



Wear Studies of Enamel and Some Restorative Materials

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Declaration

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Summary

Recent demands for more aesthetic restorative materials and the controversy surrounding the use of mercury have encouraged the development of composite resins and glass ionomer cements (GIC's) as alternatives to currently used amalgam alloys. Since the introduction of these materials, their basic chemistry has changed significantly to improve their physical and mechanical properties, however they still suffer from low wear resistance in load bearing areas.

In this study a systematic approach to the analysis of wear has been adopted. This involves:

- The *in vitro* analysis of the wear of standard composite resin and GIC's restorations under controlled conditions.
- The qualitative and quantitative investigation of wear over a range of pH's and loads which might be encountered clinically in order to develop a "wear map" of the micro-morphology of wearing teeth and restorations and a systematic modeling of wear rates.

Under neutral conditions there were significant differences between wear rates at the highest loads compared with rates at the lowest load and a consistent tendency for wear rates to increase with load for all of the materials and for enamel.

At pH=3.3 resembling acidic diet mean wear rates of enamel were significantly higher than those at pH=7.0 ($p < 0.05$). In addition the rate of enamel wear was consistently higher than the wear rates for any of the restorative materials across the range of loads.

More chemical erosion was evident for GIC's particularly for conventional-GIC. Even though there was no significant difference between mean wear rates for resin modified-GIC and conventional-GIC, resin modified-GIC appeared to exhibit relatively smoother and stable surfaces than conventional-GIC.

At lowest pH (1.2) enamel and all of restorative materials showed significantly higher wear rates than were evident at higher pH's (7.0, 3.3). Enamel and conventional-GIC appeared to be more sensitive to acidic pH showing extensive chemical destruction.

In absence of load, all materials showed significantly lower wear rates with less evidence of surface and marginal breakdown than when subjected to acidic conditions in absence of load.

Finally, statistical modeling of the wear rate data suggested that:

- Enamel is influenced most by variation in pH compared with composite resin which is least affected by acid.
- Conventional-GIC is more susceptible to the effect of variation in pH than composite resin.
- The acid susceptibility of resin modified-GIC is intermediate between that of composite resin and conventional-GIC.
- The load dependant wear rate of resin modified-GIC is intermediate between that composite resin and conventional-GIC.
- Enamel and conventional-GIC are affected similarly by load.
- Composite resin is relatively resistant to wear at higher loads.

The fact that properties of resin modified-GIC are consistently intermediate between those of composite resin and conventional-GIC reflects in intermediate composition.

The results of this study have provided new sights into both qualitative and quantitative aspects of wear of selected aesthetic restorative materials over a range of conditions providing a basis for further studies.

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SECTION 1

INTRODUCTION

Wear is a common phenomenon in dentistry resulting from:

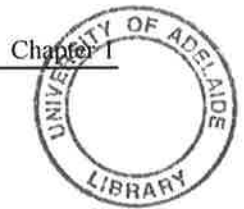
- direct contact between the teeth, restorations or prostheses during mastication or parafunctional movements
- the effects of abrasive substances
- the chemical effects of acids from various sources

Under some circumstances, non-carious lesions of dental tissues can be regarded as a normal physiological process that occurs throughout life (Pindborg, 1970). However, if the rate of loss or the degree of destruction becomes excessive, it can cause functional or aesthetic problems and sensitivity for patients (Bishop et al., 1997).

The diagnosis and management of tooth wear presents a number of problems for the clinical dentist. These include:

- difficulties in deciding whether or not tooth wear is excessive, particularly if decisions are based on comparisons with “normal” rates because of limited and conflicting data about what constitutes “normal” wear.
- problems in identifying and modifying the aetiological factors contributing to the various forms of dental wear.
- difficult decisions associated with the selection of appropriate restorative strategies when little information about the wear characteristics of materials is available.

This report describes an *in vitro* investigation of the wear characteristics of a range of commonly used aesthetic dental restorative materials. Experiments were conducted under controlled conditions simulating those that might occur naturally, to provide new information about the performance of the selected materials when subjected to wear at a range of loads and under different environmental conditions.



Chapter 1

Aetiology of Dental Wear

Understanding dental wear requires a detailed knowledge of the potential factors involved in its aetiology. Over the years, many factors have been implicated. These include **specific dental factors, general health factors, and environmental factors.**

Of the significant dental factors, it has been suggested that a number of **occlusal factors** contribute to wear. For example, evidence has been provided suggesting that a reduced number of teeth will lead to increased dental wear (Carlsson and Ingervall, 1988; Ekfeldt et al., 1990; Hansson and Nilner, 1975; Johansson et al., 1993; Silness et al., 1997). However, in one study by Smith and Robb (1996) no clinically significant relationship was found between the number of missing posterior teeth and wear of the anterior teeth. In some studies on ancient skulls a gradual transition from a normal horizontal overbite in the incisor region to an edge-to-edge relationship in those showing excessive tooth wear, has been found (Murphy, 1959; Reinhardt, 1983).

Severe tooth wear is considered to be associated with **high bite** forces (Karlsson and Carlsson, 1990). However, in one study by Dahl et al. (1985) no significant differences in bite force were found between a dental wear group and a control group. The

correlation between tooth wear and over-bite/over-jet is also often discussed in connection with bite force (Beyron, 1954; Garner and Kotwal, 1973).

The effect of opposing **restorative materials** can also significantly influence rates of tooth wear. For example, some experiments have shown porcelain to be destructive to opposite enamel (Monasky and Taylor, 1971; Ratledge et al., 1994). Furthermore, some restorative materials have the potential to accelerate tooth wear, particularly on occluding surfaces in parafunctional patients (Jacobi et al., 1991).

Correlations between conditions associated with **hyperfunction**, such as bruxism, and dental wear have often been demonstrated (Kleinberg, 1994; Pavone, 1985; Tsolka et al., 1995). In some studies, tooth wear found in bruxism had a strong association with dental erosion (Khan et al., 1998; Xhonga, 1977). Bruxism is also suggested as a possible common aetiologic mechanism that may account for the relationship between childhood and adult tooth wear (Knight et al., 1997).

Several investigations of Australian Aboriginals have revealed a strong correlation between **age** and the degree of tooth wear. This could be associated with the consumption of abrasive foods and the use of teeth as tools (Beyron, 1964; Molnar et al., 1983). Richards and Miller (1991) found a high correlation between age and tooth wear in Australian Aboriginals. In one study by Donachie and Walls (1995), increasing wear of all cervical and occlusal/incisal tooth surfaces was observed with increasing age. There is general agreement that tooth wear is age related (Beyron, 1964; Ekfeldt et al., 1990; Salonen et al., 1990).

Recent research has suggested the relationship between age and wear might be more complex in some contemporary populations. There is evidence that pathologic tooth wear is increasing not only in middle-age groups but also in younger subjects (Bishop et al., 1994; O'Brien, 1994). This changing relationship between age and wear has been

attributed to changing life styles and social pressures (Smith and Knight, 1984; Carlsson et al., 1985; Kelleher and Bishop, 1999).

There have been conflicting reports in the literature of **sex differences** in tooth wear. Several investigations have claimed a tendency for men to have more wear than women (Donachie and Walls, 1995; Johansson et al., 1993; Smith, 1996; Young, 1995) but in one study by Dahl et al. (1989) no difference was found between genders.

