerized cements is that they provide the clinician with ample time to accurately position brackets on the enamel surface and to remove excess material before photo-polymerization of the cement (Bishara et al., 2000). The wavelength of UV light is in the range of 200-400 nm and is just below that of visible light (Rock, 1974). UV activated cements could be manipulated indefinitely in the mouth until polymerization was initiated by exposure to UV radiation (Rock, 1974). The major disadvantage associated with the UV curing unit was leakage of UV radiation, which could reportedly produce skin cancer, eye damage, and erythema (Birdsell et al., 1977). In addition, the UV sensitive resin cements had a limited depth of cure that could not be improved (Rock, 1974 and Birdsell et al., 1977). The depth of cure is dependent on the composition of the material (amount of filler and particle size), the thickness of the mix, the opacity, and the intensity, position, and duration of curing of the light-source (Cook, 1980; McCabe and Carrick, 1989). As a result, the depth of cure of UV activated resin cements was limited due to attenuation of the UV radiation by the cement and the intervening tooth structure (Salako, 1979), and poor transmission through the tooth substance (De Saeytijd et al., 1994; Sargison et al., 1995). Another reason for limited depth of cure of UV activated systems was the increased amount of scattering at lower wavelengths (Ruyter and Oysaed, 1982).

Douglas et al. (1979) advocated the use of a visible light system to overcome the shortcomings associated with the UV light systems. This light system had curing units with
a blue filter that produced blue light in the range of 400-500 nm. Visible light sensitive resin cements were designed to absorb blue light and initiate polymerization. The advantage of the visible light curing system was the elimination of hazardous UV rays, an increase in the depth of cure, and a reduction in time of light exposure required for polymerization (Newman et al., 1983).

The composition of photo-polymerized RCLCs differs from the auto-polymerized RCLCs only in the activators and initiators. Photo-polymerized RCLCs use a diketone initiator and a reducing agent to initiate polymerization. The initiator is activated by light wavelengths in the range of 400-500 nm. In comparison, auto-polymerized RCLCs are dependent on the mixing of the initiator and the activator for polymerization. (American Dental Association, 1985). Leung et al. (1983) demonstrated that post-irradiation hardening of a visible light activated system continues for up to 1 day.

There are conflicting reports in the literature when photo-polymerizing RCLCs are compared to auto-polymerizing RCLCs. Some studies report lower bond strengths for photo-polymerizing RCLCs compared with those achieved with auto-polymerizing RCLCs (King et al., 1987; Greenlaw et al., 1989; Ostertag et al., 1989). Other studies, however, (Joseph and Rossouw, 1990; Wang and Meng, 1992) have reported higher bond strengths for photo-polymerizing RCLCs than for auto-polymerizing RCLCs. Because of the different materials and the different methods used in their investigation direct comparison between these studies is not possible.

When comparing the failure rates of photo-polymerizing and auto-polymerizing RCLC, O’Brien et al. (1989) reported respective failure rates of 4.6% and 6% for photo-polymerizing and auto-polymerizing RCLC. The values obtained by Armas et al. (1998) were 11.3% and 12%. These differences may be attributed to the differences in both the physical and mechanical properties of materials tested, and the testing criteria used. The results of both studies, however, confirm the clinical acceptability of both photo-polymerizing and auto-polymerizing RCLC bonding materials. In fact Sargison et al. (1995) noted comparable bond strength values for photo-polymerizing Transbond (3M/Unitek, CA)
and auto-polymerizing Right-on (TP, Orthodontics). Based on these observations, Sargison et al. 1995 suggested that although light cannot penetrate a metal bracket, there seems to be sufficient light penetration through the periphery of the base to activate polymerization of the underlying cement.

**Dual Cured RCLCs**

In an attempt to address the problem of inadequate depth of cure, dual-cured RCLCs were developed. These materials contain both auto-polymerizing and photo-polymerizing systems (Sargison et al., 1995) so that complete polymerization is enhanced by the auto-polymerizing component. As a result initial polymerization can be activated by the visible light source with auto-polymerization completing the setting reaction. In fact these bonding materials can also be left to auto-polymerize without any light exposure. A dual-cured system may be the most ideal bonding system for orthodontic purpose, since it confers both the advantages of extended working time and the continuation of polymerization when the light source is removed.

**Glass Ionomer Cements**

Despite their versatility, the use of RCLCs for bracket bonding has a number of drawbacks. Enamel loss could occur during prophylaxis (Thompson and Way, 1981), acid conditioning, (Brown and Way, 1978) as well as at the time of clean up during debonding (Pus and Way, 1980). In addition, enamel demineralization could develop within a month of bracket placement as a result of the accumulation and retention of plaque next to the bracket bases (O’Reilly and Featherstone, 1987; Mitchell, 1992). Glass ionomer cements are thought to have the potential means of addressing some of the shortcomings associated with the use of RCLCs in orthodontics.

Glass Ionomer Cements (GICs) possess the ability to adhere to non-precious metals, enamel, dentin and plastics (Hotz et al., 1977). It is also reported that less enamel damage occurs during clean up after debonding (Ostman-Andersson et al., 1993). According to Norevall et al. (1995), GICs can be more easily removed than RCLC at the time of debonding. Any cement remaining on the enamel surface can be desiccated by air drying which renders it
more friable and removable (White, 1986). As a result, the likelihood of enamel damage being incurred both during and after debonding of GIC cemented brackets is less than that of those cemented with RCLCs. The use of GICs does not require the acid conditioning of enamel (Millett & McCabe, 1996) since the cement bonds chemically to tooth structures i.e., enamel and dentin. GICs also have the ability to release (Fox, 1990; Ashcraft et al., 1997) and absorb fluoride (Hatibovic-Kofman and Koch, 1991; Creanor et al., 1994). Glass ionomer cements release considerable amounts of fluoride and they have been shown, in vitro, to prevent demineralization of enamel (Forss and Seppa, 1990). It has also been reported that a less cariogenic flora is found in plaque deposits adjacent to GICs (Hallgren et al., 1992). Wright et al. (1996) studied the effect of resin-reinforced glass ionomer cement (RRGLC) on the oral microflora. Their results showed that levels of Lactobacilli and S.mutans (cariogenic bacteria) around brackets bonded with the RRGIC were reduced when compared with the conventional diacrylate resin cements.

GICs were introduced by Wilson and Kent in 1972 and they consists of following constituents (Crisp et al., 1976):

1. Poly alkenoic acid, commonly a homo- or co-polymer of acrylic acid.
2. An ion leachable aluminosilicate glass to provide ions to cross-link the chains. These glass particles are embedded in an insoluble hydrogel matrix.
3. Water as a reaction medium.
4. Tartaric acid to improve working and setting characteristics.

There are three types of glass ionomer cement currently on the market: conventional, water hardening, and the most recently introduced, the resin-reinforced glass ionomer cement (RRGIC) (White, 1986; Antonucci et al., 1988).

The setting reaction of conventional GIC involves an acid base reaction between the aluminosilicate glass and polyacrylic acid components (Wilson and McLean 1988). Protons from the acid penetrate the glass powder to release calcium and aluminum ions, initiating a prolonged, two-phase setting reaction. Calcium ions bind to polyacrylic acid producing gelation and initial adhesion to tooth structure. Aluminum ions then contribute to the
subsequent hardening stage as more rigid cross-linking occurs with the formation of aluminum polycarboxylates (Wilson and McLean, 1988). It is during the first phase when calcium salts predominate, that conventional glass ionomers are extremely sensitive to moisture contamination and dehydration (Swift, 1986). Conventional glass ionomer cements have reportedly shown decreased bond strength when used to bond orthodontic brackets when compared to resin cements (Cook, 1990; Fajen et al., 1990; Rezk-Lega and Ogaard, 1991).

The second generation or water hardening GICs contain the same acids as conventional GICs either in a freeze dried powder form or as an alternative powdered copolymer of acrylic and maleic acids. These dried powders are supplied blended with the glass powder and require only distilled water to activate the setting reaction. Hence the name water hardening GIC (Prosser et al., 1984). These types of GICs are used to cement orthodontic bands.

**Resin-Reinforced Glass Ionomer Cements**

The new generation of GICs are hybrid cements containing water base GIC with 11.25% resin (Demke R. Material product data sheet, 1996). These hybrid GICs set partly via an acid reaction and partly via either photochemical or chemical polymerization (Bourke et al., 1992). Since these materials contain both glass ionomer and resin components, they differ considerably in their physical and chemical properties from the conventional GICs (Millett and McCabe, 1996). These cements combine the advantages of conventional GICs with the mechanical and physical properties of composite resin cements (Beress et al., 1998). A photo-polymerized, hybrid glass ionomer orthodontic cement, Fuji Ortho LC was introduced in 1994 by GC Orthodontics (Coups Smith, 1997). It is the manufacturers claim that this cement allows bonding to non-conditioned enamel in a moist environment. Two reactions take place on polymerization of this cement: the normal glass ionomer cement acid-base reaction that occurs when the material is mixed as well as a photochemical polymerization that occurs on exposure to visible light (Sidhu and Watson, 1995). RRGICs are supplied as powder and liquid. The powder comprises ion leachable fluoroaluminosilicate glass (Craig, 1997). The complex monomer liquid contains polyacrylic acid, water, and a photo-
polymerized monomer such as hydroxyethyl methacrylate (HEMA) or BIS-GMA. RRGICs are formed by a combination of the acid-base components of conventional GICs and the addition of resins. Monomers such as BIS-GMA and HEMA are used to facilitate the chemical reaction. In place of some of the water, HEMA is incorporated into the glass-ionomer composition. This provides for a dual setting mechanism that is accelerated by the light polymerization of resin monomers (Antonucci, 1988 and Nouri, 1997). A moist environment is required for all the reaction steps but, it should be noted, the presence of too much water may dissolve the reactants thus preventing the agglomeration of the setting matrix (Wilson, 1990). Resin-reinforced glass ionomer cements that possess photochemical setting reactions, appear to have a reduction in sensitivity to moisture, since the resin network reduces the diffusion of external water into the setting cement (Cho et al., 1995; Shen and Grimaudo, 1994). During bonding the enamel surface needs to be moistened with either water or saliva in order to avoid enamel desiccation, as this will adversely affect bond strength (Silverman et al., 1995). During mixing, an incorrect powder/liquid ratio will affect RRGICs clinical performance because of its effect on the physical and chemical properties of the set material. For example, a watery mix will result in an increase in the amount of the hydrophilic resin (HEMA) that increases the potential for greater water uptake and weakening of the final material (Wilson, 1990). On the other hand, a thick mix will result in increased viscosity that will reduce its ability to wet the substrate (enamel surface) effectively. The result of this may be a decrease in the ultimate bond strength. In addition, an adequate thickness is required to reduce the potential of the bracket float problem associated with a thinner mix.

In comparison with the conventional glass ionomers, the resin-reinforced glass ionomer cement is believed to have improved resistance to desiccation and acid attack. The bond to enamel and dentin is also enhanced, since the resin component imparts additional tensile strength to the set cement (van Noort, 1994).
**Conditioned and Non-Conditioned Enamel Surfaces**

The enamel treatment required with the use of Fuji Ortho LC is conditioning with a 10% aqueous solution of polyacrylic acid. This acid does not dramatically change the enamel surface compared to phosphoric acid; it simply cleans the surface and promotes a suitable bonding substrate for application of the cement (Todo et al., 1997). The early reports by Silverman et al. (1995) on the clinical performance of Fuji Ortho LC were promising, with bracket failure rate of about 3 per cent recorded; the enamel surface was not conditioned and the observation period, appeared to be about 8 months. It was also suggested that enamel acid conditioning was not necessary, unless a strong bond was required (Silverman et al., 1995).

Fricker (1994), in a clinical trial of 10 cases, reported no significant difference in failure rates of orthodontic brackets cemented with light cured resin-reinforced Fuji II LC (GC Dental Industrials, Tokyo, Japan) and those cemented using composite resin (System 1+, Ormco Corp, Glendora, Calif). Using Fuji Ortho LC as a bracket cementing agent, Powers et al. (1996) reported bond strengths to non-conditioned enamel ranging from 8 to 25 MPa. Beress et al. (1998) tested Fuji Ortho LC under different surface treatment conditions when bonding metal brackets to human enamel. They reported mean bond strength of 17.69 ± 4.6 MPa for conditioned moist environment, however, the bond strength dramatically decreased when the enamel surface was not conditioned (5.27 ± 2.15 MPa). Bishara et al. (1998b) and Millett et al. (1999) reported that Fuji Ortho LC cement, when used on conditioned enamel contaminated with a thin film of water or saliva, has a similar but slightly lower strength compared to that of traditional photo-polymerized RCLC. Their findings also indicated that conditioning the enamel surface was a critical variable that affected shear bond strength, as well as bond failure location, when the Fuji Ortho LC cement was used. Coups Smith (1997) recommended the use of 10% polyacrylic acid conditioner prior to bonding with either GC Fuji Ortho (auto-polymerizing RRGIC), or Fuji Ortho LC (photo-polymerizing RRGIC). In a study comparing the shear bond strengths of RRGICs following incubation periods of 24-hours and 30-days, Lippitz et al. (1998), also reported shear bond strengths comparable to those of the resin cements when the enamel was conditioned with 10% polyacrylic acid solution. They noted significant reductions and less consistency in bond
strengths when the enamel was not conditioned. Furthermore, with the omission of enamel conditioning, the site of bond failure shifts from the bracket base-cement interface to the enamel-cement interface thus confirming the weaker bond between the enamel and the cement (Bishara et al., 1998b). Despite the manufacturer’s claim these observations confirm that in order to attain a reliable bond strength the acid conditioning steps should be followed prior to cementation of brackets with RRGICs.

Flores et al. (1999) tested the SBS of metal brackets to acid conditioned and non-conditioned enamel surfaces using photo-polymerized Fuji Ortho LC and Transbond cement. The enamel was conditioned for 20 seconds with 37% orthophosphoric acid for both cement types. In this study, the investigators did not use the recommended 10% polyacrylic acid conditioner for Fuji Ortho LC. Their results showed that shear bond strength was dependent on enamel surface treatment. When bonding with Fuji Ortho LC a significant increase in shear bond strength was observed with the conditioned group (15.8 ± 2.08 MPa) as compared to non-conditioned group (6.4 ± 3.40 MPa). The bond strength resulting from Transbond (14.7 ± 4.22) and Fuji Ortho LC (15.8 ± 2.08 MPa) for the conditioned groups were comparable. With respect to enamel surface alteration following debonding, the non-conditioned group demonstrated no enamel changes. However, there was less damage to enamel surface, as indicated by scanning electron microscopy, when Fuji Ortho LC (conditioned) was compared to Transbond (conditioned) group. They concluded, therefore, that the use of Fuji Ortho LC for bracket bonding onto acid conditioned (37% orthophosphoric acid) enamel was a favorable option because debonding strengths were significantly increased and there was less iatrogenic damage to the enamel surface when compared to Transbond (conditioned) group.

Bishara et al. (2000) studied the effects of altering the type of enamel conditioner on the SBS of RRGICs within half an hour after bonding the bracket to the enamel. The half an hour waiting period used was based on the results of their previous study (Bishara et al., 1999b). In this study, the authors demonstrated low bond strengths following half hour bonding with RRGICs in conjunction with polyacrylic acid conditioner. The experimental sample consisted of four groups: group 1) 10% polyacrylic acid conditioner and Fuji Ortho
LC cement, group II) 20% polyacrylic acid and Fuji Ortho LC cement, group III) 37% phosphoric acid, and Fuji Ortho LC cement and group IV) 37% phosphoric acid and Transbond cement. These investigators recorded clinically acceptable SBS in the two groups that had been conditioned with 37% phosphoric acid. The bond strength of the RRGICs conditioned with 10% polyacrylic acid (0.4 ±1.0 MPa) was significantly lower than the group conditioned with 20% polyacrylic acid (3.3 ±2.6 MPa). As a result, they concluded that glass ionomer cement had significantly low initial bond strength in the first half hour after bonding. They further suggested that ligating archwires within that time frame could result in an unacceptable rate of bracket failure. Their recommendation was that in order to safely tie archwire into brackets bonded with RRGIC within half an hour of bonding, clinicians should consider conditioning with 37% phosphoric acid instead of polyacrylic acid. Another suggested alternative was to tie archwires 24-hours after bonding, since by that time bond strengths were shown to have reached an optimal level to withstand orthodontic forces. The investigators acknowledged the inconvenience incurred by both the clinicians and the patient, but it was their opinion that the benefits from fluoride release probably counterbalanced such an inconvenience. The cumulative evidence produced by these current studies is that the presence of only chemical bond (RRGIC to non-conditioned enamel) does not appear to provide clinically sufficient SBS. The addition of a mechanical bond to enamel through enamel conditioning is required to provide clinically acceptable bond strengths (Meehan, 1999).

**TYPES OF ENAMEL SURFACE CONDITIONERS**

**Acid Conditioning**

Acid etching (conditioning) was initially introduced in 1955 by Buonocore. He demonstrated a markedly increased retention of methyl methacrylate resins to enamel when their application was preceded by enamel conditioning using 85% phosphoric acid for 30 seconds. Subsequently, the optimum concentration of acid to produce a consistent evenly distributed, and optimal depth etch pattern was reported to be in the range of 30 to 50% (Buonocore, 1955; Retief, 1974; Silverstone et al., 1975). Acid conditioning modifies the enamel surface, allowing an intimate micro mechanical bond between enamel and the resin component of the RCLC. The latter has no intrinsic adhesive qualities to the enamel. The
conditioning process increases surface roughness of the enamel and hence the bonding area by removing the hydroxyapatite from the enamel surface. Thus, the surface characteristics of enamel are changed due to preferential dissolution between the prism periphery and its core. Following acid conditioning, the enamel surface assumes a microscopic honeycomb lattice appearance (Craig, 1997). Wickwire and Rentz (1973) estimated the surface layer of enamel lost during conditioning to vary between 10 and 30 μm. The acid also has the effect of raising the surface energy of enamel from a low-energy hydrophobic surface to a high-energy hydrophilic surface. This surface modification increases enamel surface tension and wettability by the cement (Retief, 1978). This facilitates the flow of the resin material over the enamel surface, allowing greater penetration of resin tags into the undercuts of the conditioned surface. After polymerization, the adhesive resin tags form a tightly interlocking mechanical bond with the conditioned enamel (Retief, 1978). Buonocore et al. (1978) showed that the depth of penetration of the resin tags reached up to 50 μm. This resin is thought to remain on the enamel after debonding, and this could affect plaque retention, susceptibility to caries and discoloration (Waveren et al., 2000).

Since phosphoric acid conditioning may potentially damage enamel integrity, numerous investigations have been conducted to assess the merits of alternative treatments such as reducing acid concentration and time, use of maleic acid (Triolo et al., 1993; MacColl, 1995; Olsen et al., 1997; Urabe, 1997), and polyacrylic acid (Smith and Cartz, 1973). Investigations concerning reducing either the concentration of the acid or the conditioning time have concluded that varying phosphoric acid concentration from 5% to 37% (Barkmeier et al., 1987; Legler et al., 1989; Sadowsky et al., 1990) or reducing the conditioning time from 60 to 15 seconds (Barkmeier et al., 1987; Legler et al., 1989; Sadowsky et al., 1990) and even 10 seconds (Olsen et al., 1994) does not significantly affect bond strength. It has been reported, however, that reducing the conditioning time, within certain limits, to 5 seconds results in inadequate bond strength (Olsen et al., 1994). Thus, reducing acid concentration and conditioning time within certain limits, produces less tooth damage whilst still yielding adequate bond strength. According to Wang and Lu (1991) the shorter the conditioning time, the less the depth of enamel loss and the fewer enamel fractures during debonding. Triolo et al. (1993) using 10% maleic acid as enamel
conditioner found that it provided bond strength essentially equal to that of 37% phosphoric acid when bonding brackets with RCLCs. In this study, the scanning electron microscopy of the enamel treated with 10% maleic acid and 37% phosphoric acid revealed a similar morphologic pattern but the depth of the etched surface was significantly less with maleic acid. MacColl (1995) compared shear bond strengths of metal brackets bonded to bovine enamel using four different conditioners: 37% Phosphoric acid (aqueous solution and gel), 10% maleic acid (aqueous solution and gel) for 20 seconds. His results demonstrated that conditioning with aqueous maleic acid (10%) was associated with the highest shear bond strength. There was no statistically significant difference between the other three acid types used.

Acid conditioning, in general, may initiate enamel decalcification by removing highly mineralized fluoride rich surface enamel; it may also promote enamel fracture during debonding due to adherent cement tags within the microporosities. The clean-up procedure of the cement after debonding may remove up to 55 microns of surface enamel (Fitzpatrick and Way, 1977). Therefore, using phosphoric acid for acid conditioning carries a potential risk for significant enamel loss, either during conditioning or following removal of penetrated cement. As a result, any bonding system that can produce adequate bond strengths without any significant enamel surface alteration, subsequent decalcification, and possible enamel fracture will be a superior system.

**Crystal Growth**

Crystal growth, introduced by Smith and Cartz (1973), is an alternative method of enamel surface preparation. Smith and Cartz (1973) showed that polyacrylic acid containing residual sulfate ions reacted with the enamel surface to produce a deposit of white spherulitic crystalline calcium sulfate to which the adhesive resin bonds. Smith and Cartz (1973) identified these crystals as calcium sulfate dihydrate (gypsum). According to Smith and Cartz (1973) the carboxyl groups in the long chain polyacrylic acid molecules have the ability to chelate to calcium in the mineral phase of tooth structure, resulting in an adhesion. The formation of these depended mainly on the sulfate ion concentration in the polyacrylic acid solution. Purified polyacrylic acid produced only slight etching of the enamel surface;
whereas polyacrylic solutions that contained residual sulfate ions produced not only slight etching of the enamel but also a crystalline deposit that bonded firmly to the enamel surface and resisted mechanical removal (Smith and Cartz 1973). These investigators also demonstrated that the maximum density of the long, needle-shaped crystals growing on the enamel surface was found to occur after conditioning for 4 minutes with 40% polyacrylic acid. With this method of enamel conditioning, the resin penetrated the deposited crystals on the surface rather than the enamel itself. The method of crystal growth for bonding has a few advantages over the etching (conditioning) technique with the phosphoric acid. These advantages are: (1) minimal damage to the enamel surface, (2) easier debonding and enamel cleanup, (3) minimal loss of outer fluoride rich enamel layer, and (4) few if any resin tag remnants after debonding (Maijer and Smith, 1986). Bishara et al. (2000) compared the etch pattern of enamel surface when it was etched with 37% phosphoric acid, 10% polyacrylic acid, and 20% polyacrylic acid. When the enamel surface was examined under an electron microscope, phosphoric acid conditioning produced a much deeper etch (rougrier enamel surface) than the polyacrylic acid. It has been demonstrated that the use of crystal growth enamel conditioning with polyacrylic acid, significantly increases the incidence of bond failure at the enamel-cement interface, but the bond actually fails within the crystals and not at the enamel surface. As a result, the incidence of enamel fracture is decreased (Beech, 1972; Maijer and Smith, 1979). Maijer and Smith (1979) tested the value of this crystalline interface as an enhancer of the mechanical retention of orthodontic brackets. The results of their study showed that the crystalline interface produced tensile bond strength equivalent to that of a conventionally acid-conditioned enamel surface. However, other investigators (Maskeroni et al., 1990; Artun and Bergland, 1984; Farquhar, 1986; and Burkey, 1985) found that bond strengths with the use of crystal growth conditioning were significantly weaker than with the conventional acid conditioning techniques.

Bishara et al. (1993) compared various conditioner-cement combinations and indicated that, in general, the use of polyacrylic acid as an enamel conditioner resulted in a 30% reduction in bond strength as compared with the use of phosphoric acid. However, despite this reduction, the bond strengths were acceptable for orthodontic purposes.
Adhesive Primer

Conventionally, after the enamel surface is conditioned with phosphoric acid, an intermediate unfilled low viscosity liquid resin (adhesive primer) is applied in order to thoroughly wet the enamel surface so that the bond strength between enamel and the resin cement is maximized. Application and curing of this adhesive primer results in resin tags that extend into the microporosities that are produced by acid conditioning. These resin tags bond the composite cement mechanically to enamel (Retief, 1978). An adhesive primer is a multifunctional monomer with a hydrophilic end that wets and bonds to tooth structure and a hydrophobic end that reacts with the double carbon bonds of the resin cement. Weisser (1973) and Reynolds (1975) advocated the use of low viscosity adhesive primers to ensure adequate wetting of the enamel surface. However, research has shown that the application of a layer of unfilled adhesive resin to the conditioned tooth surface prior to placement of the composite resin cement and bracket does not increase the bond strength and can, therefore, be omitted (O’Brien et al., 1991; Wang and Tarneg, 1991). Tang et al. (2000) recently performed a retrospective clinical study to evaluate the retention of metal orthodontic brackets bonded without adhesive primer. In both the test and control groups the enamel was conditioned using 37% phosphoric acid. In the experimental group (n=37) Phase II resin cement (two paste auto-polymerized resin cement, Reliance, Itasca, IL) without adhesive primer was used to bond brackets to patients’ maxillary teeth. Brackets in the control group (n=37) were bonded to the teeth with Phase II and adhesive primer. The results showed that the exclusion of an adhesive primer from an auto-polymerized two paste bonding resin cement appeared to have no detrimental clinical effect. Despite these observations, however, clinicians continue to utilize adhesive primers in conjunction with the RCLCs in order to comply with manufacturer’s recommendations.

A recent development in the field of bonding is the use of innovative self-etching acidic primers. These materials serve simultaneously as conditioner and primer and do not have to be rinsed off. The acidic part of the primer is neutralized at some point by the calcium and phosphate ions released during demineralization. Demineralization is, therefore, self-limiting in that the high concentration of these ions tends to limit further dissolution of hydroxyapatite (Wang and Hume, 1988). The acidic primers form a continuum between the
tooth surface and the cement material by the simultaneous demineralization and resin penetration of the enamel. The advantages of acidic primers are simplified bonding procedures and improvement in both reduced time and cost effectiveness to the clinicians and thus indirectly to patients (Bishara et al. 1998a).

The use of acidic or self-etching acidic primers for orthodontic purposes has been evaluated in two different studies by Bishara and colleagues (Bishara et al., 1998a and 1999a). The study conducted in 1998 showed that the use of an acidic primer to bond orthodontic brackets to the enamel surface provided clinically acceptable SBS (11.8 ± 4.1 MPa) when used with a highly (77%) filled RCLC (Panavia21). The shear bond strength was significantly lower (5.9 ± 5.6 MPa), however, when a lightly (10%) filled RCLC was used (Clearfil Liner Bond, J.C. Morita, Kuraway, Japan). The use of an acidic primer decreased the amount of cement left on the tooth after debonding. This observation was also illustrated by examining scanning electron micrographs (SEM) of the enamel surfaces. The SEM for phosphoric acid conditioned enamel showed thick and uniform resin tags; whereas the resin tags for the self-etching acidic primer treated enamel were thin and less uniform. The latter observation supports the finding that there is a weaker bond between the enamel and the cement with the result that less cement is left on the tooth after debonding. The results of the Bishara et al. (1999a) second study did not endorse the use of an acidic primer, but it must be noted that they used different cements. In this latter study, two types of adhesive were compared with different types of conditioners and primers. The results indicated that the resin/phosphoric acid adhesive system provided the strongest (10.4 ± 2.8 MPa), and the glass ionomer adhesive system a significantly lower SBS (6.5 ± 1.9 MPa). The lowest shear bond strength was noted when the acidic primer was used with an orthodontic cement (Transbond). Based on these observations, and the introduction of self-etching acidic primers more research is warranted to test the compatibility of self-etching acidic primer + Panavia21 using metal, and ceramic brackets.
STORAGE TIME

A review of the pertinent research shows that the majority of bonding studies use 1-hour, 24-hours, 7-days and 28-30 days (Rix et al., 2001; McCourt et al., 1991, Meehan et al., 1999, Lippitz et al., 1998, Lalani et al., 1999) as storage time prior to shear bond strength (SBS) testing. Sharma (1999) tested six different metal bracket bases bonded with Transbond cement after 1 and 24-hours of storage time. The results indicated a statistically significant difference between the SBS of data collected at 1-hour versus data collected at 24-hours. Time significantly increased mean SBS, however, this difference was not clinically significant because 5 out of 6 bracket types tested achieved clinically acceptable bond strengths after 1-hour. The conclusion was that, the data arising from 24-hours testing provides relevant clinical information and that there is no need to wait for 24-hours prior to placement of orthodontic wires and subsequent force application. These results are in disagreement with those of Greenlaw et al. (1989) who recommended that 24-hours should elapse before force application.

Chamada and Stein (1996) tested the immediate shear/peel bond strengths produced by a photo-polymerized bonding system (Transbond) in an in vitro study. They also compared the shear/peel bond strengths over a 24-hours period with those obtained by an auto-polymerized orthodontic bonding system (Concise). The times at which the bond strengths were tested were 0, 2, 5, 10 and 60-minutes and 24-hours after activation with the photo-polymerized cement. For the auto-polymerized cement, the time intervals for testing were 2, 5,10, 60-minutes and 24-hours after activation. Their findings showed that photo-polymerized cement (Transbond) produced initial bond strengths after activation that was of sufficient magnitude to withstand the immediate application of forces. Their findings were in agreement with those of Tavas and Watts (1984) and Sharma (1999). In the study of Tavas and Watts it was shown that the initial bond strength of the cements used was 60% to 70% of the bond strength realized at 24-hours which once again was adequate to withstand immediate application of orthodontic and chewing forces. In their study, initial bond strength was low but it was shown to increase subsequently.
Currently, there is no consensus on the effects of long term storage on the shear bond strength of orthodontically bonded brackets (Bishara et al., 1975; Low and von Fraunhofer, 1976; Johnson et al., 1976; Yamaguchi et al., 1989; Meng et al., 1995). Meng et al. (1995) conducted a study to determine the effects of water immersion on orthodontic resins used to bond metal brackets to human premolars. The results showed that there was a significant reduction in bond strength after one day. They speculated that the polymer matrix of composite resin cements absorb and desorb water over time causing the hydrolytic degradation of the inorganic fillers, thus, resulting in reduced bond strengths. According to Chamda and Stein (1996), shear bond strength increases over time due to the continuation of polymerization of the composite resin under the bracket base. Wilson and Mclean (1988) reported that GICs like composite resins slowly increase their strength over time thus leading to increased shear bond strengths. Yamaguchi et al. (1989) showed that there was no significant difference in shear bond strength when bonded specimens were stored in water for 24-hours to 7-days.

Recently, Mahal (2000) studied the effects of long term storage (180-days) on shear bond strength and ARI scores. Metal (Speed), ceramic (Transcend) and polycarbonate (SpiritMB) brackets were bonded to bovine enamel using Phase II composite resin and GC Fuji Ortho cements (auto-polymerizing). The long-term storage period consisted of shear bond testing at 24-hours, 7-days, and 180-days. The results indicted that in general long-term storage has a significant effect on the SBS and this effect was in turn dependant on the bracket type, and the cement used. In the Mahal (2000) study long-term storage (180-days) did not have a significant effect on the fracture pattern of brackets.

**HUMAN AND BOVINE ENAMEL**

One of the problems associated with bond strength testing is the limited availability of non-carious human teeth. Bovine mandibular incisors teeth are considered a suitable alternative to human teeth in bonding studies, and are used not only due to the limited availability of human teeth but also because of the increased concern of the infection hazards from human teeth (Rueggberg, 1991). Bovine teeth are readily available and their enamel is quite similar
to human enamel. On a histochemical and anatomic basis the teeth of all mammals appear to be similar (Leichester, 1949; Fujita, 1957; Suga et al., 1971). Despite the general similarities, however, some differences have been noted. Bovine enamel and dentin form more rapidly than human enamel so that bovine enamel has larger crystal grains and more lattice defects than human enamel (Moriwaki et al., 1968). This may contribute to the observation of the lower critical surface tension in bovine enamel compared with human enamel (Oesterle et al., 1998; Yu and Chang, 1966). This difference between the critical surface tension of bovine and human enamel has been implicated as the reason for a slight enamel bond reduction when using bovine enamel (Nakamichi et al., 1983). Nakamichi et al. (1983) also investigated the suitability of bovine teeth as an alternative to human teeth in bonding tests, using seven different cements. The results showed that the adhesive bond strength to enamel was not statistically significantly different between the bovine and human teeth although the mean values were reported to be slightly lower with bovine teeth. Fowler et al. (1992) showed that bond strength measurements in both shear and tensile mode obtained with human and bovine enamel were essentially comparable. More recently, Oesterle et al. (1998) re-examined the suitability of bovine enamel in bonding studies. In this study, the strength of the enamel bond of a photo-polymerized orthodontic cement was compared between deciduous bovine, permanent bovine, and human enamel. The results showed that the bond strength to bovine enamel was significantly weaker than that to human enamel, and that the bond strength to deciduous bovine enamel was significantly greater than to permanent bovine enamel. The difference in bond strength between permanent and deciduous bovine enamel was attributed to the fact that permanent bovine incisors have larger undulations on the facial surface than both human incisors and deciduous bovine incisors. This uneven enamel surface is usually polished to create a smooth surface prior to bonding and this may account for the decreased bond strength of permanent bovine compared to deciduous bovine incisor (Oesterle et al., 1998). Despite these observations, bovine enamel can still be successfully used to study enamel bond strength (Fox et al., 1994, Oesterle et al., 1998). Thus, the current view is that orthodontic brackets bonded to bovine enamel will perform almost in the same way as they do to human enamel (Fox et al., 1994).
BOND STRENGTH TESTING

The variables affecting bracket bond strength to enamel are the bracket base configuration, the cement used, and the type of enamel conditioner (Bisahra et al., 1993). Studies have also shown that storage time and water immersion does affect bond strength of brackets to enamel. Bond strength tests are used to assess the in vitro performance of dental bonding systems and also to predict their behavior (Bagnall, 1989). In the majority of orthodontic in-vitro studies, shear and/or tensile bond strengths are determined in order to assess the potential performance of the bracket and the bonding systems during clinical application. Ferguson et al. (1984), and Tavas and Watts (1979) both advocated the use of shear/peel testing to represent the type of forces encountered in the clinical situation. Fowler (1992) identified three variables associated with adhesion testing: (1) the test mode, shear and tension; (2) design of the testing apparatus; and (3) tooth substrate, human and bovine.

When comparing the types of bond failure produced by shear and tensile testing, it was found that tensile specimens failed cohesively whereas the shear specimens failed at the enamel cement interface. As a result, it was concluded that the values obtained from tensile testing did not represent the bond to enamel but rather showed the bulk strength of the luting material (cohesive failure). Fowler also demonstrated that the shear test might have an advantage over tensile test in that it appears to be more likely to produce failure at the enamel-cement interface. According to Thanos et al. (1979), however, the best bracket base-cement combination cannot be selected on the basis of one test alone.

The bond between the enamel and the bracket base should be strong enough to withstand orthodontic and chewing forces while still allowing debonding of the bracket without injury to tooth structure. Reynolds (1975) suggested that minimum bond strength of 5.9 to 7.8 MPa was adequate for most clinical orthodontic needs. It was postulated that clinical success could be achieved with cements that provide in vitro bond strengths of approximately 5.0 MPa. If the bond between the cement and the enamel is stronger than the enamel itself, the enamel will fracture during debonding. An investigation by Retief, (1974) on bond failure at the enamel-cement interface indicated that enamel fractures can occur on debonding with bond strengths as low as 9.7 MPa. As a result the use of bracket base-cement combinations
that can result in bond strengths that are significantly greater than 9.7 MPa should be approached with caution.

**LOCATION OF BOND FAILURE**

Clinically, bond failures occur in the presence of excessive shearing, tensile, or torque forces. Bond failures can be divided into two types: cohesive failure and adhesive failure. Cohesive failure can occur within the tooth, bracket, or the cement. Adhesive failure occurs at the tooth-cement, and the bracket base-cement interfaces (Compton et al., 1992; Wang and Meng, 1992). According to Powers et al. (1997), the most important bonding information for orthodontists is obtained by isolating these interfaces and examining the different bond strengths resulting from various conditioner-cement-bracket base combinations.

Bond failure location is an important factor when considering chair time and potential damage to the pulp and the enamel surface (Katona, 1997). Following a critical review of bond strength testing in orthodontics, Fox et al. (1994) noted that the ideal location for a clinically acceptable bond to fail is at the enamel-cement interface since this would make bonding and subsequent debonding much easier. However, the enamel-cement interface is now considered an undesirable bond failure location, because of the increased risk for damage to the enamel. To maintain enamel integrity, the ideal bond failure location in debonding should be between the bracket base and the cement (Sinha et al. 1995), although bracket cement interface debonding increases the difficulty of enamel clean up (Brown, 1978; Pus, 1980). As a result, clinicians must take great care when removing remaining cement following debonding to avoid gouging, scratching, or pitting of the enamel surface.

The Adhesive Remnant Index (ARI), formulated by (Artun and Bergland, 1984), is used to quantify the amount of cement left on the tooth following debonding of the bracket. The ARI score is also used to define the sites of bond failure between the enamel, the cement, and the bracket base. The ARI consists of a 4-point scale of 0-3: a score of 0 indicates no cement left on the tooth, 1 indicates less than half of the cement left on the tooth, 2 indicates
more than half of the cement left on the tooth, and 3 indicates all of the cement left on the tooth including a distinct impression of the bracket base.