Dental wear has been related to some **gastrointestinal disturbances** such as hiatus hernia, habitual regurgitation and chronic indigestion. *Perimylosis* is a common feature in cases of hiatus hernia and gastritis (Carlsson et al., 1985; Eccles, 1979; Järvinen et al., 1988).

Two studies found an increase in the incidence of tooth wear in subjects with **chronic alcoholism** (Smith and Knight, 1984; Smith and Robb, 1989). The ingestion of a large amount of alcohol was found to produce chronic gastritis causing subclinical regurgitation, which increased the incidence of tooth erosion. Some authors have described enlargement of the parotid glands in alcoholic people (Barsanyi and Blanchard, 1961; Mandel and Baumash, 1971). However, Echart et al. (1981) found normal saliva flow from these glands in one group of alcoholics.

Anorexia and bulimia are psychosomatic diseases with oral manifestations. Patients with eating disorders may show teeth erosion, reduced salivation, and sometimes an increased incidence of caries (Andrew, 1982; Hellstrom, 1977, Hurst et al., 1977).

Several anthropological studies have been undertaken to investigate dental wear in groups, such as Eskimos and Australian Aborigines (Beyron, 1964; Nowell, 1978). Powerful chewing and the presence of abrasive particles in food have been considered to cause dental wear. In modern societies, **dietary patterns** have changed and abrasive wear is less common. However, tooth erosion has been reported, due to excessive intake

of citrus-based drinks, some carbonated soft drinks and recently introduced “sports drinks” all of which have a low pH (Eccles and Jenkins, 1974; Kelleher and Bishop, 1999; Pindborg, 1970; Young, 1998).

The total **contact time** between opposing teeth is suggested to be an important factor for the development of tooth wear (Dahl, 1987). There is significant variation between individuals in the amount of time that teeth are in contact each day. Graf (1969) estimated 17.5 min/day as the average time contact during normal function while most bruxers exhibited longer times contact (Clark and Townsend, 1984).

Saliva dilutes and buffers any acid entering the mouth and lubricates the occluding surfaces during mastication. Reduction in flow rate and the buffering capacity of saliva has been shown to be associated with increased tooth wear (Carlsson et al., 1966; Carlsson et al., 1985; Khan et al., 1998, 1999; Smith, 1991; Young, 1995). Smith (1991) found an increase in tooth wear on the side from which a parotid gland had been removed surgically. Patients with Sjogern’s syndrome who suffer from low saliva flow, have shown severe tooth erosion and prolonged sensitivity (Atkinson and Fox, 1993). Some drugs have also been found to increase the severity of tooth wear (Milosevic et al., 1999).

Several investigations have demonstrated the effect of **environmental factors** on tooth wear (Dahl et al., 1993; Young, 1995, 1998). In a comparative study of young adults in Sweden and Saudi Arabia, greater prevalence and severity of tooth wear was found in Saudi Arabia associated with the sandy environment (Fareed et al., 1990; Johansson, 1992). Furthermore, people who work in some industrial environments have shown more teeth wear. For example, erosive lesions are often observed in workers exposed to acid vapours and miners have shown more occlusal wear associated with their work (Enbom et al., 1986). Environmental erosion predominantly affects the labial surfaces of maxillary and mandibular incisors (Bishop et al., 1997; Kelleher and Bishop, 1999). The

degree of destruction depends on length of exposure, lip level, and acid concentration (Ten Bruggen, 1968).

A range of **other factors** have also been implicated in the aetiology of dental wear. For example, extensive tooth wear is common in patients with dental tissue disorders such as dentinogenesis imperfecta and amelogenesis imperfecta.

Toothbrushing may also cause non-carious lesions on the cervical third of the teeth which usually are called “cervical abrasion” (Radentz et al., 1976) or “cervical erosion”. In recent times the relationship between mechanical abrasion in the cervical region and abfraction has made the exact interpretation of these lesions more complex (Imfeld, 1996).

Conclusion

For clinicians, identifying the aetiological factors involved in the development of tooth wear is necessary when making decisions about the long-term prognosis for the dentition and in planning restorative therapy understanding aetiological factors is required before appropriate treatment can be undertaken.

Similarly, to advance our understanding of the basic mechanisms involved in tooth wear requires carefully planned experiments and clinical studies that appropriately control for the complex relationships between these aetiological factors.

CHAPTER 2

Terminology of Dental Wear

Introduction

In clinical dentistry a large number of specific, and often inconsistent, terms have been used to describe aspects of dental wear. Recently, Mair (1992) used the terms “attrition”, “abrasion” and “erosion” to describe wear of both teeth and dental materials. The use of these specific terms has gained fairly widespread acceptance.

Attrition occurs whenever there is tooth to tooth contact particularly in parafunctional activity. It has also been called occlusal-contact-area wear (Lambrechts et al., 1989). Facets of this type are characterised by well-defined borders, highly polished, shiny and smooth surfaces with parallel scratch marks.

Primarily, attrition affects the occlusal and incisal surfaces, while slight loss may occur in the approximal contact points. It results in flattening of the cusp tips or incisal edges with associated wear facets on the occlusal or palatal surfaces (Lutz et al., 1984). If a restoration is involved in the occlusal contact area, similar facets appear on restorations (Lambrechts et al., 1984). When the contact area involves a restoration margin, the facet

will appear on both the tooth and restoration (Mair et al., 1990). Flattening of the interproximal contact points is also a form of attrition (Imfeld, 1996).

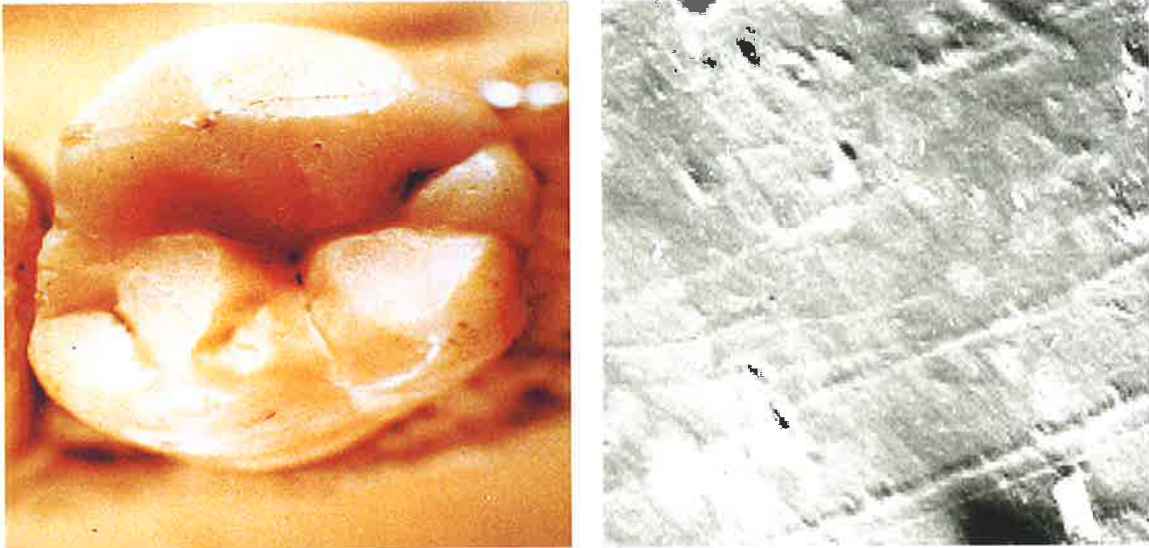


Figure 2.1 Flat and well defined wear facet on third molar showing attrition wear (left) and SEM of wear facet (right).