**Table 1: ARI Scoring Index (Artun and Bergland, 1984)**

<table>
<thead>
<tr>
<th>Description</th>
<th>ARI Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>No cement left on the tooth</td>
<td>0</td>
</tr>
<tr>
<td>Less than half of the cement left on the tooth</td>
<td>1</td>
</tr>
<tr>
<td>More than half of the cement left on the tooth</td>
<td>2</td>
</tr>
<tr>
<td>All of the cement left on the tooth plus a distinct impression of the bracket base</td>
<td>3</td>
</tr>
</tbody>
</table>
OBJECTIVES OF THE STUDY

- To identify combinations of bracket bases and cements that can provide clinically acceptable SBS which result in minimal or no damage to the enamel during debonding

- To ascertain the influence of bracket base design, cement type, enamel conditioning and long-term storage on SBS

- To ascertain the influence of bracket base design, cement type, enamel conditioning and long-term storage on ARI

- To determine if there is any association between ARI and SBS

- To investigate if there is a systematic relationship between different bracket base designs and particle size of various cements

In this study mean SBS of 8±3 MPa and Adhesive Remnant Index (ARI) scores > 2 were deemed to be clinically acceptable.

HYPOTHESIS

Not all orthodontic bracket bases are clinically compatible with all the currently available cements.
OPERATIONAL DEFINITIONS

Clarity¹: Polycrystalline ceramic bracket (3M/Unitek Dental Products, 2724 South Peck Road, Monrovia, CA 91016 USA).

Transcend²: Polycrystalline ceramic bracket (3M/Unitek Dental Products, 2724 South Peck Road, Monrovia, CA 91016 USA).

Time³: Machined, integral metal bracket with microetched base with mechanical undercuts (American Orthodontics, 1714 Cambridge Ave, P.O. Box 1048, Sheboygan, Wisconsin 53082-1048).

Speed⁴: Metal bracket with 60 gauge, microetched foil mesh of horizontal and vertical configuration (Strite Industries, 298 Shepard Ave, Cambridge, Ontario N3C 1V1).

Fuji Ortho LC⁵: Photo-polymerising resin reinforced glass ionomer cement (GC Corporation, Tokyo, Japan & distributed by GC American Inc, Chicago, IL).

Panavia²¹⁶: Photo-polymerizing restorative cement (J Morita USA Inc, Tustin, California).

Transbond⁷: Photo-polymerizing, diacrylate, highly filled, adhesive paste (3M Unitek Dental Products, 2724 South Peck Road, Monrovia, CA 91016 USA).


Plasticene⁹: Art Works (Toronto, Ontario, Canada).

180-600 Grit Silicon Carbide paper¹⁰: (Buehler Ltd., 41 Waukegan Rd., Lake Bluff, IL).

37% Orthophosphoric Acid¹¹: 37% phosphoric acid (Reliance orthodontic Products Inc., P.O. Box 678 Itasca, IL 60143).

Heliobond¹²: Photo-polymerising adhesive primer (Vivadent/Ivoclar, 23 Hanover Dr., St. Cathernves, Ont., Canada L2W 1A3).

Semi-Adjustable Hanau Articulator¹³: (Teledyne Hanau, Buffalo, NY, 14225).

Visible Curing Light Unit¹⁴: Caulk The Max (Caulk Dentsply, L.D. Caulk Division, Milford, DE).

Visible Curing Light Meter¹⁵: Cure Rite (Caulk Dentsply, L.D. Caulk Division, Milford, DE).

Electric Dryer¹⁶: 120V Handi-Dri, Lancer pacific, P.O. Box 819 Carlsbad, CA 92008).

10% Polyacrylic Acid¹⁷: (GC Corporation, Tokyo, Japan & distributed by GC America Inc.).

ED Primer¹⁸: Self-etching acidic primer (J Morita, USA Inc, California).
Intron Universal Testing Machine\textsuperscript{19} Model 4301 (Instron Corporations, 100 Royal Street, Canton, Mass, 02121).

Light Microscope\textsuperscript{20} (Bausche & Lomb, cat. No.31-35-47).

Hitachi S-2500\textsuperscript{21}: A scanning electric microscope (SEM) (Mito City, Japan).
MATERIALS AND METHODS

Bracket Types and Cements

The characteristics of the bracket bases and cements used in this study are summarized in Tables 2 and 3 (Page 39).

Table 2. BRACKET TYPES AND THEIR BASES

<table>
<thead>
<tr>
<th>BRACKET MATERIAL</th>
<th>NAME</th>
<th>MANUFACTURER</th>
<th>BASE TREATMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal</td>
<td>Speed</td>
<td>Strite Industries, Cambridge, Ontario.</td>
<td>60 gauge, microetched foil-mesh base</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td>American Orthodontics, Wisconsin.</td>
<td>Machined, integral, microetched base with mechanical undercuts</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Clarity</td>
<td>Unitek Corporation, Monrovia, California.</td>
<td>Polycrystalline ceramic bracket using crystal-like particles fused to the bracket base for mechanical retention</td>
</tr>
<tr>
<td></td>
<td>Transcend</td>
<td>Unitek Corporation, Monrovia, California.</td>
<td>Polycrystalline ceramic bracket using crystal-like particles fused to the bracket base for mechanical retention</td>
</tr>
<tr>
<td></td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brand Name</td>
<td>Fuji Ortho LC&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Transbond&lt;sup&gt;7&lt;/sup&gt;</td>
<td>Panavia21&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>GC America Inc Chicago, IL.</td>
<td>Unitek Corporation, Monrovia, California.</td>
<td>Kuraray Co., Ltd Osaka, Japan.</td>
</tr>
<tr>
<td>Description</td>
<td>Hybrid glass ionomer cement reinforced with composite</td>
<td>80% filled by weight, microfilled composite resin cement</td>
<td>77% filled by weight, low viscosity composite resin, containing 10-Methacryloyloxydecyl dihydrogen phosphate</td>
</tr>
<tr>
<td>Preparation</td>
<td>Powder mixed into liquid manually</td>
<td>One paste system</td>
<td>Catalyst and Universal paste incorporated into a dispensing unit and mixed manually</td>
</tr>
<tr>
<td>Polymerization Method</td>
<td>Photo-polymerized</td>
<td>Photo-polymerized</td>
<td>Auto-polymerized in the absence of oxygen</td>
</tr>
<tr>
<td>Fluoride Release</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Enamel Treatment</td>
<td>Either conditioned with 10% Polyacrylic Acid solution or no conditioning at all</td>
<td>Etching with 37% Orthophosphoric Acid followed by application of Heliobond (photo-polymerising adhesive primer)</td>
<td>ED Primer (Liquid A &amp; B) Applied to enamel surface, left for 60 seconds and air dried to leave a glossy surface</td>
</tr>
<tr>
<td>Dry Field</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Bracket Base Bonding Surface Area

The bonding surface-areas of the bracket bases used in the study were measured using a morphometric program (Digitel Image processing system, series 100, Digitel co., Brooklyn N.Y., 1988). Random samples of 10 brackets from each type were taken, and their mean base surface areas were recorded using the method described by MacColl (1995). The mean bonding surface area for each type of bracket was calculated and the results are recorded in Table 4.

Table 4. BRACKET BONDING BASE AREA IN MM²

<table>
<thead>
<tr>
<th>Bracket Type (N=10 Brackets)</th>
<th>Area in mm² +/- Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>7.35 +/- 0.18</td>
</tr>
<tr>
<td>Time</td>
<td>13.00 +/- 0.17</td>
</tr>
<tr>
<td>Clarity</td>
<td>11.66 +/- 0.22</td>
</tr>
<tr>
<td>Transcend 6000</td>
<td>10.53 +/- 0.19</td>
</tr>
</tbody>
</table>

Preparation of the Teeth

Bovine mandibular incisor teeth were collected from an abattoir. Following the removal of their roots on a band saw, the crowns were stored in distilled water in a freezer at −20°C until used. Prior to embedding in acrylic, the teeth were thawed in warm water and the pulp tissues were extirpated with a dental explorer. The empty pulp chamber of each tooth was rinsed with distilled water and then packed with moist cotton pledgets. Plastic cylinders (25 mm in diameter x 20 mm in depth) were filled to one third of their depth with auto-polymerizing acrylic resin and allowed to polymerize. The teeth were then placed on top of the hardened acrylic and secured with a piece of plastocene so that the labial surfaces faced upwards and were parallel to the horizontal plane. Auto-polymerizing acrylic resin was then poured around the tooth, leaving the labial surface exposed. Once the acrylic was fully polymerized, the embedded specimens were removed from their plastic cylinders. Immediately prior to bracket cementation, a flat surface was created on labial surface of each tooth by grinding it with water irrigated #180 and #600 grit Silicon Carbide (SiC) paper. Care was taken not to expose the underlying dentin. The teeth were then rinsed for 30 seconds in running distilled water and dried using a hair dryer. The brackets were bonded in groups of 12 in accordance with the protocols shown in Table 5 (Page 41).
### Table 5. Experimental Protocols

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>Adhesive</th>
<th>Enamel Treatment</th>
<th>Storage</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transbond</td>
<td>Conditioned, 37% phosphoric acid, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Panavia21</td>
<td>Self-etching Acidic Primer, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Conditioned, 10% Polyacrylic Acid, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Not-conditioned, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transbond</td>
<td>Conditioned, 37% phosphoric acid, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Panavia21</td>
<td>Self-etching Acidic Primer, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Conditioned, 10% Polyacrylic Acid, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Not-conditioned, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td><strong>Transcend 6000</strong></td>
<td>Transbond</td>
<td>Conditioned, 37% phosphoric acid, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Panavia21</td>
<td>Self-etching Acidic Primer, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Conditioned, 10% Polyacrylic Acid, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Not-conditioned, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td><strong>Clarity</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transbond</td>
<td>Conditioned, 37% phosphoric acid, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Panavia21</td>
<td>Self-etching Acidic Primer, dry</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Conditioned, 10% Polyacrylic Acid, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fuji Ortho LC</td>
<td>Not-conditioned, wet</td>
<td>Yes</td>
<td>12</td>
</tr>
</tbody>
</table>
Bonding Protocol

All of the specimens were bonded in the following manner regardless of the type of cement used. The clean flattened dry enamel surface was prepared as described previously. The cement was prepared according to the manufacturer’s instructions and was then applied to the bracket base with a plastic instrument. The bracket was then seated with its slot parallel with the incisal edge and held in position using the guide pin of a semi-adjustable Hanau articulator (Teledyne Hanau, Buffalo, NY, 14225). A stone (dental stone) cylinder weighing 610 grams attached to the upper member of the articulator was used to provide a standardized and constant force during bracket placement (MacColl, 1995). This enabled the investigator to use both hands to carefully remove the excess extruded bonding agent with a sharp explorer and, at the same time produce a consistently thin layer of cement (MacColl, 1995). The cements were then light cured, using a visible-light-curing unit, for 20 seconds on the mesial and distal sides of the bracket base, for a total of 40 seconds (Transbond and Fuji Ortho LC) or allowed to auto-polymerize (Panavia). The output of the light unit was measured after polymerizing every five specimens with a curing radiometer to insure a constant light intensity value of at least 380 mW/cm² (Rueggeberg et al., 1994).

Bonding Protocol for Transbond

The clean flattened dry enamel surface was conditioned with 37% orthophosphoric acid for 20 seconds and then rinsed with distilled water for 30 seconds and hot air dried with a hair drier. Heliobond bonding agent was brushed in a thin layer onto the conditioned enamel surface and light-cured for 10 seconds. The Transbond cement was applied to the bracket base with a plastic instrument, and the bracket placed near the center of the labial surface of the tooth. The cement was then photo-polymerized, using a visible-light-curing unit, for 20 seconds on the mesial and distal sides of the bracket, for a total of 40 seconds.

Bonding Protocol for Fuji Ortho LC

Conditioned (etched) and not-conditioned (not etched) bonding protocols were followed for Fuji Ortho LC cement. When the enamel surface was conditioned, it was conditioned by brushing 10% polyacrylic acid onto the labial surface. The conditioner was left undisturbed for 20 seconds and then rinsed thoroughly with distilled water for 30 seconds. In both
groups the enamel surface was not dried but was moistened with distilled water just before bonding. The Fuji Ortho LC\textsuperscript{5} cement was mixed following manufacturer's guidelines. One level spoonful of powder and two drops of liquid were dispensed on to a mixing pad. The powder was incorporated into liquid in two equal portions. The first portion was mixed into the liquid for 10 seconds. The second part was then added and mixed for another 10-15 seconds. The total mixing time did not exceed 20-25 seconds. The brackets were bonded to enamel surfaces as described in the bonding protocol section. Each mix was used to bond two brackets only. The cement was then polymerized for 40 second as described above.

**Bonding Protocol for Panavia21\textsuperscript{6}**

Prior to bracket bonding, the ED primer\textsuperscript{18} (self-etching acidic primer) was mixed and applied to the dry enamel surface and hot air dried after 60 seconds. Panavia21\textsuperscript{6} was dispensed using the two-paste delivery system and mixed in accordance with the manufacturer's instructions and then applied to bracket bonding surface. The bracket was then placed on the prepared tooth surface, excess cement removed and left to set undisturbed for 15 minutes before storage in distilled water.

**Storage**

Upon completion of bonding and curing procedures, each specimen was placed in a small self-capping plastic container in distilled water. A few crystals of thymol were added to prevent bacterial growth (Rueggeberg, 1991). The specimens were then placed in a humidor at 37° C for 24-hours or 180-days. The water and thymol solution was changed once a week for the specimens that were stored for 180-days.

**Shear Bond Strength Testing**

The specimens were shear tested to failure using an Instron Universal Testing Machine\textsuperscript{19} (model 4301, Intron Corporation, 100 Royal Street, Canton, Mass, 02021). Each specimen was clamped in a holding ring so that the bracket base was parallel to the direction of the force. The sharpened chisel blade suspended from the moving arm of the testing machine was placed at the bracket enamel interface just short of contact in an incisogingival direction. Using a one a Kilo-Newton (KN) compression cell and a crosshead speed of 0.5
mm/minute the bracket bases were shear tested to failure. The maximum force was recorded in Newtons (N) and converted to megapascals (MPa). Diagrams of the testing apparatus can be viewed in Mahal (2000) thesis, pages 77 and 78.

**Nature of Bond Failure**

The Adhesive Remnant Index (ARI) (Table 1- Page 34) was used to quantify the amount of cement left on the tooth following debonding of the bracket. (Artun and Bergland, 1984). The ARI scores were also used to define the sites of bond failure between the enamel, the cement, and the bracket base. The ARI consists of a 4-point scale of 0-3: a score of 0 indicates no cement left on the tooth, 1 indicates less than half of the cement left on the tooth, 2 indicates more than half of the cement left on the tooth, and 3 indicates all of the cement left on the tooth including a distinct impression of the bracket base.

The adhesive remnant index score was reported for each debonded specimen by examining the bracket bases and enamel surfaces under a light microscope\(^{20}\) at a magnification of x35.

**Inter and Intra-Operator Error Study on ARI**

To test for possible intra-operator error in assigning the ARI scores, 12 debonded specimens were selected and viewed under the light microscope\(^{20}\) by the principal investigator on two separate occasions. A second examiner also viewed the same specimens in order to assess for inter-operator reliability.

**Scanning Electron Microscopy (SEM)**

A cylindrical sample of each cement used in this study was prepared by following the manufacturer guidelines for mixing as described previously. The cylinders of each cement were obtained by placing the cement in a hole punched into a Polyvinyl Chloride (PVC) clear mouthguard material with thickness and diameter of 3 mm and photo-polymerized (Transbond\(^7\), Fuji Ortho LC\(^5\)) or auto-polymerized (Panavia21\(^6\)). The bases of these cylindrical cement samples were then polished with #180 grit, #600 grit and finally #4000 grit SiC paper\(^{10}\) on a water irrigated grinding wheel. These specimens and one of each bracket type with the bases facing up were mounted on an aluminum SEM stub. All the
specimens were then sputter coated with 3 nm of platinum in a Polaron E5100 SEM coating unit and viewed with a Hitachi-S-2500 SEM at an operating voltage of 10 kV (Sharma, 1999).

Scanning electron microscopy views of each specimen were obtained at x25, x100 and x1000 magnifications. The average cement particle size was determined using the x1000 magnification SEM images of each cement. The SEM micrograph of each bracket base was matched with the three cements at the same magnification. Visual analysis was made to investigate compatibility of each bracket base surface characteristic with the cement particle size.

Statistical Analysis
Descriptive statistics including the mean and standard deviation values of the SBS and ARI scores were calculated for each of the groups tested.

A one-way analysis of variance (ANOVA) test was used to determine the effect of bracket base design on the mean SBS. The one-way analysis of variance was also used to study the effect of the cement material on the mean ARI scores and the mean SBS. A two-way analysis of variance was used to determine the effect of long-term storage on mean SBS. This two-way analysis of variance was also used to study the effects of bracket base design, cement type and the interaction between these two variables on the mean SBS. Duncan’s multiple range test was used to group different cement materials with respect to SBS and ARI scores. This test was also used to group different bracket base designs with respect to the mean SBS. Multiple pair wise comparisons of the least square means were carried out to compare the mean SBS recorded with various bracket base-cement combinations.

A linear regression analysis was used to determine if there was any association between the SBS and ARI scores. Fischer's Exact test was used to determine the effect of long-term storage on the distribution of ARI scores. An un-weighted Kappa statistics was used to highlight inter-operator and intra-operator differences when assigning ARI scores. The statistical significance for all the tests was established at a 5% level. The SAS system was used for all the above analysis of the data (SAS 6.23, 1996, Cary, NC).
RESULTS

1. CLINICAL ACCEPTABILITY OF VARIOUS BRACKET BASE-CEMENT COMBINATIONS

The criteria for clinical acceptability was defined as ARI scores of 2-3 and mean shear bond strengths (SBS) in the range of 8±3 MPa. The mean ARI scores and the mean SBS values of all the bracket base-cement combinations tested after 1-day and 180-days of storage are summarized in Figure 1 (Page 48) and Figure 2 (Page 49).

i) 1-Day Storage Group

The mean SBS and the corresponding ARI scores for the various bracket base-cement combinations tested after 1-day of storage are summarized in Table 6 (Page 50). Of all the 16 bracket base-cement combinations tested after 1-day of storage 69% (11 out of 16) were clinically acceptable. Therefore, only 31% (5 out of 16) performed in unacceptable fashion. These were Speed-Panavia, Time-Panavia, Time-Fuji Ortho LC (not-conditioned), Transcend-Fuji Ortho LC (not-conditioned), Clarity-Fuji Ortho LC (not-conditioned) combinations. These combinations are highlighted in Table 6 (Page 50). These bracket base-cement combinations were deemed clinically unacceptable because of low SBS (less than 5 MPa) and/or low ARI scores (less than 2).

ii) 180-Days Storage Group

The mean SBS and the corresponding ARI scores for the various bracket base-cement combinations tested after 180-days of storage are summarized in Table 7 (Page 51). Of all the 12 combinations tested after 180-days of storage 83% (10 out of 12) were clinically acceptable and 17% (2 out of 12) of these combinations debonded in an unfavorable fashion. These were Speed-Panavia and Time-Panavia combinations that produced acceptable bond strengths but low ARI scores with most of the cement remaining on the bracket base after debonding. All of the bracket base-cement combinations tested after 180-days of storage produced clinically acceptable SBS. This increase in the clinical acceptability of the various bracket base-cement combinations after 180-days of storage was because of the omission of the combinations (brackets bonded to not-conditioned enamel using Fuji Ortho LC) that produced poor SBS and/or ARI scores in the 1-day storage group.
If the effects of time on clinical acceptability are compared between the same bracket base-cement combinations at the two storage times (i.e. eliminating the Fuji Ortho LC not-conditioned protocol), then it becomes evident that the storage time had no significant effect on the clinical acceptability. At both storage times, Speed-Panavia21 and Time-Panavia21 combinations performed poorly. Therefore, the clinical acceptability at time 1-day and 180-days of storage was 83% (10 out of 12 bracket base-cement combinations).
Figure 1: Mean ARI Scores for Various Bracket Base-Cement Combinations Tested After 1 and 180-Days of Storage

The horizontal black line indicates the acceptable ARI scores; in this study it was considered to be ≥ 2
Bracket Base-Cement Combinations, 1 and 180-Days of Storage

- Transbond
- Panavia
- Fuji (Cond)
- Fuji (No Cond)

Figure 2: Mean Shear Bond Strength (SBS) for Various Bracket Base-Cement Combinations Tested After 1 and 180-Days of Storage

The horizontal black lines represent the acceptable range for SBS; in this study it was considered to be 8±3 MPa
Table 6: Shear Bond Strength (SBS) and Adhesive Remnant Index (ARI) Scores Percent Distribution (1-Day of Storage)

<table>
<thead>
<tr>
<th>BRACKET TYPE</th>
<th>BONDING PROTOCOL</th>
<th>Transbond&lt;sup&gt;1&lt;/sup&gt; Conditioned with 37% Phosphoric acid, dry</th>
<th>Panavia&lt;sup&gt;2&lt;/sup&gt; Self-etching Acidic Primer, dry</th>
<th>Fuji Ortho LC&lt;sup&gt;3&lt;/sup&gt; Conditioned with 10% Polycrylic acid, wet</th>
<th>Fuji Ortho LC&lt;sup&gt;4&lt;/sup&gt; Not-conditioned, wet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SBS in MPa</td>
<td>11.69±2.3</td>
<td>9.34±1.20</td>
<td>11.79±2.2</td>
<td>6.47±3.13</td>
</tr>
<tr>
<td>Speed&lt;sup&gt;1&lt;/sup&gt;</td>
<td>ARI Score</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 17 33 50</td>
<td>18 0 0 0</td>
<td>0 25 50 25</td>
<td>42 0 58 0</td>
</tr>
<tr>
<td>Time&lt;sup&gt;1&lt;/sup&gt;</td>
<td>SBS in MPa</td>
<td>12.75±2.66</td>
<td>11.07±1.26</td>
<td>8.5±1.69</td>
<td>4.8±2.36</td>
</tr>
<tr>
<td></td>
<td>ARI Score</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 0 67 33</td>
<td>35 25 17</td>
<td>0 0 42 58</td>
<td>42 22 33 0</td>
</tr>
<tr>
<td>Transcend&lt;sup&gt;2&lt;/sup&gt;</td>
<td>SBS in MPa</td>
<td>15.33±4.86</td>
<td>10.63±1.57</td>
<td>10.30±2.18</td>
<td>7.77±1.73</td>
</tr>
<tr>
<td></td>
<td>ARI Score</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 0 17 83</td>
<td>0 0 0 10</td>
<td>0 0 0 10</td>
<td>78 8 8 8</td>
</tr>
<tr>
<td>Clarity&lt;sup&gt;1&lt;/sup&gt;</td>
<td>SBS in MPa</td>
<td>13.38±4.27</td>
<td>9.47±3.06</td>
<td>9.91±2.90</td>
<td>5.09±1.9</td>
</tr>
<tr>
<td></td>
<td>ARI Score</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 17 17 64</td>
<td>0 17 25 58</td>
<td>8 0 25 67</td>
<td>92 0 0 8</td>
</tr>
</tbody>
</table>

The bracket base-cement combinations with ARI and/or SBS that are highlighted and underlined are clinically unacceptable.
Table 7. Shear Bond Strength (SBS) and Adhesive Remnant Index (ARI) Scores Percent Distribution (180-Days of Storage)

<table>
<thead>
<tr>
<th>BRACKET TYPE</th>
<th>BONDING PROTOCOL</th>
<th>Transbond&lt;sup&gt;1&lt;/sup&gt; Conditioned with 37% phosphoric acid, dry</th>
<th>Panavia21&lt;sup&gt;2&lt;/sup&gt; Self-etching acidic primer, dry</th>
<th>Fuji Ortho LC&lt;sup&gt;3&lt;/sup&gt; Conditioned with 10% Polyacrylic acid, wet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SBS in MPa</td>
<td>14.05±2.84</td>
<td>8.77±1.32</td>
<td>12.69±2.13</td>
</tr>
<tr>
<td>Speed</td>
<td>ARI Score Distribution %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 25 33 42</td>
<td>28 14 8 0</td>
<td>0 17 25 58</td>
</tr>
<tr>
<td>Time&lt;sup&gt;3&lt;/sup&gt;</td>
<td>SBS in MPa</td>
<td>12.1±3.23</td>
<td>9.61±13.5</td>
<td>8.44±1.69</td>
</tr>
<tr>
<td></td>
<td>ARI Score Distribution %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 0 17 83</td>
<td>0 66 17 17</td>
<td>0 0 8 92</td>
</tr>
<tr>
<td>Transcend&lt;sup&gt;2&lt;/sup&gt;</td>
<td>SBS in MPa</td>
<td>14.76±4.56</td>
<td>8.32±1.5</td>
<td>9.84±2.07</td>
</tr>
<tr>
<td></td>
<td>ARI Score Distribution %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>0 0 8 92</td>
<td>0 0 0 100</td>
<td>0 0 0 100</td>
</tr>
<tr>
<td>Charly&lt;sup&gt;1&lt;/sup&gt;</td>
<td>SBS in MPa</td>
<td>11.86±3.35</td>
<td>8.64±2.46</td>
<td>10.13±2.58</td>
</tr>
<tr>
<td></td>
<td>ARI Score Distribution %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td></td>
<td>Distribution %</td>
<td>8 8 0 84</td>
<td>0 0 0 100</td>
<td>0 0 0 100</td>
</tr>
</tbody>
</table>

The bracket base-cement combinations with ARI scores that are highlighted and underlined are clinically unacceptable.
2. COMPARISON OF MEAN SBS (1-DAY OF STORAGE)

i) Comparison of Mean SBS of Various Bracket Base-Cement Combinations (1-Day of Storage)

The mean SBS after 1-day of storage of 16 different bracket base-cement combinations were compared using a two-way ANOVA test. In this test the mean SBS was the dependent variable and the bracket base types, cement materials, and the bracket base-cement combinations were the sources of variation. P values of less than 0.05 were recorded for brackets (p=0.0071) and cements (p=0.0001), which demonstrate that these variables had a significant effect on mean SBS (Table 8). The interaction between the bracket base and the cement material was also significant at (p=0.0103). The result of this test showed that there was a statistically significant difference between the SBS of the 16 various bracket base-cement combinations tested after 1-day of storage (p=0.0103). (Table 8)

Table 8: Two-way Analysis of Variance for Mean SBS of 4 Bracket Bases and 4 Cements/Bonding Protocols (1-day of storage)

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracket</td>
<td>3</td>
<td>87.07</td>
<td>29.034</td>
<td>0.0071</td>
</tr>
<tr>
<td>Cement</td>
<td>3</td>
<td>1274.664</td>
<td>424.888</td>
<td>0.0001</td>
</tr>
<tr>
<td>Bracket*Cement</td>
<td>9</td>
<td>157.102</td>
<td>17.455</td>
<td>0.0103</td>
</tr>
</tbody>
</table>

P<0.05 denotes statistical significance
df= degrees of freedom

Multiple pairwise comparisons of least square means were carried out to perform pairwise comparisons between the mean SBS of 16 bracket base-cement combinations tested after 1-day of storage. The results of this test are summarized in Table 14 (Page 57) and the combinations that are significantly different from each other are denoted with ** symbol.
ii) Comparison of Mean SBS of Various Bracket Bases (1-Day of Storage)

A Duncan’s Multiple Range test was carried out to identify the bracket bases that resulted in different mean SBS. To perform this test, the mean SBS of each bracket base type was calculated by pooling and averaging the mean SBS resulting from all the cement types for each bracket base type. Then the mean SBS of each bracket base type was compared with the other three bracket base types. The mean SBS with the same letter as indicated by the Duncan’s grouping are not statistically significantly different. (Table 9) Therefore, there was no significant difference between the bond strengths recorded using Speed, Time or Clarity bracket bases. Of all the bracket bases tested after 1-day of storage, Transcend bracket bases had the highest mean SBS and performed significantly differently than the other three bracket bases. Speed, Time and Clarity bracket bases had mean SBS that were statistically similar.

Table 9: Duncan’s Grouping of the Mean SBS for Different Bracket Base Types (1-day of storage, holding the cements constant)

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>N</th>
<th>Mean SBS (MPa)</th>
<th>Duncan grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>48</td>
<td>9.83</td>
<td>B</td>
</tr>
<tr>
<td>Time</td>
<td>48</td>
<td>9.27</td>
<td>B</td>
</tr>
<tr>
<td>Transcend</td>
<td>48</td>
<td>11.0</td>
<td>A</td>
</tr>
<tr>
<td>Clarity</td>
<td>48</td>
<td>9.46</td>
<td>B</td>
</tr>
</tbody>
</table>

Groups with different letters are significantly different from each other.

iii) Comparison of Mean SBS of Various Cements (1-Day of Storage)

A one-way ANOVA test was carried out in order to compare the mean SBS resulting from different cements and independent of bracket base design. The results showed that there was a statistically significant difference between the mean SBS recorded for each cement material after 1-day of storage (p=0.0001). Then a Duncan’s Multiple Range test was performed to identify the cement materials that had significantly different mean SBS (Table 10- Page 54).
Table 10: Duncan’s Grouping of Mean SBS for Different Cement Material (1-day of storage, holding the brackets constant)

<table>
<thead>
<tr>
<th>Cement Material</th>
<th>N</th>
<th>Mean SBS (MPa)</th>
<th>Duncan grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transbond</td>
<td>48</td>
<td>13.29</td>
<td>A</td>
</tr>
<tr>
<td>Panavia</td>
<td>48</td>
<td>10.13</td>
<td>B</td>
</tr>
<tr>
<td>Fuji Ortho (Cond)</td>
<td>48</td>
<td>10.13</td>
<td>B</td>
</tr>
<tr>
<td>Fuji Ortho (no Cond)</td>
<td>48</td>
<td>6.03</td>
<td>C</td>
</tr>
</tbody>
</table>

Groups with different letters are significantly different from each other.

The mean SBS with the same letter as indicated by the Duncan’s grouping are not statistically significantly different (Table 10). The results showed that there was no significant difference between the bond strengths recorded using Panavia2 or Fuji Ortho LC (conditioned). Of all the cements tested after 1-day of storage, Transbond cement produced the highest mean SBS and performed significantly differently than the other three cements. Fuji Ortho LC (not-conditioned) resulted in the lowest mean SBS and performed significantly differently than all the other cements.

3. COMPARISON OF MEAN SBS (180-DAYS OF STORAGE)

i) Comparison of Mean SBS of Various Bracket Base-Cement Combinations (180-Days of Storage)

The mean SBS after 180-days of storage of 12 different bracket base cement combinations were compared using a 2-way ANOVA test. In this test the mean SBS was the dependent variable and the bracket base types, cement materials, and the bracket base-cement combinations were the sources of variation. P values of less than 0.05 were recorded for brackets (p=0.0157) and cements (p=0.0001) thus these variables had a significant effect on the mean SBS (Table 11- Page 55). The interaction between the bracket base and the cement material was also significant at (p=0.0071). The result of this test showed that there was a statistically significant difference between the mean SBS of the 12 various bracket base-cement combinations tested after 180-days of storage (p=0.0071). (Table 11- Page 55)
Table 11: Two-way Analysis of Variance for SBS of 4 Bracket Bases and 4 Cements/Bonding Protocols (180-days of storage)

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracket</td>
<td>3</td>
<td>72.47</td>
<td>24.16</td>
<td>0.016</td>
</tr>
<tr>
<td>Cement</td>
<td>2</td>
<td>473.13</td>
<td>236.56</td>
<td>0.0001</td>
</tr>
<tr>
<td>Bracket*Cement</td>
<td>6</td>
<td>125.48</td>
<td>20.91</td>
<td>0.0071</td>
</tr>
</tbody>
</table>

P<0.05 denotes statistical significance
df=degrees of freedom

Multiple pairwise comparisons of least square means were carried out to perform pair wise comparisons between the mean SBS of 12 bracket base-cement combinations tested after 180-days of storage. The results of this test are summarized in Table 15 (Page 58) and the combinations that are significantly different from each other are denoted with ** symbol.

A Duncan’s Multiple Range Test was carried out to identify the brackets that resulted in different mean SBS. To perform this test, the mean SBS of each bracket base type was calculated by pooling and averaging the mean SBS resulting from all the cement types for each bracket base types. Then the mean SBS of each bracket base type was compared with the other three bracket base types. The mean SBS with the same letters as indicated by the Duncan’s grouping are not significantly different (Table 12). Therefore, there was no significant difference between the bond strengths recorded using Transcend, Time or Clarity bracket bases. Speed bracket bases yielded the highest mean SBS which was significantly greater than the mean SBS resulting from using the other three bracket base types: Time, Transcend and Clarity.

Table 12: Duncan’s Grouping of the Mean SBS for Different Bracket Base Types (180-days of storage, holding the cements constant)

<table>
<thead>
<tr>
<th>Bracket tested</th>
<th>N</th>
<th>Mean SBS (MPa)</th>
<th>Duncan grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>36</td>
<td>11.84</td>
<td>A</td>
</tr>
<tr>
<td>Time</td>
<td>36</td>
<td>10.05</td>
<td>B</td>
</tr>
<tr>
<td>Transcend</td>
<td>36</td>
<td>10.97</td>
<td>AB</td>
</tr>
<tr>
<td>Clarity</td>
<td>36</td>
<td>10.2</td>
<td>B</td>
</tr>
</tbody>
</table>

Groups with different letters are significantly different from each other.
ii) Comparison of Mean SBS of Various Cements (180-Day of Storage)

A one-way ANOVA test was carried out in order to compare mean SBS resulting from different cements and independent of bracket base design. The results of this test showed that there was a statistically significant difference between the mean SBS produced by each cement material after 180-days of storage ($p=0.0001$). Then a Duncan’s Multiple Range test was used to identify the cements that were different with respect to recorded mean SBS. (Table 13)

Table 13: Duncan’s Grouping of the Mean SBS for Different Cement Material
(180-days of storage, holding the brackets constant)

<table>
<thead>
<tr>
<th>Cement Material</th>
<th>N</th>
<th>Mean SBS (MPa)</th>
<th>Duncan grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transbond</td>
<td>48</td>
<td>13.19</td>
<td>A</td>
</tr>
<tr>
<td>Panavia</td>
<td>48</td>
<td>10.27</td>
<td>B</td>
</tr>
<tr>
<td>Fuji Ortho (Cond)</td>
<td>48</td>
<td>8.83</td>
<td>C</td>
</tr>
</tbody>
</table>

Groups with different letters are significantly different from each other.

The mean SBS with different letters as indicated by the Duncan’s grouping are significantly different (Table 13). Therefore, there were significant differences between the bond strengths recorded using Transbond, Panavia21 and Fuji Ortho LC (conditioned) cements. Of all the cements tested after 180-days of storage, Transbond cement produced the highest mean SBS and performed significantly differently than the other two cements. Fuji Ortho LC (conditioned) cement resulted in the lowest mean SBS and performed significantly differently than Transbond and Panavia 21 cements.
### Table 14: The Pairwise Comparison of Mean SBS of Various Bracket Base-Cement Combinations (1-Day of Storage)

<table>
<thead>
<tr>
<th>GROUPS</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>**</td>
<td>**</td>
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</table>

** denotes significance at p<0.05

**Legend**

1. Clarity-Fuji Ortho LC (not-conditioned)
2. Clarity-Fuji Ortho LC (conditioned)
3. Clarity-Panavia21
4. Clarity-Transbond
5. Speed-Fuji Ortho LC (not-conditioned)
6. Speed-Fuji Ortho LC (conditioned)
7. Speed-Panavia21
8. Speed-Transbond
9. Time-Fuji Ortho LC (not-conditioned)
10. Time-Fuji Ortho LC (conditioned)
11. Time-Panavia21
12. Time-Transbond
13. Transcend-Fuji Ortho LC (not-conditioned)
14. Transcend- Fuji Ortho LC (conditioned)
15. Transcend-Panavia21
16. Transcend-Transbond
Table 15: The Pairwise Comparison of Mean SBS of Various Bracket Base-Cement Combinations (180-Days of Storage)

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** denotes Significance at P<0.05

Legend
1 Clarity-Fuji Ortho LC (conditioned)
2 Clarity-Panavia21
3 Clarity-Transbond
4 Speed-Fuji Ortho LC (conditioned)
5 Speed-Panavia21
6 Speed-Transbond
7 Time-Fuji Ortho LC (conditioned)
8 Time-Panavia21
9 Time-Transbond
10 Transcend-Fuji Ortho LC (conditioned)
11 Transcend-Panavia21
12 Transcend-Transbond
4. **THE EFFECT OF LONG-TERM STORAGE ON MEAN SBS OF VARIOUS BRACKET BASE-CEMENT COMBINATIONS**

In summary, the storage time of 180-days had a statistically significant effect on the mean SBS of 25% (3 out of 12) of the bracket base-cement combinations tested. 8% (1 out of 12) of the samples showed statistically significant increases in SBS while 17% (2 out of 12) demonstrated reductions in SBS. However, these changes were not clinically significant.

i) **Speed Brackets Bonded with Different Cements**

Long-term storage significantly increased the mean SBS of Speed brackets bonded with Transbond cement \((p = 0.037)\). Long-term storage, however, had no statistically significant effect on the mean SBS of Speed brackets bonded with Panavia21 \((p = 0.269)\) or Fuji Ortho LC (conditioned) cements \((p = 0.32)\). The mean SBS of Speed brackets bonded with Panavia21 decreased slightly after 180-days of storage. The mean SBS of Speed brackets bonded with Fuji Ortho LC (conditioned) cement increased slightly when tested after 180-days of storage. (Table 16- Page 63, Figure 3)