Although the most common cause of attrition is probably parafunctional activity, such as bruxism, tooth wear can be observed in patients with “primitive” diets (Boero, 1989; Smith, 1989).

Abrasion is caused by friction from an abrasive foreign body and is independent on contact between the teeth. The amount of wear increases with higher contact pressures (Sarkar, 1980). When compared with attrition facets, areas of abrasion shows less well defined borders and a slightly dull appearance.

Every (1972) explained abrasion as tooth wear arising from friction as exogenous materials are forced over the surface by incisive, masticatory and grasping function. The abrasive materials may be any substances foreign to the tooth. A high prevalence of abrasion has been found among prehistoric and aboriginal populations (Berry and Poole, 1974; Beyron, 1964) where abrasive particles within food accelerate wear. In addition, a

dusty environment can cause abrasion. For example, in iron-works employees, miners, and quarry-men, this type of tooth wear is common. Furthermore, climatic conditions

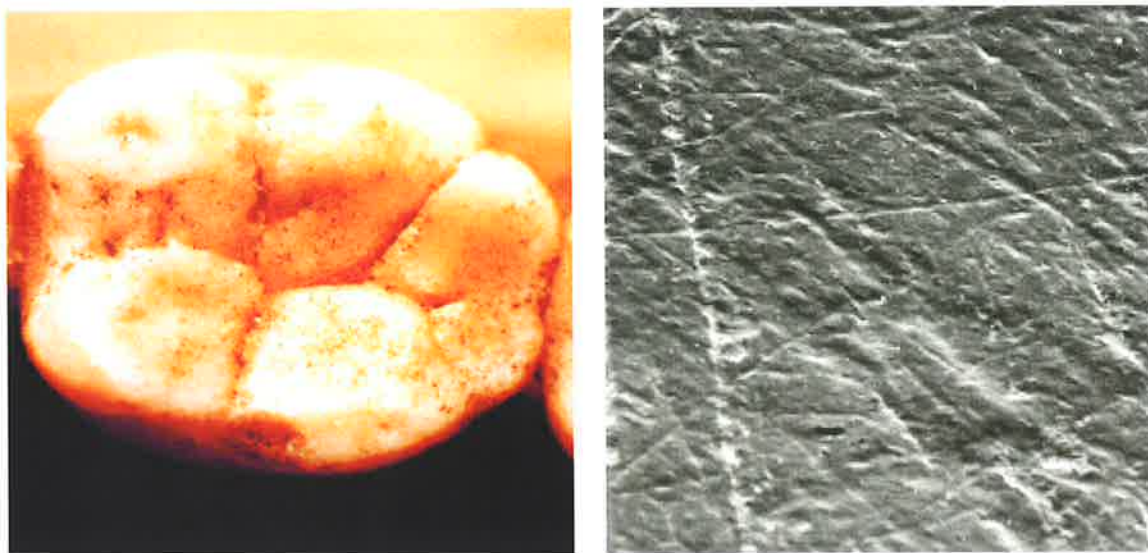


Figure 2.2 Pitted appearance over lower third molar showing abrasion wear (left), and SEM of facet wear (right).

(For example, a dry and dusty environment) can be associated with increased wear rates (Johansson, 1992). Abrasion on proximal surface can be caused by extensive use of inter-dental cleaning device such as tooth picks or inter-dental brushes, particularly, when they are used with toothpaste or toothpowder (Imfeld, 1996).

Erosion results from a chemical reaction between non-bacterial acid causing enamel to lose its shiny appearance, taking on a matte sheen (Johansson and Omar, 1994; Sarkar, 1980).

A range of intrinsic and extrinsic acids can cause erosive wear (Mair, 1992; Young, 1998). Intrinsic acid generally affects the palatal surfaces of maxillary anterior teeth while extrinsic acids affect the dentition more randomly (Johansson and Omar, 1994). It has been suggested that citric acid is the most destructive acid (Sarkar, 1980) although erosion can result from other acids. Erosion is evident in patients with anorexia, bulimia, chronic indigestion, heartburn chronic alcoholism (Mair, 1992; Smith, 1989), and hiatus

hernia (Nunn et al., 1996). Frequent swimming in heavily chlorinated water or occupational exposure to acids can cause also cause erosion (Centerwall et al., 1986).

Because of the role of acid in the aetiology of erosion, there is the potential for confusion between caries and erosion. The significant difference is that caries results from acids produced by plaque bacteria during metabolism of dietary sugars and it is limited to plaque covered sites. In contrast, erosion results from dissolution by acids which are not of bacterial origin and it is less localized and generally more rapid than caries (Nunn et al., 1996).

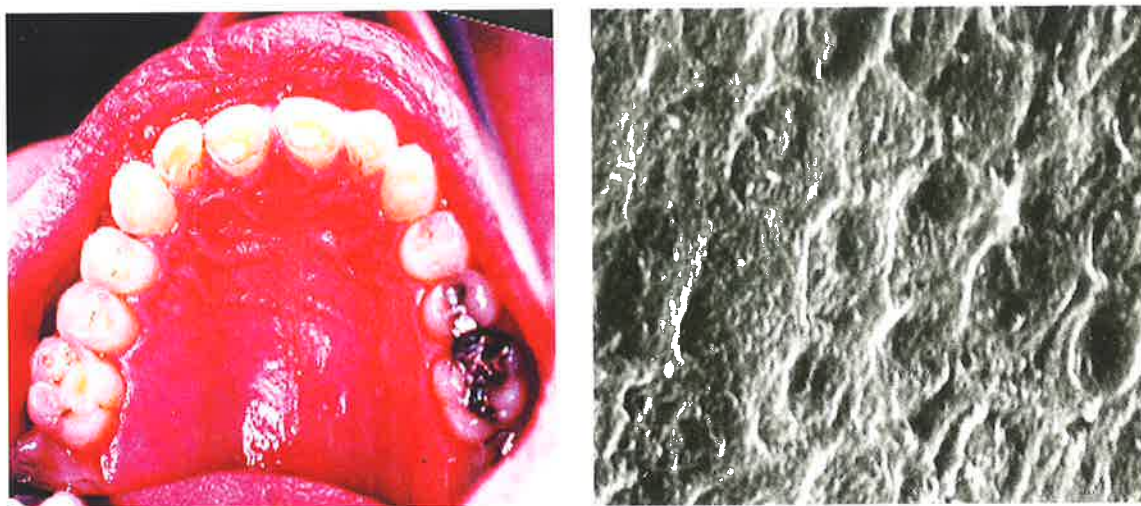


Figure 2.3 Eroded surface of occlusal surfaces of the upper teeth showing erosion wear (left), SEM of eroded surfaces (right).

Sarkar (1980) classified erosion lesions as:

- “Dish Shape Lesions” on the labial surface of incisors which show shallow saucer-shaped depressions. These lesions can be arrested if the conditions change. However, if the aetiological conditions prevail, the lesions extend and shallow depressions become “U-shaped lesions”.
- “Wedge Shape or V-Shape lesions” usually appear as thin straight lines near the cemento-enamel junction on the buccal surfaces of posterior teeth

- “Irregular Shape lesions” are common on proximal and lingual surfaces and appear to be related to environment conditions such as when the atmosphere is laden with chemical fumes and dust.

Perimylosis is special type of erosion resulting from a low pH along the tongue border combined with muscle hyperactivity of tongue. The palatal surfaces of the maxillary teeth are most commonly affected (Dahl et al., 1993).