**Figure 3: Comparison of Mean SBS after 1 and 180-Days of Storage for Speed Brackets Bonded with Different Cements**

Legend for Figures 3-6:  
Panavia= Panavia21  
GI= Fuji Ortho LC (conditioned)
ii) Time Brackets Bonded with Different Cements

Long-term storage significantly decreased the mean SBS of Time brackets bonded with Panavia21 cement ($p=0.012$). However, long-term storage had no significant effect on the mean SBS of Time brackets bonded with Transbond ($p=0.596$) or Fuji Ortho LC (conditioned) cement ($p=0.928$). The mean SBS of Time brackets bonded with Transbond cement decreased slightly after 180-days of storage and the mean SBS of those bonded with Fuji Ortho LC (conditioned) cement was basically unchanged. (Table 16- Page 63, Figure 4)

Figure 4: Comparison of Mean SBS after 1 and 180-Days of Storage for Time Brackets Bonded with Different Cements
iii) Transcend Brackets Bonded with Different Cements.
Long-term storage significantly decreased the mean SBS of Transcend brackets bonded with Panavia21 cement ($p = 0.001$). Long-term storage, however, had no significant effect on the mean SBS of Transcend brackets bonded with Transbond ($p = 0.768$) or Fuji Ortho LC (conditioned) cements ($p = 0.597$). The mean SBS of Transcend brackets bonded with Transbond or Fuji Ortho LC (conditioned) was reduced slightly after 180-days of storage. These changes were not statistically or clinically significant. (Table 16- Page 63, Figure 5)

Figure 5: Comparison of Mean SBS after 1 and 180-Days of Storage for Transcend Brackets Bonded with Different Cements
iv) Clarity Brackets Bonded with Different Cements.
Long-term storage had no significant effect on the mean SBS of Clarity brackets bonded with the three different cements. The mean SBS of Clarity brackets bonded with Transbond (p=0.343) or Panavia21 (p=0.473) decreased slightly after 180 days. Clarity brackets bonded with Fuji Ortho LC (conditioned) showed a slight increase in mean SBS after 180-days of storage (p=0.844). (Table 16- Page 63, Figure 6)

Figure 6: Comparison of Mean SBS after 1 and 180-Days of Storage for Clarity Brackets Bonded with Different Cements
Table 16: Comparison of the Mean Shear Bond Strengths (SBS)
(1 and 180-Days of Storage)

<table>
<thead>
<tr>
<th>Bonding Protocol</th>
<th>Transbond&lt;sup&gt;7&lt;/sup&gt; Conditioned with 37% Phosphoric Acid, dry</th>
<th>Panavia21&lt;sup&gt;6&lt;/sup&gt; Self-etching Acidic primer, dry</th>
<th>Fuji Ortho LC&lt;sup&gt;5&lt;/sup&gt; Conditioned with 10% Polyacrylic Acid, wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracket Type</td>
<td>1-day Storage</td>
<td>180-days Storage</td>
<td>P value</td>
</tr>
<tr>
<td>Speed&lt;sup&gt;4&lt;/sup&gt;</td>
<td>11.69±2.3</td>
<td>14.85±2.84</td>
<td>0.037</td>
</tr>
<tr>
<td>Time&lt;sup&gt;3&lt;/sup&gt;</td>
<td>12.75±2.66</td>
<td>12.1±3.23</td>
<td>0.596</td>
</tr>
<tr>
<td>Transcend&lt;sup&gt;2&lt;/sup&gt;</td>
<td>15.33±4.86</td>
<td>14.76±4.56</td>
<td>0.768</td>
</tr>
<tr>
<td>Clarity&lt;sup&gt;1&lt;/sup&gt;</td>
<td>13.38±4.27</td>
<td>11.86±3.35</td>
<td>0.343</td>
</tr>
</tbody>
</table>

P<0.05 denotes statistical significance

Long-term storage had a statistically significant effect on the shear bond strength of bracket base-cement combinations that are highlighted.
5. ARI SCORES DISTRIBUTION AFTER 1-DAY OF STORAGE

The mean ARI scores for various bracket base-cement combinations tested after 1-day of storage are summarized in Table 17.

Table 17: Mean ARI Scores for Various Bracket Base-Cement Combinations (1-day of storage)

<table>
<thead>
<tr>
<th>BONDING PROTOCOL</th>
<th>Transbond Cond*, dry</th>
<th>Panavia21 Acidic Primer, dry</th>
<th>Fuji Ortho LC Cond**, wet</th>
<th>Fuji Ortho LC Not-Cond***, wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRACKET TYPE</td>
<td>Mean ARI Score ± SD</td>
<td>Mean ARI Score ± SD</td>
<td>Mean ARI Score ± SD</td>
<td>Mean ARI Score ± SD</td>
</tr>
<tr>
<td>Speed</td>
<td>2.33 ± 0.78</td>
<td>0</td>
<td>2.0 ± 0.65</td>
<td>1.0 ± 1.04</td>
</tr>
<tr>
<td>Time</td>
<td>2.33 ± 0.49</td>
<td>1.58 ± 0.79</td>
<td>2.58 ± 0.51</td>
<td>0.92 ± 0.90</td>
</tr>
<tr>
<td>Transcend</td>
<td>2.83 ± 0.39</td>
<td>3.0 ± 0</td>
<td>3.0 ± 0</td>
<td>0.5 ± 1</td>
</tr>
<tr>
<td>Clarity</td>
<td>2.5 ± 0.80</td>
<td>2.42 ± 0.79</td>
<td>2.5 ± 0.90</td>
<td>0.25 ± 0.87</td>
</tr>
<tr>
<td>Mean ARI Scores</td>
<td>2.45</td>
<td>1.75</td>
<td>2.52</td>
<td>0.67</td>
</tr>
</tbody>
</table>

SD= Standard Deviation
Sample size=12
Storage time=1 day
*Conditioned with 37% Phosphoric Acid
**Conditioned with 10% Polyacrylic Acid
***Enamel surface not conditioned

Bracket bases bonded with Transbond and Fuji Ortho LC (conditioned) cements demonstrated the most favourable ARI scores when debonded after 1-day of storage.

Comparison of ARI Scores Associated with Various Cements (1-Day of Storage)

A one-way ANOVA test was carried out in order to compare the ARI scores resulting from different cements and independent of bracket base design. The results of this test showed that there was a statistically significant difference between the ARI scores produced by
different cements after 1-day of storage (p=0.0001). A Duncan’s Multiple Range test was then used to identify the cements that were different with respect to ARI scores. The results of this test are summarized in Table 18.

Table 18: Duncan’s Grouping of the ARI Scores Associated with Different Cement Materials (1-day of storage, holding the brackets constant)

<table>
<thead>
<tr>
<th>Cement Material</th>
<th>N</th>
<th>Mean ARI Score</th>
<th>Duncan grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transbond</td>
<td>48</td>
<td>2.45</td>
<td>A</td>
</tr>
<tr>
<td>Fuji Ortho (Cond)</td>
<td>48</td>
<td>2.52</td>
<td>A</td>
</tr>
<tr>
<td>Panavia 21</td>
<td>48</td>
<td>1.75</td>
<td>B</td>
</tr>
<tr>
<td>Fuji Ortho (no Cond)</td>
<td>48</td>
<td>0.67</td>
<td>C</td>
</tr>
</tbody>
</table>

Groups with different letters are significantly different from each other.

The mean ARI Scores with different letters as indicated by the Duncan’s grouping are significantly different (Table 18). There were no significant differences between the mean ARI scores recorded using Transbond, Fuji Ortho LC (conditioned) cements. This indicates that these two cements debonded in a similar fashion leaving more than half of the cement on the enamel. Panavia21 cement produced significantly different mean ARI scores than other cements. After debonding brackets bonded with Panavia21 less than half of the cement was left on the tooth. Of all the cements tested after 1-day of storage, Fuji Ortho LC (not conditioned) produced significantly different ARI scores than the other cements. Fuji Ortho LC (not conditioned) produced the poorest ARI scores and less than half of the cement was left on enamel after debonding brackets bonded with Fuji Ortho LC (not conditioned).

6. THE MEAN ARI SCORES FOR VARIOUS BRACKET BASE-CEMENT COMBINATIONS (1-DAY OF STORAGE)

   i) The Mean ARI Scores for Brackets Bonded with Transbond (1-day of storage)

The mean ARI scores for brackets bonded with Transbond cement ranged from 2.33 to 2.83. These scores indicate that failures for all the bracket base types bonded with Transbond cement occurred at the bracket base-cement interface with more than half of the cement remaining on the tooth. These results indicate that all bracket base types cemented with
Transbond resulted in clinically acceptable (ARI≥2) bond failure location, which was identified at bracket base-cement interface with most of the cement remaining on the enamel. (Tables 6 and 17- Pages 50 and 64)

ii) The Mean ARI Scores for Brackets Bonded with Panavia21 (1-day of storage)
The mean ARI scores for bracket bases bonded with Panavia21 cement range from 0 to 3. Speed and Transcend brackets bonded with Panavia21 produced the lowest and the highest ARI scores respectively. These scores indicate that failures for Transcend (ARI=3) and Clarity brackets (ARI=2.42) occurred at bracket base-cement interface with more than half of the cement remaining on the tooth. The Speed brackets bonded with Panavia 21 cement produced the poorest ARI scores (ARI=0) with all the cement remaining on the bracket base. Time brackets bonded with Panavia21 also resulted in poor ARI scores (ARI=1.58) with most of the cement remaining on the bracket base after debonding. (Tables 6 and 17- Pages 50 and 64)

iii) The Mean ARI Scores for Brackets Bonded with Fuji Ortho LC (conditioned) (1-day of storage)
The mean ARI scores for brackets bonded with Fuji Ortho LC (conditioned) cement ranged from 2 to 3 with Speed and Transcend brackets producing the lowest and the highest ARI scores respectively. These scores indicate that failures for Transcend (ARI=3), Time (ARI=2.58), Clarity (ARI=2.42) and Speed brackets (ARI=2.0) were all favourable and occurred at the bracket base-cement interface with greater than half of the cement remaining on the tooth. (Tables 6 and 17- Pages 50 and 64)

iv) The Mean ARI Scores for Brackets Bonded with Fuji Ortho LC (not-conditioned) (1-day of storage)
The mean ARI scores for brackets bonded with Fuji Ortho LC (not-conditioned) cement ranged from 0.5-0.92. Therefore, the mean ARI scores for all the bracket types bonded with Fuji Ortho LC (not-conditioned) were all unfavourable and most of the cement was left on the bracket base after debonding. (Tables 6 and 17- Pages 50 and 64)
7. **ARI SCORES DISTRIBUTION (180-DAYS OF STORAGE)**

The mean ARI scores for various bracket base-cement combinations tested after 180-days of storage are summarized in Table 19.

**Table 19: Mean ARI Scores for Various Bracket Base-Cement Combinations (180-days of storage)**

<table>
<thead>
<tr>
<th>BONDING PROTOCOL</th>
<th>Transbond Cond*, dry</th>
<th>Panavia 21 Acidic Primer, dry</th>
<th>Fuji Ortho LC Cond**, wet</th>
<th>Mean ARI Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRACKET TYPE</td>
<td>Mean ARI Score ± SD</td>
<td>Mean ARI Score ± SD</td>
<td>Mean ARI Score ± SD</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>2.17 ± 0.83</td>
<td>0.33 ± 0.65</td>
<td>2.42 ± 0.79</td>
<td>1.63</td>
</tr>
<tr>
<td>Time</td>
<td>2.83 ± 0.39</td>
<td>1.5 ± 0.80</td>
<td>2.92 ± 0.29</td>
<td>2.42</td>
</tr>
<tr>
<td>Transcend</td>
<td>2.92 ± 0.29</td>
<td>3.0 ± 0</td>
<td>3 ± 0</td>
<td>2.97</td>
</tr>
<tr>
<td>Clarity</td>
<td>2.58 ± 1.0</td>
<td>3.0 ± 0</td>
<td>3 ± 0</td>
<td>2.86</td>
</tr>
<tr>
<td>Mean ARI Score</td>
<td>2.62</td>
<td>1.95</td>
<td>2.8</td>
<td></td>
</tr>
</tbody>
</table>

SD= Standard Deviation  
Sample size=12  
Storage time=1 day  
*Conditioned with 37% Phosphoric Acid  
**Conditioned with 10% Polyacrylic Acid

Bracket bases bonded with Transbond and Fuji Ortho LC (conditioned) cement demonstrated the most favourable ARI scores when debonded after 180-days of storage.

**Comparison of ARI Scores Associated with Various Cements (180-Days of Storage)**

A one-way ANOVA test was carried out in order to compare the ARI scores resulting from different cements and independent of bracket base design. The results of this test showed
that there was a statistically significant difference between the ARI scores produced by different cements after 180-days of storage (p=0.0001). Then a Duncan’s Multiple Range test was performed to identify the cements that were different with respect to ARI scores. The results of this test are summarized in Table 20.

Table 20: Duncan’s Grouping of the ARI Scores Associated with Different Cement Materials (180-days of storage, holding the brackets constant)

<table>
<thead>
<tr>
<th>Cement Material</th>
<th>N</th>
<th>Mean ARI Score</th>
<th>Duncan grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transbond</td>
<td>48</td>
<td>2.63</td>
<td>A</td>
</tr>
<tr>
<td>Fuji Ortho (Cond)</td>
<td>48</td>
<td>2.83</td>
<td>A</td>
</tr>
<tr>
<td>Panavia 21</td>
<td>48</td>
<td>1.96</td>
<td>B</td>
</tr>
</tbody>
</table>

Groups with different letters are significantly different from each other.

The mean ARI scores with different letters (Table 20) as indicated by the Duncan’s grouping are significantly different. The results show that there were no significant differences between the mean ARI scores recorded using Transbond, Fuji Ortho LC (conditioned) cements. This indicates that these two cements debonded in a similar fashion leaving more than half of the cement on the tooth. Panavia21 cement produced significantly different mean ARI scores and less than half of the cement was left on the tooth after debonding.

8. THE MEAN ARI SCORES FOR VARIOUS BRACKET BASE-CEMENT COMBINATIONS (180-DAYS OF STORAGE)

i) The Mean ARI Scores for Brackets Bonded with Transbond (180-days of storage)

The mean ARI scores for brackets bonded with Transbond cement ranged from 2.16 to 2.92. These scores indicate that failures for all the bracket base types bonded with Transbond cement occurred at the bracket base-cement interface with more than half of the cement remaining on the tooth. These results indicate that all bracket base types cemented with Transbond resulted in clinically acceptable (ARI≥2) bond failure locations that were
identified at bracket base-cement interface with most of the cement remaining on the tooth surface. (Tables 7 and 19- Pages 51 and 67)

ii) The Mean ARI Scores for Brackets Bonded with Panavia21 (180-days of storage)
The mean ARI scores for brackets bonded with Panavia21 cement ranged from 0.3 to 3 with Speed brackets producing the lowest ARI score and Transcend and Clarity brackets bonded with Panavia21 producing the highest ARI scores. The mean ARI score for the Time brackets bonded with Panavia21 was 1.5 indicating that most of the cement was left on the bracket base after debonding. (Tables 7 and 19- Pages 51 and 67)

iii) The Mean ARI Scores for Brackets Bonded with Fuji Ortho LC (conditioned) (180-days of storage)
The mean ARI scores for brackets bonded with Fuji Ortho LC (conditioned) cement ranged from 2.4 to 3. Bond failures for all bracket base types bonded with Fuji Ortho LC (conditioned) were all favourable and occurred at the bracket base-cement interface with more than half (Speed and Time brackets) or all of the cement (Transcend and Clarity brackets) remaining on the tooth after debonding. (Tables 7 and 19- Pages 51 and 67)
9. THE EFFECT OF LONG-TERM STORAGE ON THE FREQUENCY OF ARI SCORES DISTRIBUTION

Table 21 (Page 73) includes a summary of ARI scores distribution for each bracket base-cement combination. The results of the two-tail Fischer’s Exact test comparing the ARI scores distribution after 1 and 180-days of storage are also recorded in this table.

i) Speed Brackets Bonded with Transbond
A two-tail Fischer’s Exact test showed no significant differences between the ARI scores at times of 1 and 180-days of storage when Speed brackets were bonded with the Transbond cement. The ARI scores for both the 1 and 180-day storage groups ranged from 1 to 3 with more than half of the scores being 2 and 3. (Table 21, Page 73)

ii) Speed Brackets Bonded with Panavia21
A two-tail Fischer’s Exact test showed a significant difference between the ARI scores at times of 1 and 180-days of storage when Speed brackets were bonded with Panavia21 cement. The ARI scores after 1-day of storage were all 0, however, after 180-days of storage a significant shift was noted in the distribution of the ARI scores ($p<0.001$). After 180-days of storage the ARI scores ranged from 0 to 2 with 76% of the scores being 0. (Table 21, Page 73)

iii) Speed Brackets Bonded with Fuji Ortho LC (conditioned)
A two-tail Fischer’s Exact test showed a significant difference between the ARI scores at times 1 and 180-days of storage when Speed brackets were bonded with Fuji Ortho LC (conditioned) cement ($p<0.001$). The ARI scores after 1-day of storage ranged from 1 to 3 with the majority of scores being 2. After 180-days of storage there was a significant change in the ARI scores distribution so that the range was 1 to 3 with the majority of scores being 3. (Table 21, Page 73)
iv) **Time Brackets Bonded with Transbond**
A two-tail Fischer's Exact test showed a significant difference between the ARI scores at times of 1 and 180-days of storage when Time brackets were bonded with Transbond cement (p<0.001). The ARI scores ranged from 2 to 3 after both the 1 and 180-days storage periods. For the 1-day storage group 67% of the ARI scores were 2 and for the 180-days storage group 83% of the ARI scores were 3. (Table 21- Page 73)

v) **Time Brackets Bonded with Panavia21**
A two-tail Fischer's Exact test showed a significant difference between the ARI scores at time 1 and 180-days of storage when Time brackets were bonded with Panavia21 cement. The ARI scores for both storage times ranged from 1 to 3. (Table 21- Page 73)

vi) **Time Brackets Bonded with Fuji Ortho LC (conditioned)**
A two-tail Fischer's Exact test showed a significant difference between the ARI scores at times of 1 and 180-days of storage when Time brackets were bonded with Fuji Ortho LC (conditioned) cement (p<0.001). The ARI scores for both storage times ranged from 2 to 3, however 92% of the ARI scores were 3 for the 180-days storage group as compared to 58% ARI scores of 3 for the 1-day storage group. (Table 21- Page 73)

vii) **Transcend Brackets Bonded with Transbond**
A two-tail Fischer's Exact test showed no significant differences between the ARI scores at times of 1 and 180-days of storage when Transcend brackets were bonded with Transbond cement. The ARI scores for both storage times ranged from 2 to 3, with more than 50% of the scores being 3 for both of the storage times. (Table 21- Page 73)

viii) **Transcend Brackets Bonded with Panavia21**
A two-tail Fischer's Exact test was not performed for this combination since the ARI scores for both of the storage times were all 3. (Table 21- Page 73)
ix) **Transcend Brackets Bonded with Fuji Ortho LC (conditioned)**
The two-tail Fischer’s Exact test was not performed for this combination since the ARI scores for both of the storage times were all 3. (Table 21- Page 73)

x) **Clarity Brackets Bonded with Transbond**
A two-tail Fischer’s Exact test showed a significant difference between the ARI scores at times of 1 and 180-days of storage when Clarity brackets were bonded with the Transbond cement (p<0.001). The ARI scores for the 1-day storage group ranged from 0 to 3 with 64% of the scores being 3. The ARI score for the 180-days storage group ranged from 1 to 3 with 84% of the ARI scores being 3. (Table 21- Page 73)

xi) **Clarity Brackets Bonded with Panavia21**
A two-tail Fischer’s Exact test showed a significant difference between the ARI scores at times of 1 and 180-days of storage when Clarity brackets were bonded with Panavia21 cement (p<0.001). The ARI scores for the 1-day storage group ranged from 1 to 3 with 58% of the scores being 3. The ARI score for the 180-days storage group were all 3. (Table 21- Page 73)

xii) **Clarity Brackets Bonded with Fuji Ortho LC (conditioned)**
A two-tail Fischer’s Exact test showed a significant (p<0.001) difference between the ARI scores at times of 1 and 180-days of storage when Clarity brackets were bonded with Fuji Ortho LC (conditioned) cement. The ARI scores for the 1-day storage group ranged from 0 to 3 with 67% of the scores being 3. The ARI scores for the 180-days storage group were all 3. (Table 21- Page 73)
Table 21: The Effects of Storage Time on ARI Scores