Conclusion

A variety of terms particularly in the field of material science have been used to describe wear. In recent times the terms attrition, abrasion, and erosion have been used to describe the wear of both teeth and dental materials.

CHAPTER 3

Tribology

Introduction

Tribology is the science of the interaction of surfaces in relative motion (Dahl, 1993). Moore (1975) defined tribology as “the science and practice of friction, lubrication and wear applied to engineering surfaces in relative motion”. The definition can be extended to include an understanding of surface interactions in detail and the prescribing of improvements in given applications.

According to Dr. Salomon, former editor of the international journal “Wear”, “Tribology means a state of mind and an art: the intellectual approach to a flexible cooperation between people of widely differing background. It is the art of applying operational analysis to problems of great economic significance, namely: reliability, maintenance and wear of technical equipment ranging from spacecraft to household appliances.” (Moore, 1972).

The oral environment is an ideal site for wear because:

- normal forces during mastication can be large and have been reported to be around 75 to 90 kg.
- very large forces are applied during parafunctional activities.

- the instantaneous temperature change during the ingestion of food and liquids may be around 65°C which can produce dimensional changes in restorative materials.
- tooth surfaces are usually coated with a film salivary pellicle which resists acid.
- ingested food and other substances can also be extremely destructive (Phillips, 1966).

Factors such as these contribute to the complexity of the oral environment and put both the teeth and restorative materials at risk of different types of wear (Dowson et al., 1976).

Mechanisms of Wear

Generally, all materials have rough surfaces at a microscopic level with the highest polished surfaces having irregularities (known as asperities) of approximately 0.05 μm (Bowden and Taylor, 1950; Reid et al., 1990).

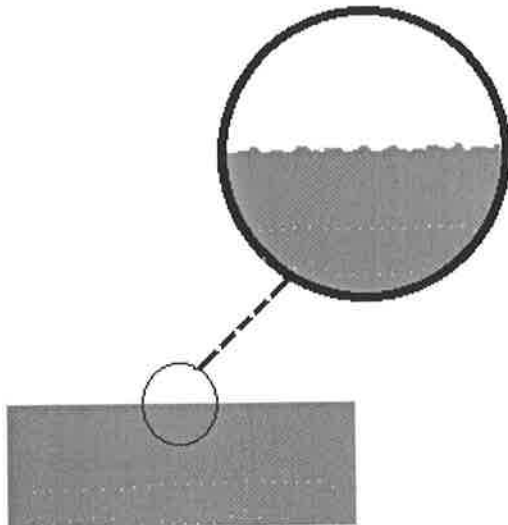


Figure 3.1 Material surface under high magnification.

Consequently surfaces meet as point-to-point contact between their asperities which can deform both elastically and plastically. When two surfaces slide against each other, adhesion and deformation between the contacting asperities happens (Mair 1992; Reid et al., 1990).

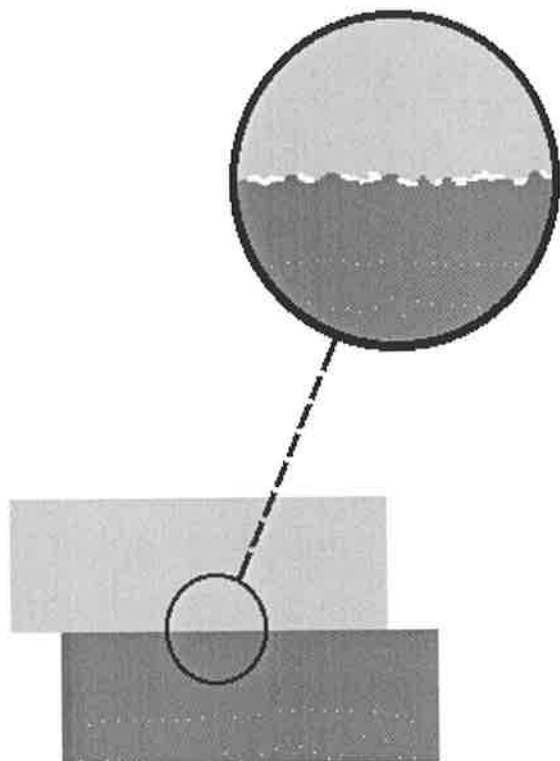


Figure 3.2 Microscopic details of contact surfaces.

The wear mechanism of materials is a complex process that occurs whenever two or more surfaces move in contact with one another (Dahl et al., 1993; Mair et al., 1996; Sarkar, 1980; Zum-Gahr, 1997). The Institute of Mechanical Engineers of the United Kingdom described wear as “the progressive loss of substances from the surface of a body brought about by mechanical action” (Mohd and Aziz, 1990). It has been customary to regard tooth wear and material wear as separate fields of research, however the same fundamental processes are active on all structures (Mair et al., 1996). In the study of dental materials, wear resistance of materials and the likely effect of these materials on the opposing teeth must be considered.

Tribologists (Dahl et al., 1993) describe the most common forms of wear as:

- Adhesive wear arising from direct contact between opposing surfaces.
- Abrasive wear involving both two-body and three-body wear.
- Fatigue involving the propagation of sub-surface cracks.
- Corrosive wear involving chemical destruction.

Each of these involves different kinematics and specific mechanisms depending on the physical and chemical interactions between the elements of the tribosystem.

Adhesive wear

This type of wear occurs during relative movement of opposing surfaces and results in transfer of material from one surface to another by shearing of the asperities which come into contact (Halling, 1975; Mair et al., 1996; Reid et al., 1990). Initially, local cold-welding occurs between asperities (Mair, 1992). Further movement of surfaces results in fractures of these welds. However, these lines of separation are not necessarily coincident with the original weld. As a result of this transfer, plates of material may build up on one surface and subsequently break away producing a three-body abrasive slurry (Mair, 1992; Sarkar, 1980; Zum Gahr, 1997).



Figure 3.3 Schematic presentation of adhesive wear.

Halling (1975) developed a simplified law to describe adhesive wear. It assumes that the contact is made up a number of similar asperities each of radius α . The area of each contact is $\pi\alpha^2$ and each contact supports a maximum load $\rho\pi\alpha^2$ where ρ is the pressure. The wear fragment produced at each asperity is considered hemispherical in shape, with α volume of unit $2/3\pi\alpha^3$. The total wear volume Q per unit distance of sliding is:

$$Q = \sum \frac{\frac{2}{3}\pi\alpha^3}{2\alpha}$$

or

$$\frac{1}{3}\pi\alpha^2n$$

n shows the total number of contacts and each contact supports a load of $\rho\cdot\pi\alpha^2$,

$$n\pi\alpha^2 = \frac{W}{\rho}$$

therefore total load (W)

$$W = \rho\cdot\pi\alpha^2n$$

or

$$Q = \frac{W}{3\rho}$$

In this equation, it is assumed that all asperity encounters produce a wear particle. If only a fraction k of all encounters produce wear particles then

$$Q = k\frac{W}{3\rho}$$

Where k is the probability of an asperity contact producing a wear particle.

This simplified law of adhesive wear proposed by Halling (1975) which was based on by Burwell and Strang (1957) implies that the volume of wear is:

- proportional to the distance of travel (Q).
- proportional to the load (W).
- inversely proportional to the yield stress (ρ), or the hardness, of the softer material.

Abrasive wear

This is the most common type of wear. It occurs when hard asperities plough into softer surfaces (Mair et al., 1996). It can also be described as “the cutting away of a surface by abrasive asperities or particles” (Mair, 1992). If there are many sharp protrusions on a softer surface then these are cut by the abrasive surface. If the surface is smoother, the abrasive asperities plough into it.

Generally, abrasive wear is proportional to the:

- hardness of the materials in contact,
- geometry of abrasive particles,
- load
- sliding distance (Abebe and Apple, 1988; Richardson, 1967)

Physical characteristics of the abrasive particles including size, hardness, and shape have been shown to affect their ability to wear surfaces. Coarse particles produce more wear and rougher surfaces. The hardness of particles relative to that of each of the two rubbing surfaces is also important. In order to survive as a loose rolling particle between two surfaces, it should be harder than opposing surfaces. The shape of abrasive particles has also been shown to affect the amount of wear with angular particles causing more wear than round particles (Söderholm, 1998).

Abrasive wear is subdivided into two types:

Two-body abrasion is caused by hard protuberances or embedded particles (Zum Gahr, 1997) where the cutting asperities are fixed to one or both surfaces such as files, wheels and sandpaper. In this type of abrasion, the shape of the harder or sharper surface penetrates the softer surface (Mair, 1992).

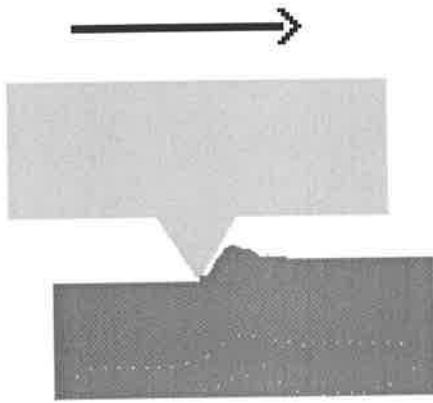


Figure 3.4 Schematic presentation of two-body abrasive wear.

As abrasive particles are firmly attached to one of the surfaces, they move forward and hit and scratch any object in front of their moving path. A typical example of this type of wear is cutting tooth structure with a diamond bur (Söderholm, 1998). Materials can be removed from a softer surface by three different mechanisms: microplowing, microcutting, and microcracking (Friedrich, 1984).

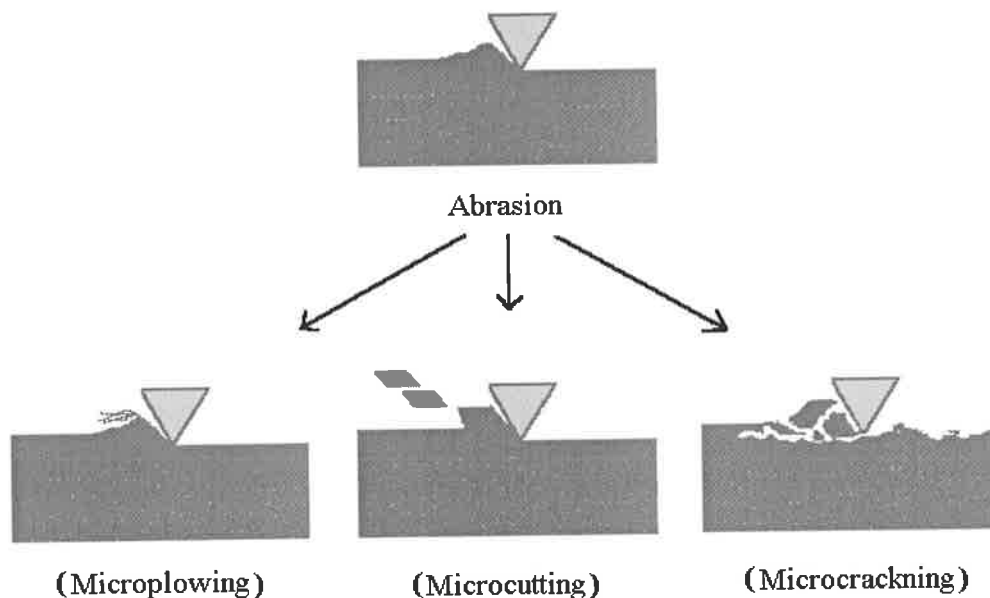


Figure 3.5 Schematic presentation of different types of two-body abrasive wear.

Three-body abrasion occurs when the hard particles can move freely (roll or slide) between the contacting surfaces. Generally, there is slurry of loose, abrasive particles

between the surfaces. The slurry may 'hollow out' the softer areas in a heterogeneous surface (Mair, 1992). As there is slip between two surfaces, the abrasive particles slide, and plow furrows, rotate, and find their path of least resistance. Angular particles generally cause higher wear than spherical particles. However, in three-body abrasion, particle shape should be less important because the loose particles can reorient themselves during sliding and rolling contact (Söderholm, 1998).



Figure 3.6 Schematic presentation of three-body abrasive wear.

To obtain a quantitative expression for abrasive wear, Halling (1975) assumed a simplified model, involving a single asperity creating a track through the softer surface as shown in Figure 3.7.

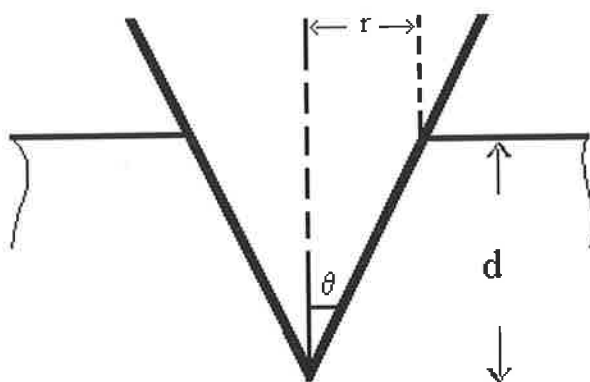


Figure 3.7 Schematic diagram of mathematical relationship of abrasive particle and softer surface.

In this model $d=r \cot \theta$, the volume displaced by one asperity in unit distance = $r^2 \cot \theta$. If materials considered to be yielded under normal load, the total normal load with n asperity contacts is

$$W = \frac{n\pi r^2 \rho}{2}$$

and the total volume displaced in unit distance is

$$Q = \frac{2W \cot \theta}{\pi \rho}$$

This equation is based on a simple model and is expressed in the same form as the adhesive wear equation and similarly implies that the volume of wear is:

- proportional to the distance of travel.
- proportional to the load.
- inversely proportional to the yield stress, or the hardness, of the softer material.

Alternatively Halling (1975) proposed that a wide range of abrasive situations can be described by the equation:

where H is the hardness of the softer material and ka is the abrasive wear constant.

This equation describes two-body abrasive wear but in three-body abrasive wear ka will be lower because many particles will tend to roll rather than slide.

Fatigue wear

Fatigue wear occurs when two surfaces move under dynamic loads. This results in the formation and propagation of subsurface microcracks. Cyclic loading of surface layers

with repetitive compressive and tangential stresses cause subsurface cracks to grow and to propagate to the surface with subsequent loss of material (Friedrich, 1984; Söderholm, 1998).