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>Bonding Protocol</th>
<th>Transbond Conditioned with 37% Phosphoric Acid, dry</th>
<th>Panavia Self-etching Acidic Primer, dry</th>
<th>Fuji Ortho LC Conditioned with 10% Polyacrylic Acid, wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed ²</td>
<td>ARI %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td>Storage Time (Days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>- 17% 33% 50%</td>
<td>100 %</td>
<td>- 25% 50% 25%</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>- 25% 33% 42%</td>
<td>76% 16% 8%</td>
<td>- 17% 25% 58%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P=0.329</td>
<td>P&lt;0.001</td>
<td>P&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Time ³</td>
<td>ARI %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td>Storage Time (Days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>- - 67% 33%</td>
<td>- 58% 25% 17%</td>
<td>- - 42% 58%</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>- - 17% 83%</td>
<td>- 66% 17% 17%</td>
<td>- - 8% 92%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P&lt;0.001</td>
<td>P=0.385</td>
<td>P&lt;0.001</td>
<td></td>
</tr>
<tr>
<td>Transcend ²</td>
<td>ARI %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td>Storage Time (Days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>- - 17% 83%</td>
<td>- - 100%</td>
<td>- - 100%</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>- - 8% 92%</td>
<td>- - 100%</td>
<td>- - 100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P=0.086</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarity ¹</td>
<td>ARI %</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
<td>0 1 2 3</td>
</tr>
<tr>
<td>Storage Time (Days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>- 17% 17% 64%</td>
<td>- 17% 25% 58%</td>
<td>8% 25% 67%</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>8% 8%</td>
<td>- 84%</td>
<td>- - 100%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P&lt;0.001</td>
<td>P&lt;0.001</td>
<td>P&lt;0.001</td>
<td></td>
</tr>
</tbody>
</table>

P<0.05 denotes statistical significance
10. THE RELATIONSHIP BETWEEN SBS AND ARI SCORES DISTRIBUTION FOR VARIOUS BRACKET BASE-CEMENT COMBINATIONS (1 AND 180-DAYS OF STORAGE)

In general, when comparing ARI scores and corresponding SBS of each bracket base-cement combination, there were no consistent associations between ARI scores and SBS. 44% (7 out of 16) of the combinations tested after 1-day of storage showed a significant association between ARI scores and SBS values. Of these associations 57% (4 out of 7) were positive associations and 43% were negative. The groups in which a positive association was noted higher ARI scores were associated with higher mean SBS values. The groups in which a negative association was noted higher ARI scores were associated with a reduction in SBS. 17% (2 out of 12) of the combinations tested after 180-days of storage showed a significant negative association between the ARI scores and the SBS values.

i) Speed Brackets Bonded with Transbond Cement (1 and 180-days of Storage)

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Speed brackets bonded with Transbond cement tested after 1 or 180-days of storage. (Table 22- Page 75)

ii) Speed Brackets Bonded with Panavia21 Cement (1 and 180-days of Storage)

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Speed brackets bonded with Panavia21 cement regardless of the storage time. (Table 22- Page 75)

iii) Speed Brackets Bonded with Fuji Ortho LC (conditioned) Cement (1 and 180-days of Storage)

The results of the linear regression test showed that there was a statistically significant relationship between the ARI scores and SBS for Speed brackets bonded with Fuji Ortho LC (conditioned) cement that were tested after 1-day (p=0.015). For this group higher ARI
scores were associated with an increase in SBS. No significant association was noted for the groups tested after 180-days of storage. (Table 22- Page 75)

iv) **Speed Brackets Bonded with Fuji Ortho LC (not-conditioned) Cement (1-day of Storage)**

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Speed brackets bonded with Fuji Ortho LC (not-conditioned) cement. (Table 22- Page 75)

Table 22: Mean SBS and Corresponding ARI Scores Distribution for Speed Brackets Bonded with Different Cements (1 and 180-Days of Storage)

<table>
<thead>
<tr>
<th>Bracket Base-Cement Combinations</th>
<th>Storage Time (Days)</th>
<th>Frequency of ARI Scores %</th>
<th>P value</th>
<th>Mean SBS (MPa) Corresponding to ARI Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Speed-Transbond</td>
<td>1</td>
<td>-</td>
<td>17</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>Speed-Panavia21</td>
<td>1</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>76</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Speed-Fuji Ortho (conditioned)</td>
<td>1</td>
<td>-</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Speed-Fuji Ortho (not-conditioned)</td>
<td>1</td>
<td>42</td>
<td>-</td>
<td>58</td>
</tr>
</tbody>
</table>

* P<0.05 denotes statistical significance

P values denote association between ARI scores and SBS

v) **Time Brackets Bonded with Transbond Cement (1 and 180-days of Storage)**

The results of the linear regression test showed that there was a significant relationship between the ARI scores and SBS for Time brackets bonded with Transbond cement and
tested after 1-day (p=0.03) and 180-days of storage (p=0.044). For both storage groups higher ARI scores were associated with a reduction in SBS. (Table 23- Page 77)

vi)  **Time Brackets Bonded with Panavia21 Cement (1 and 180-days of Storage)**
The results of the linear regression test showed that there was a significant relationship between the ARI scores and SBS for Time brackets bonded with Panavia21 cement that were tested after 1-day (p=0.0055) and 180-days (p=0.0035) of storage. For both of these groups their higher ARI scores were associated with a reduction in SBS. (Table 23- Page 77)

vii) **Time Brackets Bonded with Fuji Ortho LC (conditioned) Cement (1 and 180-days of Storage)**
The results of the linear regression test showed that there was a significant relationship between the ARI scores and SBS for Time brackets bonded with Fuji Ortho LC (conditioned) cement that were tested after 1-day of storage (p=0.0017). For this group higher ARI scores were associated with a reduction in SBS. There was no significant association between the ARI scores and SBS for the group tested after 180-days of storage. (Table 23- Page 77)

viii) **Time Brackets Bonded with Fuji Ortho LC (not-conditioned) Cement (1-day of Storage)**
The results of the linear regression test showed that there was a significant relationship between the ARI scores and SBS for Time brackets bonded with Fuji Ortho LC (not-conditioned) cement that were tested after 1-day of storage (p=0.0015). For this group higher ARI scores were associated with an increase in SBS. (Table 23- Page 77)
Table 23: Mean SBS and Corresponding ARI Scores Distribution for Time Brackets Bonded with Different Cements (1 and 180-Days of Storage)

<table>
<thead>
<tr>
<th>Bracket Base- Cement Combinations</th>
<th>Storage Time (Days)</th>
<th>Frequency of ARI Scores %</th>
<th>P value</th>
<th>Mean SBS (MPa) Corresponding to ARI Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Time-Transbond</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>Time-Panavia21</td>
<td>1</td>
<td>-</td>
<td>58</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>66</td>
<td>17</td>
</tr>
<tr>
<td>Time-Fuji Ortho (conditioned)</td>
<td>1</td>
<td>-</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>8</td>
<td>92</td>
</tr>
<tr>
<td>Time-Fuji Ortho (not-conditioned)</td>
<td>1</td>
<td>42</td>
<td>25</td>
<td>33</td>
</tr>
</tbody>
</table>

*P<0.05 denotes statistical significance
P values denote association between ARI scores and SBS

ix) Transcend Brackets bonded with Transbond Cement (1 and 180-days of Storage)

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Transcend brackets bonded with Transbond cement that were tested after 1 and 180-days of storage. (Table 24- Page 78)

x) Transcend Brackets Bonded with Panavia21 Cement (1 and 180-days of Storage)

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Transcend brackets bonded with Panavia21 cement that were tested after 1 and 180-days of storage. For both of these groups all of the ARI scores were 3 and independent of SBS. (Table 24- Page 78)
x) Transcend Brackets Bonded with Fuji Ortho LC (conditioned) Cement (1 and 180-days of Storage)

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Transcend brackets bonded with Fuji Ortho LC (conditioned) cement that were tested after 1 and 180-days of storage. For both of these groups all of the ARI scores were 3 and they were independent of SBS. (Table 24)

xii) Transcend Brackets Bonded with Fuji Ortho LC (not-conditioned) Cement (1-day of Storage)

The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Transcend brackets bonded with Fuji Ortho LC (not-conditioned) cement that were tested after 1-day of storage. (Table 24)

Table 24: Mean SBS and Corresponding ARI Scores Distribution for Transcend Brackets Bonded with Different Cements (1 and 180-Days of Storage)

<table>
<thead>
<tr>
<th>Bracket Base-Cement Combination</th>
<th>Storage Time (Days)</th>
<th>Frequency of ARI Scores %</th>
<th>P value</th>
<th>Mean SBS (MPa) Corresponding to ARI Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Transcend-Transbond</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Transcend-Panavia21</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transcend-Fuji Ortho LC (conditioned)</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transcend-Fuji Ortho LC (not-conditioned)</td>
<td>1</td>
<td>76</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

* P<0.05 denotes statistical significance
P values denote association between ARI scores and SBS
Clarity Brackets Bonded with Transbond Cement (1 and 180-days of Storage)
The results of the linear regression test showed that there was a significant relationship between the ARI scores and SBS for Clarity brackets bonded with Transbond cement that were tested after 1-day of storage (p=0.009). For this group higher ARI scores were associated with an increase in SBS. No significant association was noted for the group tested after 180-days of storage. (Table 25- Page 80)

Clarity Brackets Bonded with Panavia21 Cement (1 and 180-days of Storage)
The results of the linear regression test showed that there was no significant relationship between the ARI scores and SBS for Clarity brackets bonded with Panavia21 cement that were tested after 1 and 180-days of storage. (Table 25- Page 80)

Clarity Brackets Bonded with Fuji Ortho LC (conditioned) Cement (1 and 180-days of Storage)
The results of the linear regression test showed that there was a statistically significant relationship between the ARI scores and SBS for Clarity brackets bonded with Fuji Ortho LC (conditioned) cement that were tested after 1-day of storage (p=0.02). For this group higher ARI scores were associated with an increase in SBS. No significant association was noted for the group tested after 180-days of storage. For this group all the scores were 3 and they were independent of SBS. (Table 25- Page 80)

Clarity Brackets Bonded with Fuji Ortho LC (not-conditioned) Cement (1-day of Storage)
The results of the linear regression test showed that there was no significant relationship between the ARI scores and the mean SBS for Clarity brackets bonded with Fuji Ortho LC (not-conditioned) cement that were tested after 1-day of storage. (Table 25- Page 80)
Table 25: Mean SBS and Corresponding ARI Scores Distribution for Clarity Brackets Bonded with Different Cements (1 and 180-Days of Storage)

<table>
<thead>
<tr>
<th>Bracket Base-Cement Combination</th>
<th>Storage Time (Days)</th>
<th>Frequency of ARI Scores %</th>
<th>P value</th>
<th>Mean SBS (MPa) Corresponding to ARI Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Clarity-Transbond</td>
<td>1</td>
<td>17 17 64</td>
<td>0.009**</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>8 8 - 84</td>
<td>0.49</td>
<td>10.62±0</td>
</tr>
<tr>
<td>Clarity-Panavia21</td>
<td>1</td>
<td>17 25 58</td>
<td>0.36</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>- - 100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Clarity-Fuji Ortho LC (conditioned)</td>
<td>1</td>
<td>8 25 67</td>
<td>0.02*</td>
<td>5.41±0</td>
</tr>
<tr>
<td></td>
<td>180</td>
<td>- - 100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Clarity-Fuji Ortho LC (not-conditioned)</td>
<td>1</td>
<td>92 - 8</td>
<td>0.46</td>
<td>5.22±1.95</td>
</tr>
</tbody>
</table>

* P<0.05 denotes statistical significance

P values denote association between ARI scores and SBS
11. THE EFFECT OF CONDITIONING THE ENAMEL WITH 10% POLYACRYLIC ACID ON THE MEAN SBS & AR1 SCORES OF BRACKETS BONDED WITH FUJI ORTHO LC CEMENT

i) The Effects of 10% Polyacrylic Acid Conditioning on Mean SBS

Table 26: Comparison of Mean SBS of Brackets Bonded with Fuji Ortho LC with and without Enamel Conditioning

<table>
<thead>
<tr>
<th>Bracket Base Type</th>
<th>Mean SBS ± SD Enamel conditioned</th>
<th>Mean SBS ± SD Enamel not conditioned</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>11.79±2.2</td>
<td>6.47±3.13</td>
<td>0.0001*</td>
</tr>
<tr>
<td>Time</td>
<td>8.50±1.69</td>
<td>4.80±2.36</td>
<td>0.0007*</td>
</tr>
<tr>
<td>Transcend</td>
<td>10.30±2.18</td>
<td>7.77±1.73</td>
<td>0.0200*</td>
</tr>
<tr>
<td>Clarity</td>
<td>9.91±2.90</td>
<td>5.09±1.9</td>
<td>0.0001*</td>
</tr>
</tbody>
</table>

* P<0.05 denotes statistical significance

The omission of the polyacrylic acid conditioning step when bonding brackets with Fuji Ortho LC cement resulted in a significant reduction in mean SBS for all of the bracket base types tested in this study. However, this reduction in bond strength was clinically unacceptable only for Time brackets bonded with Fuji Ortho LC. The mean SBS for the Time brackets bonded with Fuji Ortho LC and without conditioning the enamel was 4.8 ±2.36 MPa and this falls below the acceptable range (8±3 MPa). As a result this protocol was not included in the long-term storage part of this study.
ii) The Effects of Polyacrylic Acid Conditioning on ARI Scores Distribution

Table 27: Comparison of ARI Scores Distribution and the Mean ARI Scores of Brackets Bonded with Fuji Ortho LC Cement

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>Enamel conditioned ARI Distribution</th>
<th>Enamel not conditioned ARI Distribution</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ARI 0 1 2 3</td>
<td>Mean ARI 0 1 2 3</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>2.0±0.65 0 25 50 25</td>
<td>1±1.04 42 0 58 0</td>
<td>0.001*</td>
</tr>
<tr>
<td>Time</td>
<td>2.58±0.51 0 0 42 58</td>
<td>0.92±0.90 42 25 33 0</td>
<td>0.001*</td>
</tr>
<tr>
<td>Transcend</td>
<td>3±0 0 0 0 100</td>
<td>0.5±1.0 76 8 8 8</td>
<td>0.001*</td>
</tr>
<tr>
<td>Clarity</td>
<td>2.5±0.90 8 0 25 67</td>
<td>0.25±0.87 92 0 0 8</td>
<td>0.001*</td>
</tr>
</tbody>
</table>

* P<0.05 denotes statistical significance

Polyacrylic acid conditioning of the enamel had a significant effect on the distribution of ARI scores after the debonding of all the bracket base types that were bonded with Fuji Ortho LC cement. For all the bracket base types tested, there was a significant shift from ARI scores of 2 and 3 to ARI scores of 0 and 1 when the enamel was not conditioned. This indicates that, acid conditioning caused the bond failures to occur mostly at the bracket base-cement interface (favorable) compared to not conditioning. The latter resulted in bond failures at the enamel-cement interface (unfavorable).

In summary, acid conditioning had a significant and favorable effect on the type of bond failures of all the bracket base types bonded with Fuji Ortho LC cement with the result that the effect of not conditioning enamel was eliminated from the long-term storage part of the study.
12. COMPATIBILITY BETWEEN BRACKET BASE DESIGN AND THE CEMENT PARTICLE SIZE

Scanning electron microscopy (SEM) micrographs of each specimen were obtained at magnifications of x25, x100 and x1000. The SEM micrographs are shown in Figure 7. (Page 84). The x1000 magnification SEM micrographs were used to measure the average particle size of each cement. The micrographs of each bracket base surface were matched against the three cements at the same magnification. Visual analysis was made to investigate the compatibility of each bracket base surface characteristic with the cement particle size and the following observations were made: (Table 28)

Table 28. Compatibility of Different Bracket Base Designs and the Particle Size of Various Cements

<table>
<thead>
<tr>
<th>Cement Type</th>
<th>Particle Size</th>
<th>Description</th>
<th>Compatibility with Bracket-Bases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panavia21</td>
<td>1-9 microns</td>
<td>Particles smaller than that of Fuji Ortho LC and Transbond and more uniformly distributed</td>
<td>Compatible with all bracket base types</td>
</tr>
<tr>
<td>Fuji Ortho LC</td>
<td>1.5-27 microns</td>
<td>Quite similar in particle size and distribution to Transbond</td>
<td>Compatible with all bracket base types</td>
</tr>
<tr>
<td>Transbond</td>
<td>1.5-27 microns</td>
<td>Quite similar in particle size and distribution to Fuji Ortho LC</td>
<td>Compatible with all bracket base types</td>
</tr>
</tbody>
</table>
Figure 7: Compatibility of Different Bracket Base Designs and Particle Size of Various Cements

Top Row: SEM view of bracket bases at 20X magnification
Middle Row: SEM view of bracket bases at 100X magnification
Bottom Row: SEM view of different cements at 100X magnification
13. ERROR STUDY

i) Tests of Reliability for ARI Scores Assigned by Two Different Investigators

To assess the consistency in assigning ARI scores between two different investigators an un-weighted Kappa (K) statistics was carried out. This is a useful measure for quantifying agreement beyond chance between assessments of the same variable. K value of zero represents random agreement, and 1.00 represents perfect agreement. The following ranges have been suggested for interpretation of Kappa: (Fleiss 1979)

0.40 and below represents poor agreement beyond chance, 0.40-0.75 represents fair to good agreement, and 0.75 and above represents excellent agreement. The Kappa statistics was calculated to be equal to 0.83, which denotes excellent agreement between the two operators in assigning ARI scores.