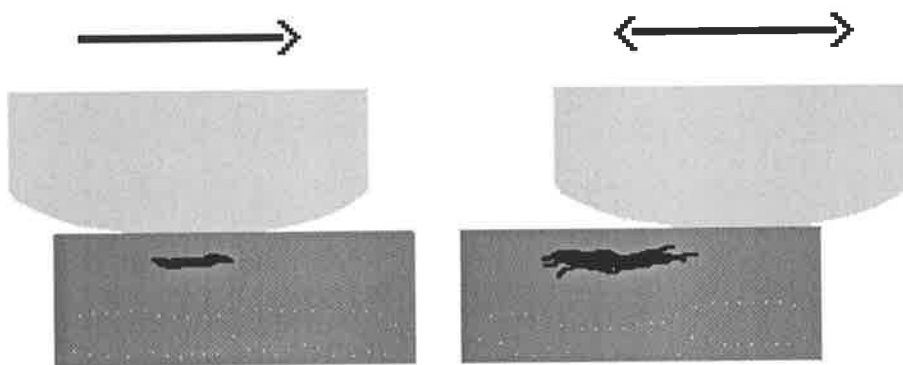


Figure 3.8 Schematic presentation of fatigue wear.

Reid et al. (1990) considered two types of loading, reversed loading and steady loading in the presence of a chemically active agent.

Suh (1973, 1977) introduced the delaminating theory for fatigue wear, which is based on dislocation at the surface, sub-surface cracking and void formation and subsequent joining of shear deformation of the surface.

According to this theory, when two moving surfaces are in contact, normal and tangential loads are transmitted through the contact points by adhesive and plowing actions. Asperities of the softer surface are easily deformed and some are fractured due to repeated loading action. Either deformation of asperities or removal of them, generate a relatively smooth surface. Once the surface is smooth; the contact is more plane contact rather point-to-point contact. The harder asperities exert surface traction on the softer surface. This induces plastic shear deformation, which is accumulated with repeated loading. Cracks are nucleated below the surface as subsurface deformation continues. Further loading and deformation causes cracks to extend, to propagate laterally, and to link to each other.

Finally, when these cracks shear to the surface in certain weak sites, long and thin wear sheets “delaminate”. The amount of wear depends on the location of subsurface crack growth, which is controlled by the normal and the tangential loads at the surface.

Sometimes the term fatigue and delaminating are used synonymously (Mair, 1992).

Corrosive wear

Corrosive wear occurs by the interaction of chemical degradation and movement of the surfaces (Mair, 1992; Sarkar, 1980). In some classifications the term “tribochemical wear” is used to distinguish this form of surface loss from static corrosion which happens in the absence of movement (Dahl et al., 1993; Söderholm, 1998).

When two surfaces are rubbing in a corrosive environment, either gaseous or liquid, then surface reactions occur. Reaction products can be on one or both surfaces. As reaction products are poorly adherent to the surfaces, further rubbing removes them from surfaces. The nature of the reaction products depends on the composition of the environment (Halling, 1975). The warm, humid environment of the oral cavity is most conducive to corrosion.

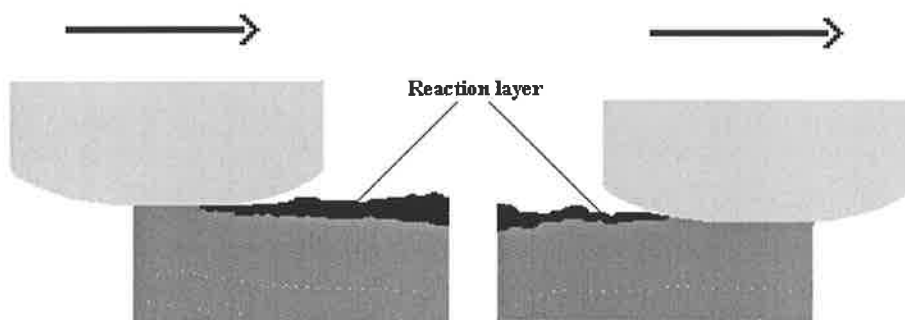


Figure 3.9 Schematic presentation of corrosive wear.

Other types of wear

Tribologists have described a number of other types of wear. These include fretting wear resulting from prolonged slow slipping between surfaces under load (Mair, 1992), erosion, cavitation and impact chipping (Halling, 1975).

Conclusion

The science of tribology draws on knowledge derived from many inter-related areas of research to provide a clearer insight into the mechanisms of wear than has been provided by the terminology and understanding applied by dentists working alone.

Tribologists have provided clear descriptions of wear mechanisms and general mathematical models to quantify the main types of wear affecting teeth and restorative materials in the oral environment. Under most conditions wear of dental tissues and materials involves:

- Adhesive wear arising from direct contact between opposing surfaces. This accounts for some of the wear described by clinicians as attrition.
- Abrasive wear involving both two-body and three-body wear. In clinical dentistry this accounts for some of the wear associated with attrition (after the formation of a slurry including enamel fragments) and for abrasion.
- Fatigue wear involving the propagation of sub-surface cracks and subsequent surface loss.
- Corrosive wear involving chemical destruction in the presence of surface-to-surface contact.

Chapter 4

Assessment of Dental Wear

Introduction

Over the years numerous methods have been developed to describe the extent of functional loss of teeth and restorative materials. Advancing technology, required resolution, and reproducibility within and between observers have been among the factors that have contributed to the development of new methods. Each of the methods has offered both advantages and disadvantages.

Wear assessment methods

The range of proposed methods for wear assessment can be considered as:

- non-instrumental methods.
 - direct
 - indirect
- instrumental methods

The **non-instrumental methods** are generally simple, inexpensive, fast and well suited for clinical studies involving large numbers of subjects (Stephen et al., 1994).

The **direct, non instrumental methods** have the advantage that they do not require the fabrication of models or replicas. These methods include:

— United State Public Health Service (USPHS) or Ryge System.

In this method, teeth and restorations are evaluated at fixed time intervals for marginal adaptation, anatomic form, color match with the surrounding enamel, and cavo-surface marginal discoloration with the aid of a mirror, dental probe, and operating lamp (Cvar and Ryge, 1971). The method is simple, fast, and inexpensive however, it is not sufficiently sensitive to distinguish the early stages of wear (Leinfelder, 1987; Ratledge et al., 1994; Taylor et al., 1989). Furthermore, the data derived by this method can not be used easily with more powerful statistical analyses (Leinfelder, 1987).

— Smith and Knight Method

Wear measurement in this method is based on the degree of worn enamel, the area of the exposed dentine, and the reduction in length of the clinical crown on the incisal and occlusal surfaces (Smith and Knight, 1984). Wear scores are assigned by comparison with standard illustrations with the scores subsequently compared with age standards to facilitate judgments about the rate of wear for a subject.

— Olio System

This system is a combination of a qualitative evaluation with the clinical estimation of the need for treatment (Olio et al., 1987). The disadvantage of this system is the subjectivity of the process, which might cause a reduction in the discriminating power (Roulet, 1987; Vrijhoef et al., 1985).

The most commonly reported **indirect, non instrumental methods** include:

– Goldberg method

In this method, restored teeth are compared with a standard calibration series of models exhibiting different levels of material loss. Wear varies from “no wear” to “extensive wear” (Goldberg et al., 1984). To find this standard series, a microscope was used to measure the difference in height between the occlusal surface of composite restoration and the cavo-surface margin. The most significant advantage of this method is that conventional parametric statistical analysis can be used to evaluate the obtained data (Leinfelder, 1987).

– Leinfelder method

In this method, restorations are compared with standard casts. To derive the standard models, silicone impressions were made of a selection of models of restorations. These impressions were sectioned in three planes in the bucco-lingual direction. With the aid of floodlighting, the loss of materials on the cavity wall was measured from the shadows (Leinfelder et al., 1983, 1986). This method has been partially confirmed using laser profiling (Stephen, 1994).

Instrumental methods

These methods generally involve more expensive but more accurate technology. There are many instrumental methods. They include:

– Handelman method

This method was initially developed for the volumetric assessment of *in-vivo* wear of pit and fissure sealants. It is based on the weight of a film of impression material between tooth replica fabricated after a period of wear and a silver coping constructed immediately after sealing (Handelman et al., 1978). Urquiola and Charbeneau (1981) applied a similar method using mercury instead of impression materials. These methods are not very expensive but no distinction can be made

between contact-area wear and non-contact area wear (Kreulen and Van Amerongen., 1991).

Stereomicroscope

This method, introduced by Mettler et al. (1978), involves a contact-free measurement using a stereo-microscope in which the vertical location of a measurement point is established by the movement of the two microscope objectives to bring the “cross-hairs” in the objective into focus. The main disadvantage of this method involves the definition of the reference plane which usually involves the highest point of a cusp tip. This can lead to inaccuracy as the cusp tips are worn (Kreulen and Van Amerongen, 1991).

Stereometric technique

This method uses stereo-photographs to generate contour plots from which volumes are derived. Adams and Wilding (1985) used this method to monitor changes in residual alveolar ridge morphology. The disadvantages of this method include the problems involved in obtaining high-resolution stereo-paired photographs and the difficulties encountered in obtaining results in analog form (Adams and Wilding, 1988).

Profilometry

Most designs for profilometers involve a movable stylus that is connected to an X-Y recorder. The X-Y coordinate information can be used to produce images of the surface profile and to quantify changes in surface profile. Three reference points on the profiling surface permit accurate alignment and repositioning. Winkler et al. (1996) found the computer-controlled custom profilometer 61% more accurate than visual estimation and measurements obtained by means of a profilometer gave almost the same wear values as those derived from more complex image-analyzing systems (Kawai and Tsuchitani, 1994.)

Laser

Williams et al. (1983) used a laser for optical contouring of surfaces by generating contour maps to quantify the volume of material loss in class II restorations. Other techniques using lasers such as laser profilometry, laser scanning, laser topography, and laser reflection have also been used to study dental wear (Johannsen et al., 1989; Kreulen and van-Amerongen, 1991; Wassell et al., 1994).

Reflex microscopy

Reflex microscopes have also been used to measure the volume and average depth of tooth wear. This method permits direct measurements in three dimensions without photography (Scott, 1981). Adams and Wilding (1985) evaluated this method using lead casts, which were experimentally worn and were compared, by microscopic and gravimetric methods. The mean difference between the measurements was found to be small. The main disadvantage of this method is that it is time-consuming and technically sensitive (Johansson et al., 1993).

Scanning Electron Microscopy or SEM

Recently SEM has been used extensively in the surface analysis of materials. With the aid of SEM, surface characteristics of teeth and restorative materials and the margins of restorations can be studied (Metzler et al., 1999; Pillar et al, 1984; Shkurkin et al, 1975; Xiaoqing et al., 1999). This method is highly accurate but is time-consuming as replicas generally need to be constructed from impressions and coated in preparation for analysis.

Michigan profiling system

In this system a three-dimensional digitizer interfaced with a computer is used to measure wear (McDowell et al., 1988). Between 3000 and 5000 points on the surface of each tooth are evaluated. Like all methods involving contact between a stylus and a surface, this method is sensitive to the angle of stylus contact. In assessing the accuracy of this method. Hewlett et al. (1992) found a linear

relationship between surface slope angle and measurement error indicating that the system was less reliable on more steeply inclined surfaces.

3-D digitizing and computer graphic system

This method introduced by DeLong et al. (1985) and developed by Pintado et al. (1991) is capable of measuring changes of 0.0006 mm^3 in anatomical contour. Mehl et al. (1997) used an optical 3D-device with an accuracy of $10\mu\text{m}$ to detect the wear of composite filling functioning in the mouth. Currently a 3-D digitization and computer graphic system (MTS bio-mechanical test system) has been developed to visualize and reconstruct surface characteristics (Dastane et al., 1996).

Comparison of methods

The range of available methods is an indication that no single measurement technique is appropriate for every application. Some clinical studies require quick, direct, low cost, non-invasive methods that can be applied to large samples. Other studies require the detection of very small, wear-related changes to surfaces and consequently involved more time-consuming, indirect methods. The selection of an appropriate measurement method is therefore an important part of the planning of any study. The relative accuracy, expense and required time for the analysis of a single specimen using a range of the available methods are summarised in the following table.

Table 4.1 A range of available wear evaluation methods.

WEAR EVALUATION METHODS					
	METHOD	AUTHORS	TIME	EXPENSE	ACCURACY
Non Instrumental	USPHS	Cvar and Ryge (1973)	1-2 min	Low	qualitative
	Smith & Knight	Smith and Knight (1984)	1-2 min	Low	qualitative
	Olio System	Olio et al (1987)	1-2 min	Low	qualitative
	Goldberg	Goldberg et al. (1981)	30-60 min	Med	qualitative
	Leinfelder	Leinfelder et al. (1983, 1986)	5 min	Low	qualitative
Instrumental	Handelman	Handelman et al. (1978)	30-60 min	Med	quantitative
	Stereomicroscope	Metller et al. (1978)	10-20 min	High	quantitative
	Stereometric	Adams and Wilding (1985)	-	Med	quantitative
	Laser Optical Contouring	Williams et al. (1983)	-	Med	quantitative
	Profilometry	Winkler et al. (1996)	-	Med	quantitative
	Reflex-Microscope	Adams & Wilding (1988)	-	High	quantitative
	SEM	Shkurkin et al. (1975)	10-30 min	High	quantitative
	Michigan Profil System	McDowell et al (1988)	60-120 min	High	quantitative
	MTS system	Delong et al. (1986)	60-120 min	High	quantitative

Conclusion

In conclusion, there are a vast number of methods for evaluating dental wear, ranging from simply scoring the “presence” or “absence” of wear, to sophisticated procedures such as computer graphics and electron microscopy. Each method has both advantages and disadvantages. To choose an appropriate measurement method requires consideration of criteria such as the type of the experiment, required accuracy, available time, and expense.

Chapter 5

Wear Characteristics of Composite Resin and Glass Ionomer Cement

Introduction

Since the introduction of composite resins in the mid-1960's, use of these materials in load-bearing areas has increased due to their advantages as an alternative to amalgam. Their advantages include better aesthetics, lower thermal conductivity, lower thermal expansion, and the absence of mercury (Lee et al., 1976; Swift, 1987). In combination with the acid-etch technique introduced by Buonocore (1955), improved aesthetic and mechanical properties have been reported (Deheny and Fuller, 1976; Gru, 1974; Parkin, 1973). However, for posterior teeth, the physical properties of these materials mean that their clinical performance has not yet clearly surpassed that of amalgam (Kreulen and Amerongen, 1991). Composite resin materials still suffer from lower wear resistance in comparison with amalgam and polymerisation shrinkage resulting microleakage is associated with secondary caries (Leinfelder, 1991; McLean, 1987; Swift, 1987).

Over time manufacturers have developed a range of composite resin based materials including "conventional" or "traditional" composites with large filler particles to "microfills", "hybrids", "condensables" and many more.