Table 29: ARI Scores Assigned by Two Different Investigators

<table>
<thead>
<tr>
<th></th>
<th>Principal Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>ARI</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Un-weighted Kappa=0.83
ii) Test of Reliability for ARI Scores Assigned by One Investigator at Two Different Times

To assess the variability between successive assignments of ARI scores by the same investigator, an un-weighted Kappa statistics was carried out. In this investigation the K was found to be equal to one, which accounts for excellent consistency in assigning ARI scores by the principal investigator at two different times.

Table 30: ARI Scores Assigned by the Principal Investigators at Two Different Times

<table>
<thead>
<tr>
<th>ARI</th>
<th>Time 1</th>
<th>Time 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Un-weighted Kappa=1.0
DISCUSSION

Clinical Acceptability of Various Bracket Base-Cement Combinations

Bond failure and the possibility of damage to enamel subsequent to acid conditioning and debonding of the brackets both during and after orthodontic treatment remains a major concern despite the advancements in the field of bonding. Bracket bond failure is an orthodontic emergency that is inconvenient for both the patient and the clinician since it is costly and may prolong the course of treatment. An acceptable orthodontic bonding system should be strong enough to withstand orthodontic and chewing forces and be easily removed with minimal or no damage to enamel. Reynolds (1975) postulated that clinical success could be achieved with cements that provide in vitro minimum bond strengths of approximately 5.0 MPa. To maintain enamel integrity, the ideal failure site in debonding should be between the bracket base and the cement (Sinha et al., 1995), although failure at bracket-base cement interface increases the difficulty of enamel clean up (Brown, 1978; Pus, 1980). Clinicians must take great care when removing remaining cement following debonding to avoid gouging, scratching, or pitting of the enamel surface.

In this investigation bracket base-cement combinations that produced mean SBS in the range of 5-11 MPa with the majority of ARI scores being 2 and/or 3 were deemed clinically acceptable. If the bond strength for a combination was greater than 11 MPa, provided that the bond failure pattern was acceptable, a SBS of more than 11 MPa for a bracket base-cement combination was considered clinically acceptable. In this investigation in order to determine an ideal combination the ease of the bonding procedure (clinical practicality), performance over time, iatrogenic damage to enamel due to the bonding procedure (acid conditioning) and the protective traits of the bonding cements (fluoride release) were also taken into account.

In this study, 16 and 12 different bracket base-cement combinations were tested after 1 and 180-days of storage respectively. After 1-day of storage 69% (11 out of 16) of the bracket base-cement combinations were clinically acceptable. The bracket base-cement combinations that performed poorly were Speed-Panavia21, Time-Panavia21, Time-Fuji.
Ortho LC (not-conditioned), Transcend-Fuji Ortho LC (not-conditioned), and Clarity-Fuji Ortho LC (not-conditioned) combinations. (Table 6- Page 50) Only the Time-Fuji Ortho LC (not-conditioned) combination produced clinically unacceptable SBS (4.8±2.36 MPa). All of the above five combinations resulted in unacceptable bond failure patterns i.e. most of the cement was left on the bracket base. The results obtained with Fuji Ortho LC (not-conditioned) were in disagreement with the manufacturer's claim and the observations of Silverman et al. (1995) and Fricker (1994) that Fuji Ortho LC performs similarly with or without the use of an enamel conditioner. The results of the present study support the current opinion that advocates the use of an enamel conditioner either 10% polyacrylic acid (Beress et al., 1998; Bishara et al., 1998b; Lippitz et al., 1998; Flores et al., 1999; Millett et al., 1999; Meehan et al., 1999) or 37% phosphoric acid (Flores et al., 1999; Bishara et al., 2000) prior to bonding with resin reinforced glass ionomer cements. Based on the poor results obtained for the majority of the bracket bases (Time, Transcend and Clarity) when bonded to not-conditioned enamel with Fuji Ortho LC cement, this bonding protocol was omitted from the long-term storage study.

Twelve different combinations were tested after 180-days of storage. The results showed that long-term storage had no clinically significant effect on the acceptability of both the bond strength and the bond failure pattern of the different bracket base-cement combinations (Tables 16, 21-Pages 63, 73). In both 1-day and 180-days storage groups only Speed-Panavia21 and Time-Panavia21 resulted in unfavorable failure patterns while producing adequate bond strengths. The possible causes for this result will be discussed later. With respect to the effects of long-term storage, the data are limited and study-dependent. Comparisons can only be made with studies that have utilized the same type of cement, bonding protocol and bracket base design. The only study closely resembling the protocol and the materials tested in this study is that of Mahal (2000). In this study metal (Speed), ceramic (Transcend) and polycarbonate (SpiritMB) brackets were bonded to bovine enamel using Phase II composite resin and GC Fuji Ortho. Both of these cements are auto-polymerizing. The samples were subjected to thermocycling and long-term storage. The thermocycling period was 24-hours and 6.5-days. The long-term storage period consisted of shear bond testing at 24-hours, 7-days, and 180-days. The results indicated that long-term
storage had a significant effect on the SBS and this effect was in turn dependent on the bracket base type, and the type of cement used. The mean SBS in the present study were considerably lower than those of Mahal (2000) at the corresponding storage periods of 24-hours and 180-days. This difference is most likely due to different cement types used. In the Mahal (2000) study both the RCLC and RRGIC were of the auto-polymerizing type. It is possible that polymerization continued after the initial set so that these cements produced higher mean SBS. In the present study, long-term storage had a statistically significant effect on the SBS of 3 out of 12 bracket base-cement combinations. The SBS for the Speed-Transbond combination increased from 11.69±2.3 MPa to 14.05 ± 2.84 MPa. The SBS for the Time-Panavia21 combination and the Transcend-Panavia21 combination decreased from 11.07 ± 1.26 MPa and 10.63±1.57 to 9.61±3.5 MPa and 8.32±1.5 MPa respectively. However, these changes in SBS did not detract from clinical acceptability of these combinations. In the Mahal study, long-term storage (180-days) did not have a clinically significant effect on the fracture pattern of bonded brackets. The results of the present study are in agreement with this observation.

The Effects of Bracket Base Design, Cement Type, Enamel Conditioning and Long-term Storage on the Mean SBS

In general, the results of this study showed that bracket base design, cement materials, enamel conditioning and bracket base-cement combinations had a significant effect on the mean SBS.

i) The Effects of Bracket-Base Design on the Mean SBS, 1-Day vs 180-Days of Storage

In this study the Duncan’s grouping showed that Transcend brackets performed significantly differently than the Time, Speed and Clarity brackets by producing the highest overall SBS. (Table 9- Page 53) When comparing the bracket base design of the Transcend and Clarity brackets (Figure 7- Page 84), it is evident that these brackets have different base sizes and designs. The Clarity bracket is a larger bracket, but this should not have an affect on SBS.
Both of these brackets are of the polycrystalline aluminum oxide type with randomly oriented crystals fused on to their bases. As seen on the SEM micrographs (Figure 7- Page 84), the Clarity bracket base has both a midline groove running in gingival-incisal direction, and the sizes of the crystals and recesses in between the crystals are smaller than those of Transcend bracket base. The manufacturers have incorporated the midline groove in the base of Clarity bracket to allow for flexure during debonding thus making it easier to debond. The Transcend bracket base lacks this feature. It is thought that the presence of this groove resulted in reduction in the bond strength of Clarity brackets when compared to Transcend brackets regardless of the cement type used. The Clarity bracket base also has no crystal particles around its periphery, resulting in a reduced surface area for bonding. Subsequently, lower SBS values were recorded for Clarity brackets as compared to Transcend brackets.

The metal Speed and Time bracket bases produced respective cumulative mean SBS of 9.83 MPa and 9.27 MPa, which were independent of the cement type, used. (Table 9- Page 53) These mean SBS were not statistically different from each other except that Speed bracket bases produced slightly higher mean SBS. This difference in bond strengths is due to differences in the base surface design of these brackets. The Speed bracket has a 60-gauge, microetched foil-mesh base as compared to the Time bracket, which has a machined, integral, microetched base with mechanical undercuts (Figure 7- Page 84). As seen in the SEM micrographs (Figure 7- Page 84), the channels between the mesh of Speed bracket base are more retentive than the undercuts on the Time bracket base because they are deeper and more numerous. Sharma (1999) compared the SBS of 6 different metal bracket base designs bonded to bovine enamel using Transbond cement and tested after 1 and 24-hours. The highest 24-hour SBS she reported were achieved with Time bracket bases followed by Speed bracket bases. These findings are in agreement with the results of this study since the Time-Transbond combination produced higher SBS values than the Speed-Transbond combination. However, when comparing SBS of different bracket bases for all the different cements combined, Speed brackets performed slightly but not statistically significantly better than Time brackets for the reasons mentioned above. These latter findings are also in agreement with two other studies (Deidrich and Dickmeiss, 1984; Regan and Van Noort, 1989) which demonstrated that machined integral bases show lower bond strengths.
compared to foil-mesh bases. The overall conclusion is that bracket base design does have an effect on SBS as shown in previous studies (Reynolds and von Fraunhofer 1977; Faust et al., 1978; Thanos et al., 1979; Dickinson and Powers, 1980; Lopez, 1980; Maijer and Smith, 1981, Deidrich and Dickmeiss, 1983; Regan and Van Noort, 1989; Sharma, 1999)

The same pattern of performance was noted for both metal and ceramic bracket bases tested after 180-days of storage when compared to those tested after 1-day of storage. At both storage times, Speed and Transcend bracket bases produced higher SBS than the Time and Clarity bracket bases. (Table 12- Page 55)

ii) The Effects of Cement Type and Enamel Conditioning on the Mean SBS

Another variable affecting bond strength is the cement type. The SBS values for the three cements and four different bonding protocols after 1-day of storage indicated that Transbond cement performed significantly differently than Panavia21 and Fuji Ortho LC (conditioned and not-conditioned) cement (Table 10- Page 54). The cumulative mean SBS for Transbond cement was 13.29 MPa. The values for Panavia21 (10.13 MPa) and Fuji Ortho LC (conditioned, 10.13 MPa) were identical. The mean SBS for Fuji Ortho LC cement dropped significantly to 6.03 MPa when conditioning of enamel with 10% polyacrylic acid was excluded. The bonding protocols for these cements were different in that different types of conditioners were used for each cement type. The differences in performance of these cements are not only due to their differing chemical and physical properties but also due to the differences in the modes of enamel treatment. Conditioning with 37% phosphoric acid produces a different enamel etch pattern compared with conditioning with 10% polyacrylic acid (Coups Smith, 1997; Bishara, 2000). 10% polyacrylic acid is a milder acid than the 37% phosphoric acid. Phosphoric acid produces deeper micro-porosities than polyacrylic acid, which results in stronger retention of Transbond cement by tooth than the Fuji Ortho LC cement. As a result, the observation of higher mean SBS for Transbond cement in combination with 37% phosphoric acid is in part due to differences in adherence of Transbond and Fuji Ortho LC (conditioned) cements to enamel. The differences in bond strengths of these two cements are also in part attributed to their different chemical composition. In general, RRGIC are weaker cements than RCLC since the resin content of
RRGIC is only 11.25% as compared to Transbond which is a BIS-GMA resin based cement. The consensus in the current literature is that RRGIC continues to produce lower but reliable bond strengths when compared to RCLC (Bishara et al., 1998b; Bishara et al., 1999b; Meehan et al., 1999; Millett, 1999). The results of this study are in agreement with the current literature. Even though bond strengths of Fuji Ortho LC with conditioner were statistically lower than Transbond, they were, however, clinically acceptable.

Another property of Fuji Ortho LC cement is that being glass ionomer cement it bonds chemically to tooth structure and the metal. The results of this study showed that a chemical adhesion to the tooth surface is not enough and that mechanical interlocking of the cement to enamel by polyacrylic acid conditioning is required for consistent clinically acceptable bond strengths. This is in agreement with the findings of Beress et al., 1998; Bishara et al., 1998b; Flores et al., 1999; Lippitz et al., 1998; Meehan et al., 1999; Millett et al., 1999. These results, however, are contrary to manufacturer’s claim that conditioning with polyacrylic acid is optional and not required when bonding brackets with Fuji Ortho LC cement. In this study, the combination of Time-Fuji Ortho LC (not-conditioned) produced an unacceptable low mean bond strength, 4.7± 2.36 MPa. (Table 26- Page 81) The bond strengths of the Speed, Transcend and Clarity brackets when bonded with Fuji Ortho LC (not-conditioned) were all clinically acceptable but were significantly lower than the same brackets bonded with either Panavia21, Transbond or Fuji Ortho LC (conditioned) cements.

Panavia21 cement produced cumulative bond strengths that were less than Transbond but exactly equal to Fuji Ortho LC (conditioned). (Table 10- Page 54) Panavia21 is a low viscosity restorative RCLC with a filler content of over 70% by weight. This cement is auto-polymerized in the absence of oxygen. Panavia21 contains the adhesive monomer MDP (10-Methacryloyloxydecyl dihydrogen phosphate) that provides chemical adhesion between tooth structure and metal, silanated porcelain, or composite. (Rux et al., 1991) The reason that Panavia21 and Fuji Ortho LC (conditioned) cements provided the same cumulative mean SBS is probably due to their common unique property of chemical adherence to metal. In this study, Panavia21 did not chemically adhere to ceramic bracket bases since the bracket bases used in this study (Transcend and Clarity) were not silanated. The bond
strength values for Panavia21 used as orthodontic cements to bond brackets to enamel is limited to one study by Bishara et al. (1998a). Bishara and colleagues (1998a) were interested in Panavia21 as an orthodontic cement because of the unique properties of its self-etching acidic primer. Unlike other conventional resin cements that require a conditioner plus a low viscosity adhesive primer prior to bonding brackets to enamel, Panavia21 system has the conditioning and priming steps combined into one step of a self-etching acidic primer. The unique characteristic of this self-etching acidic primer is that it allows the clinician to combine conditioning and priming into a single treatment step. This results in an improvement in both time and cost effectiveness to the clinician and indirectly to the patient (Bishara et al., 1998a). Bishara et al. (1998a) used Panavia21 with a self-etching acidic primer to bond metal brackets (Victory series, 3M, Unitek, Monrovia, Calif) to human molars. Their results showed that the use of acidic primers to bond brackets to the enamel provided clinically acceptable SBS (10.4 ± 4.4 MPa) when used with a highly (77% by weight) filled adhesive (Panavia21). The results of the present study are in agreement with these findings in that the use of the self-etching acidic primer with Panavia21 to bond four different bracket bases produced acceptable bond strengths after 1 and 180-days of storage.

iii) The Effects of Long-Term Storage on the Mean SBS of Different Cements, and Various Bracket Base-Cement Combinations

Fuji Ortho LC cement with enamel conditioner produced a cumulative mean SBS (8.83 MPa) that was significantly lower than the SBS of Transbond (13.19 MPa) and Panavia21 (10.27 MPa), after 180-days of storage. (Table 13- Page 56) In addition, the cumulative mean SBS for Transbond and Panavia21 did not change significantly after 180-days of storage. These results indicate that Transbond and Panavia21 cements, which are RCLC, perform better than Fuji Ortho LC, which is a RRGIC. The resin content of both Transbond and Panavia21 cements surpass that of Fuji Ortho LC. The improved bond strength of RRGIC as compared to conventional GIC is due to the addition of the resin. Based on the results of the present investigation it appears that the higher the resin content the stronger the cement and the better the performance over time. From the results of this study, it can be interpreted that the resin content imparts resistance to degradation and solubility over time.
in water. The reduction in bond strength following long-term storage of RRGIC may be attributed to cement degradation. Since RRGIC has less resin content compared to RCLC, it is therefore more soluble and as a consequence produces lower SBS after long-term storage in water. It is important to note, however, that these changes are not clinically significant and the rate of reduction in bond strength is very slow, and the performance of the cement over the average length of time required for orthodontic treatment is not affected.

Long-term storage had a statistically significant effect on the bond strength of 3 out of 12 bracket base-cement combinations. (Table 16- Page 63) The storage periods of 180-days resulted in statistically significant reductions in SBS of Time and Transcend brackets bonded with Panavia21 cement. There are no long-term storage data on Panavia21. It is manufacturer’s recommendation that any exposed Panavia21 cement should be covered by Oxyguard™ since the setting reaction is anaerobic. The reason that Panavia21 cement was included in the present investigation was due to simplified step of using self-etching acidic primer and the use of Oxyguard™ would have detracted from its simplicity. It should be noted that, Bishara et al. (1998a) did not use Oxyguard™ in their bonding protocol. Another reason for omission of this step was that the thickness of cement between the bracket and the tooth is quite thin. Using the same bracket seating force used in this study, MacColl (1995) measured this interface to be 0.07 mm thick. For the purposes of this study, it was postulated, therefore, that the amount of potentially un-polymerised cement at the periphery of the bracket base would not affect the bond strength. The results of this study indicate that Time and Transcend brackets cemented with Panavia21 showed a reduction in bond strength after 180-days of storage. The SBS of Speed and Clarity brackets bonded with Panavia21 were not significantly affected by the storage time of 180-days. This observation can be attributed to the base design of these brackets and the amount of un-polymerised cement at the periphery, which may have dissolved in water over the period of 180-days of storage. Time and Transcend bracket bases are not as retentive when compared to Speed and Clarity bracket bases respectively. Therefore, it is possible that the poor interlocking of the cement material into the bases of Time and Transcend brackets, in combination with the presence of the un-polymerised resin at the periphery, may have accelerated cement dissolution in water.
and thus resulted in lower bond strengths over time for these bracket bases. The results of the present study can not be compared to any other studies since the Bishara et al. (1998a) study used 48-hours storage period when using Panavia21 as bracket cementing agent.

Independent of bracket base design and material, Transbond cement performed similarly with respect to SBS at both time intervals. However, if the bracket base design is included in the comparisons between SBS at the two different storage times, a difference is noted. Long-term storage resulted in an increase in SBS of Speed brackets bonded with the Transbond cement. The SBS of Time, Clarity and Transcend brackets bonded with Transbond were not affected by the long-term storage. Sharma (1999) showed that the SBS of 6 different metal bracket bases (Speed and Time included) bonded with Transbond cement increased from 1-hour to 24-hours storage. The results of the present study can’t be compared to that of Sharma’s, since the storage periods are different. The only study using the same storage period with different cements was that conducted by Mahal (2000).

In the Mahal (2000) study, long-term storage resulted in a significant increase in the SBS of Speed, Transcend and SpiritMB brackets when they were bonded with either auto-polymerising RCLC or auto-polymerising RRGIC cements. This is probably because the polymerisation of auto-polymerised cements may continue for longer periods than that of photo-polymerising cements. In the present investigation, long-term storage resulted in a significant increase in the SBS of only the Speed-Transbond combination.

There were no statistically significant differences in SBS over time for the brackets that were bonded with Fuji Ortho LC cement (conditioned). (Table 16- Page 63) These results are not in agreement with those of Mahal (2000). Mahal (2000) demonstrated an increase in the bond strengths of all the bracket types bonded with GC Fuji Ortho cement (conditioned). Once again, it should be noted that GC Fuji Ortho is an auto-polymerising cement that may have had continued polymerisation overtime.

In general, long-term storage had no clinically significant effect on the SBS of the different bracket base cement combinations used in this study. All of the 12 combinations continued
to produce shear bond strengths, which were greater than the cut off value of 5.0 MPa. (Table 16- Page 63)

**ARI Scores**

**i) The Effects of Cement Type and Enamel Conditioning on ARI Scores**

Duncan’s grouping showed that Transbond (mean ARI=2.45) and Fuji Ortho LC conditioned (mean ARI=2.5) produce the optimum ARI scores followed by Panavia21 (mean ARI=1.75) and Fuji Ortho LC not-conditioned (mean ARI=0.67) after 1-day of storage. (Table 18- Page 65) The same pattern of performance was observed for each cement after 180-days of storage; Transbond (mean ARI=2.63), Fuji Ortho LC (conditioned) (mean ARI=2.83) and Panavia 21 (mean ARI=1.96). (Table 20- Page 75) Long-term storage resulted in a slight increase in ARI scores for all the cement types. These observations did not take into account the bracket-base design.

These data clearly show that enamel conditioning had a significant effect on the ARI scores. For Fuji Ortho LC cement, when the enamel surface was not conditioned all the failure patterns were unacceptable and independent of the bracket-base design. Conditioning with 10% polyacrylic acid significantly improved the failure patterns of all the bracket-base types bonded with Fuji Ortho LC cement in that the majority of the cement was left on the tooth rather than the bracket base after debonding. The results of this study show that enamel conditioning had a greater effect on the bond failure pattern of all bracket base types than the cement material itself.

**ii) The Effects of Various Bracket Base-Cement Combinations on ARI Scores**

**a. Transbond Cement and Various Bracket Base Types**

After 1-day of storage, Transbond cement produced mean ARI scores with all of the bracket base types that ranged from 2.33 to 2.83 with an overall mean of 2.45. (Table 17- Page 64) These results indicate that Transbond cement was compatible with all the bracket-base types
tested in this study in producing clinically acceptable ARI scores where most of the cement was left on the tooth thus minimising iatrogenic enamel damage during debonding.

ARI scores distributions were more favourable for the Time bracket-base than the Speed bracket-base. Even though the majority of the ARI scores for both metal brackets were 2 and 3, Speed bracket bases had 17% of the failures occurring so that less than half of the cement was remaining on the tooth i.e. ARI score of 1. However, all of the scores for Time brackets were 2 and 3. This result is due to differences in the retentive capability of the bases of these two metal brackets. The Time bracket base has less retentive characteristics when compared to the meshwork of Speed bracket base. As a result, less of the cement is left on the Time bracket base and more on the tooth after debonding compared to Speed bracket base, which retains most of the cement. Long-term storage had no effect on the ARI score distribution for Speed brackets bonded with Transbond cement. In the case of the Time bracket, more ARI scores of 3 were observed after long-term storage but these differences were not clinically significant. (Table 21 - Page 73)

Transcend bracket bases bonded with Transbond cement produced higher ARI scores than Clarity bracket bases bonded with the same cement. It seems that mechanical interlocking between the Transcend bracket base and Transbond cement was less than that between the Clarity bracket base and Transbond. When comparing the base design of these brackets the Clarity bracket base is more retentive, because it has smaller particles and smaller recesses in between the particles (Figure 7- Page 84). In addition, the Clarity bracket base has a midline groove. In comparison, the Transcend bracket-base has relatively larger particles and larger recesses and no midline groove. The Clarity bracket base is more retentive than the Transcend bracket base and retains more cement during debonding, which results in poorer but acceptable ARI scores. Long-term storage had no clinically significant effect on the ARI score distribution of either of these bracket bases. (Table 21 - Page 73)

b. Panavia21 Cement and Various Bracket Base Types

Panavia21 cement produced poor and unacceptable ARI scores in combination with the metal bracket bases (Speed and Time). The ARI scores for the Speed bracket bases were all
0 and the mean ARI score for the Time bracket base was 1.58 ±0.79. Unlike Transbond cement, Panavia21 has chemical adhesive properties to metal. As a result, it appears that the bond strength (micro-mechanical interlocking plus chemical adhesion) between Panavia21 and the metal bracket bases was stronger than that between Panavia21 and enamel. As a result, most of the cement was left on the metal bracket bases. The Time bracket base produced higher ARI scores than the Speed bracket base because its base is less retentive resulting in a weaker micro mechanical bond between its base and the cement. Subsequently, more cement remained on the tooth after debonding the Time brackets compared with the Speed bracket base. Storage time had no clinically significant effect on ARI score distributions of these bracket base-cement combinations and they consistently produced poor ARI scores. (Table 21- Page 73)

The ARI scores for both of the ceramic bracket bases at storage times of 1 and 180-days were acceptable when Panavia21 was used to bond them to enamel. Once again the ARI scores were more favourable for Transcend brackets than for Clarity brackets owing to the different bracket base designs. Panavia21 cement performed better with ceramic bracket bases than with metal bracket bases because of its chemical properties. Panavia21 bonds to metal and ceramic surfaces that are treated with silane. The ceramic bracket bases used in this study were not treated with silane. As a result, there was no chemical bonding between the ceramic bracket bases and Panavia21 so that the bond between the enamel and the cement was stronger than the micro-mechanical bond between the cement and the bracket base. As a result, more cement was left on the tooth than on the bracket base. The storage time had no clinically significant effect on the ARI scores distributions of these bracket base-cement combinations. (Table 21- Page 73)

c. **Fuji Ortho LC (conditioned) Cement and Various Bracket Base Types**

The same trend was observed for Fuji Ortho LC (conditioned) cement as with Transbond in that all the bracket bases resulted in clinically acceptable ARI scores with this cement. Unlike Panavia21 cement, which produced clinically unacceptable bond strengths with the metal bracket bases, Fuji Ortho LC (conditioned) resulted in acceptable ARI scores with
both the metal and ceramic bracket bases. It appears that the chemical adhesive properties of Fuji Ortho LC cement to metal are not as strong as those of Panavia21. Time and Transcend bracket bases produced higher ARI scores than the Speed and Clarity bracket bases respectively. Once again, time had no appreciable effect on the clinical performance of these bracket base-cement combinations with respect to ARI scores. (Table 21- Page 73)

d. Fuji Ortho LC (not-conditioned) Cement and Various Bracket Base Types

All the bracket base cement combinations with Fuji Ortho LC (not-conditioned) cement produced unacceptable ARI scores due to the omission of the acid conditioning step. Therefore, regardless of bracket base type or design, less cement was left on the tooth after bracket debonding since there was no mechanical interlocking between the cement and the enamel. The chemical adhesion of the cement to enamel was very low compared to the bond between the bracket bases and the cement. The bracket base design had the same effect as recorded with other cements on the ARI scores. The same trend was observed in that Time and Transcend brackets performed better than Speed and Clarity brackets respectively.

The Relationship between SBS and ARI

In this investigation a consistent association was not demonstrated between the ARI scores and shear bond strengths in either of the storage groups. 44% (7 out of 16) of the combinations tested after 1-day of storage showed a significant association between the ARI scores and SBS values. Of these associations, 57% (4 out of 7) were positive associations and 43% were negative. A positive association implied that the higher the SBS, the higher the ARI score with the result that more cement remained on the enamel after debonding. In contrast, a negative association implied that the specimens with the lower bond strengths debonded with most of the cement remaining on the tooth producing a higher ARI score. 17% (2 out of 12) of the combinations tested after 180-days of storage showed a significant negative association between the ARI scores and SBS values.

A previous study, using Transbond, Phase II, Fuji Ortho LC and GC Fuji Ortho cements to bond Speed brackets to bovine enamel, showed a positive correlation between SBS and ARI
scores for both 1 and 7-days storage times (Coups Smith, 1997). This positive correlation implies that as the mean SBS increases, so does the ARI score. MacColl (1995) investigated the effects on SBS by sandblasting bracket base surfaces, reducing the base surface area and conditioning enamel with various acid types. In this study, the general trend was that higher shear bond strengths were associated with most of the cement remaining on the bracket base i.e. lower ARI scores (MacColl, 1995). Similarly, Sharma (1999) showed a negative linear relationship between the mean SBS and mean ARI scores. A high bond strength was correlated with a low ARI score. The results of the present study are in disagreement with all of the above findings since no consistent association was noted between the ARI score and SBS. According to O'Brien et al. (1988), the amount of cement remaining on the enamel after the debonding of bonded brackets is not related to the mean SBS of the separate interfaces but rather it is related to the bracket base characteristics and the properties of the cement used. The results of this study were in agreement with this conclusion in that SBS was not a determinant of ARI score. The ARI score as shown in this study was influenced by the modes of enamel surface treatment, the bracket base design and the chemical properties of the cement materials. The results of this study clearly indicated that bonding with Fuji Ortho LC cement without conditioning the enamel surface resulted in a significant shift in ARI scores distributions. (Table 27- Page 82) When the enamel surface was not conditioned with 10% polyacrylic acid the majority of the failures occurred at the enamel-cement interface (ARI scores of 0 and 1). On the other hand, enamel conditioning with 10% polyacrylic acid resulted in failures at bracket base-cement interface. Bracket base design also had an effect on the ARI scores regardless of the cement types used; Time and Transcend bracket bases performed differently from Speed and Clarity bracket bases respectively. In addition, chemical adhesion of Panavia21 cement to metal bracket bases resulted in a shift in the ARI score distribution. For Time and the Speed bracket bases bonded with Panavia21 cement, the bond failures occurred at enamel-cement interface rather than at the bracket base-cement interface as recorded for Transbond and Fuji Ortho LC (conditioned) cement. The results of the current study indicate that enamel conditioning is the variable that most significantly affects the bond failure pattern when considering all the factors that can influence bond failure pattern, i.e. bracket base design, cement type, enamel treatment and long-term storage.
Bracket Base Design and the Cement Particle Size Compatibility

The orthodontic literature lacks studies that are aimed at matching cement particle size with bracket base design. Currently, there is no information on the compatibility of cement particle size and bracket base design. It seems logical, however, that in order for cement particles to be micro-mechanically retained by the bracket base surface, the particle sizes should be compatible with the recesses and the undercuts on the bracket bases. The results of this study (Figure 7- Page 84) clearly demonstrated that the particle size of the Transbond, Panavia21 and Fuji Ortho LC cements were all compatible with the bracket base design of the Speed, Time, Transcend, and Clarity brackets.

The Ideal Bracket Base-Cement Combinations

In this study the clinical acceptability of each bracket base-cement combination using ARI scores and SBS values was assessed. As stated previously, a clinically acceptable system not only should produce reliable bond strengths over the course of orthodontic treatment, and minimize damage to the enamel during debonding, but should also be easy and practical to use. This system should not cause iatrogenic damage to enamel during bonding, over the course of treatment and debonding.

When considering SBS and ARI scores, both Transbond and Fuji Ortho LC cements produced clinically acceptable results with all the bracket base types. The Panavia21 cement combination with Time and Speed bracket bases resulted in unfavourable ARI scores. Similarly, Time-Panavia21 and Transcend-Panavia21 combinations produced SBS that were statistically significantly reduced over the long-term storage.

From a practical standpoint, even though Panavia21 cement required fewer steps of enamel preparation compared to the Transbond and Fuji Ortho LC cements it had, however, a low viscosity which may result in bracket slippage during the initial phases of cement polymerization. Panavia21 cement's low viscosity and bracket slippage did not pose a problem in this study because the brackets were held horizontally in place under the
weighted guide pin of an articulator. In a clinical situation, however, it is not practical to hold a bracket onto the tooth in a vertical position while the cement is polymerizing.

Of the two acceptable cements, Transbond and Fuji Ortho LC (conditioned), Fuji Ortho LC is considered to be a superior alternative for the following reasons:

1. Fuji Ortho LC uses a milder conditioner, 10% polyacrylic acid as compared to Transbond, which requires conditioning with 37% phosphoric acid. Coups Smith (1997) showed different enamel etch patterns using 10% polyacrylic acid compared to 37% phosphoric acid. The etch pattern created by 10% polyacrylic acid was less pronounced and not of honeycomb-like appearance as found with the 37% phosphoric acid. Based on this observation, Coups Smith (1997) suggested that polyacrylic acid creates less of a risk of damage to the enamel upon debonding and less of a risk of staining of the enamel over time, since the enamel would be less penetrated by the resin tags (Urabe, 1996).

2. Fuji Ortho LC cement, unlike the Transbond cement, is not moisture sensitive so that the brackets can be bonded to enamel that is contaminated with water and/or saliva.

3. It has been reported that less enamel damage occurs during clean up after the debonding of resin reinforced glass ionomer cements (Ostman-Andersson et al., 1993). According to Norevall et al. (1995) RRGIC can be more easily removed than RCLC at the time of debonding, since any cement remaining on the enamel surface can be desiccated by air-drying. This renders it more friable and removable (White, 1986). As a result, the likelihood of enamel damage being incurred after debonding GIC cemented brackets is less than that of those cemented with RCLC.

4. Fuji Ortho LC has the ability to release (Fox, 1990; Ashcraft et al., 1997) and absorb fluoride (Hatibovic-Kofman and Koch, 1991; Creanor et al., 1994). Glass ionomer cements release considerable amounts of fluoride and they have been shown, in vitro, to prevent demineralization of enamel (Forss and Seppa, 1990). It has also been reported that a less cariogenic flora is found in plaque deposits adjacent to GICs.
(Hallgren et al., 1992). Wright et al. (1995) studied the effect of resin-reinforced glass ionomer cement (RRGLC) on the oral microflora. Their results showed that levels of Lactobacilli and S.mutans (cariogenic bacteria) around the brackets bonded with RRGIC were reduced when compared with the conventional diacrylate resin cements.

**Future Research**

When this study was conducted there was no self-etching acidic primer available for orthodontic bonding purposes that would be compatible with currently available orthodontic cements. The studies of Bisahar et al. (1998a, 1999a) showed that acidic primer was only compatible with Panavia21 cement and could not be used with the Transbond cement. Recently, the Unitek Company introduced Transbond Plus Self Etching Primer™. This system is a unit-dose system, with conditioner, primer, adhesive, and micro-brush sealed into a triple-lollipop-shaped aluminium foil package. Acid conditioning, rinsing, and more than half of the cement remaining on the tooth. The Speed brackets bonded with Panavia 21 cement produced the poorest ARI aid to produce a well defined etch pattern similar to that of phosphoric acid (3M/Unitek, California) and it forms a micro retentive bond with the treated surface. It also allows the conditioner and priming monomer to penetrate at the same time, avoiding potential technique errors. Also no light polymerisation is required and moisture contamination is tolerated. This system is specifically designed for orthodontic bonding and is compatible with the Transbond cement. An orthodontic adhesive system such as this is of tremendous value since it can save valuable chair side time.

It is imperative that the manufacturer’s claims are tested, as there is no independent study conducted using this adhesive system. The protocol developed in this study can be used to evaluate the clinical acceptability of this product.
CONCLUSIONS

- SBS and ARI scores of 69% (11/16) and 83% (10/12) of bracket base-cement combinations were acceptable when tested after 1-day and 180-days of storage respectively.

- Bracket base design had a significant effect on the SBS at both 1 and 180-days of storage time. Speed and Transcend brackets produced higher SBS than Time and Clarity brackets respectively.

- Bracket base-cement combination had a significant effect on the ARI scores at both 1 and 180-days of storage time. Time and Transcend brackets in combination with Transbond and Fuji Ortho LC (conditioned and not-conditioned) cements produced higher ARI scores than the Speed and Clarity brackets. Metal brackets (Time and Speed) in combination with Panavia21 cement resulted in lower ARI scores than the ceramic brackets (Transcend and Clarity) irrespective of bracket base design. This was due to chemical adhesion of this cement to the surface of the metal.

- Cement type and the enamel treatment (conditioning or not-conditioning) had a significant effect on the SBS and ARI scores. Transbond produced the highest mean SBS at both 1 and 180-days of storage followed by Panavia21 and Fuji Ortho LC (conditioned). Fuji Ortho LC (not-conditioned) produced the lowest SBS values with all the bracket base designs tested in this study.

- Of all the cements tested (independent of bracket base design), Transbond and Fuji Ortho LC (conditioned) produced the best fracture mode by leaving more than half of the cement on the tooth.

- Conditioning with 10% polyacrylic acid had a statistically and clinically significant effect on the SBS and ARI scores. Based on these results, the not-conditioned protocol
when bonding with Fuji Ortho LC cement was not repeated for the long-term storage study.

- Transbond and Fuji Ortho LC conditioned cements were both compatible with the four bracket bases tested in producing clinically acceptable SBS and ARI scores, however, the most ideal cement for all the bracket base types tested in this study was Fuji Ortho LC (conditioned).

- Panavia21 cement showed that it had limited application in orthodontic bonding. Although it resulted in favorable bond failure patterns when used to bond ceramic brackets, bond failure patterns were unacceptable when Panavia21 was used to bond metal brackets. Panavia21 has chemical adhesive properties to metal but not to non-silanated ceramic. During debonding of metal brackets bonded with Panavia21, most of the cement was left on the bracket base.

- Of all the variables that can affect SBS and ARI scores, enamel conditioning had the most significant influence. Conditioning with 10% polyacrylic acid was a requirement when bonding with Fuji Ortho LC cement.

- Long-term storage had no effect on the clinical acceptability of various bracket base-cement combinations. After 1 and 180-days of storage, the Speed-Panavia21 and Time-Panavia21 combinations produced unacceptable ARI scores. Storage time of 180-days had a significant effect on the SBS of 25% (3 out of 12) of the groups tested. After 180-days of storage, 17% of the samples showed statistically significant (P<0.05) increase in SBS and 8% showed a significant reduction in SBS. These changes were not, however, clinically significant.

- Un-weighted Kappa confirmed agreement within and between investigators when assigning ARI scores. There was consistency in assigning ARI scores by the same investigator over time, and also between two different investigators.
- There was no consistent association between the ARI scores and SBS in this study.

- The particle sizes of Fuji Ortho LC, Transbond, and Panavia21 cements were compatible with base designs of Speed, Time, Transcend, and Clarity brackets.
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