Since the introduction of GIC's (Wilson and Kent, 1972) the use of these materials has expanded tremendously. They offer favourable adhesion (to enamel, dentine, tinned-plated gold and platinum), fluoride release, and biocompatibility (Abdalla et al., 1997; Brooks et al., 1996; Forsten, 1993; Fruits et al., 1996; Hotz et al., 1977; Modesto et al., 1997; Peutzfeldt et al., 1997; Simonsen, 1996). Over time, the basic composition of these materials has changed. Initially these materials were very sensitive to uptake and loss of moisture (Mount and Makinson, 1982), were too weak to withstand occlusal tensile stresses, showed low wear resistance, and were unacceptable aesthetically (Fruits et al., 1996).

In the last 20 years, manufacturers have introduced a range of composite resins and GIC's. In parallel, many *in vitro* and *in vivo* experiments comparing the durability of these materials have been reported. As both of these materials suffer from low wear resistance, particularly in areas of posterior occlusal contact, many of studies have been focused on this aspect of their performance. A knowledge of the basic chemistry and structure of these materials is important in understanding their properties and performance.

Basic Chemistry

All **composite resins** used in dentistry consist of three major components (Anusavice, 1996; Craig, 1993; Craig et al., 1992; Noort, 1994):

1. Resin matrix

The resin is the chemically active component of the composite. It is initially a viscous fluid monomer and is capable of conversion from a plastic mass into a rigid solid. The most common resins used in composites are (Braden et al., 1998; Peutzfeldt, 1997):

- Methyl methacrylate which is a clear, transparent liquid at room temperature. Unfortunately, it suffers from large polymerisation shrinkage, a high coefficient of

thermal expansion, serious discolouration, and is associated with severe pulp damage, and a high incidence of secondary caries.

- Bowen's resin or bis-GMA which is derived from the reaction of glycidyl methacrylate with bis-phenol-A to give "2, 2-bis-4- (2-hydroxy-3-methacryloyl-oxypropoxy) phenyl propane". Bis-GMA is relatively viscous at room temperature due to its high molecular weight. After polymerisation the resin is stronger and stiffer than methyl methacrylate and also shows less polymerisation shrinkage than some other resins. To reduce the viscosity, a low-viscosity dimethacrylate such as TEGDMA (triethyleneglycoldimethacrylate) is added. However, reduced stiffness and increased shrinkage of composite resin result as undesirable consequences. An increased content of TEGDMA to bis-GMA can also increase wear resistance (Kawai et al., 1998).
- Modified Bowen resins were introduced to overcome the disadvantages of using diluents with the original bis-GMA. Modifications have been based on alternatives diluents such as bis-MA or "2, 2-bis-4-(3-methacryloyl) phenyl propane", bis-EMA or "2, 2-bis-4-(3-methacryloyl-oxyethoxy) phenyl propane", and bis-PMA or "2, 2-bis-4- (3-methacryl-oxypropoxy) phenyl propane".
- Aliphatic dimethacrylates are less viscous than bis-GMA and since there is no phenyl group in the polymer chain, their flexibility and toughness is significantly higher than Bowen's resin. UDMA or "1, 6-bis-(methacryloxy-2-ethoxy carbonylamino)-2,4,4-trimethylhexane", which is derived from the reaction of an aliphatic di-isocyanate with a hydroxylalkyl methacrylate, is used to reduce the viscosity and increase the degree of conversion.
- Recently, modified monomers (polyfluorinated polymethacrylate) which claimed to be opaque have been introduced. These contain a brominated aromatic diacrylate with acrylate reactive diluent.

2 Inorganic fillers

Fillers are used in composite resins to increase strength and stiffness (Ferracane, 1985; Kim et al., 1994), improve aesthetics and handling (Ferracane, 1995), reduce polymerisation shrinkage and dimensional change (Anusavice, 1996; Yamagouchi et al., 1989), and to provide radiopacity (Van Dijken et al., 1989). In general, they improve the mechanical and physical properties of composite resins (Ferracane, 1995) except when they are not well bonded to the matrix in which case the filler particles can weaken the composite resins (Anusavice, 1996; Noort, 1994).

Initially, glass beads, synthetic calcium phosphate or fused silica were used as fillers. Later, quartz was used extensively because of its ready availability, high optical match to the polymer resin, and chemical inertness. However, it is not radiopaque and the surfaces of restorations tend to be rough and less enamel-like. In addition it is very abrasive when in contact with opposing enamel (Anusavice, 1996, Ferracane, 1995).

Composite resins with lithium-aluminium silicate fillers were introduced to overcome the thermal mismatch expansion between composite resin and tooth structure. It has also been suggested that when this filler with its negative thermal expansion is mixed with the resin matrix with positive thermal expansion, increased tensile stresses at the filler-matrix interface could result and this may result in debonding of the matrix from the fillers (Söderholm, 1985).

To provide radiopacity, a number of glasses and ceramics containing heavy metals such as barium, strontium, zirconium, aluminium, and zinc have been used. Some experiments have shown that radiopaque glass containing strontium, zirconium and bromine is more water-soluble than quartz or silica (Söderholm et al., 1984; Söderholm, 1990).

In addition to their chemical structure, the physical properties of fillers (such as particle size, size distribution, index of refraction, radiopacity, and hardness) determine the properties and the clinical application of the composite resins.

Most fillers used in composite resins have irregular shapes with a roughened surface. This increases the mechanical retention of the matrix phase. However, some microfillers are spherical in shape with a smooth surface finish. Spherical particles provide reduced stress concentration and improved packing when mixed with the resin phase (Braden et al., 1998). Based upon the results of a study by Suzuki et al. (1995), filler shape as well as filler size have a strong influence on the mechanical properties and wear resistance of posterior composite resins. Li et al. (1985) found that increased filler level improves resistance of composite resin to toothbrush abrasion. Furthermore, they found higher wear resistance for conventional composite resin compared with microfilled composite resin.

It is generally accepted that the size, hardness, shape, and volume percent of the fillers particles affect wear behaviour of composite resins (Draughn and Harrison, 1978).

Traditional composite resins with relatively large filler particle size (8-12 μm) have showed rough surface and low wear resistance while microfilled composite resins with colloidal amorphous silica particles (0.04-0.07 μm) have shown smoother surfaces. Hybrid composite resins have been developed to overcome the problems with both traditional and microfilled composite resins. They consist of colloidal silica and ground particles of glasses (0.04-1 μm) containing heavy metals. The range of particle sizes allows a filler content of approximately 65-80 wt%.

3 Coupling agent

To optimise the properties of composite resins, matrix resin and filler particles should be bonded strongly to each other. Mechanical bonding between filler particles

and resin matrix due to the surface roughness and imperfections of the filler particles is not sufficient. In addition, a chemical bond should exist between filler particles and resin matrix. This can be achieved by coupling agents. Of the available agents, γ -methacryloxy-propyltrimethoxy silane is the most frequently used. Alternative coupling agents such as titanate, zirconate have also been employed.

Several investigations have shown that there is a strong correlation between low wear and high concentrations of silane-treated fillers (Condon and Ferracane, 1997; Venhoven et al., 1994).

4 Other constituents

To prevent the possibility of pre-polymerisation of the resin matrix, stabilisers or inhibitors like hydroquinones are also included in commercial composite resins. These inhibitors have a strong reactivity potential with free radicals (which initiate the polymerisation reaction).

In addition, pigments such as iron oxide are frequently added in minute quantities to achieve shading. Furthermore, because UV light causes a dull and lifeless appearance in composite resins, ultraviolet stabilisers are also employed to overcome the effects of discolouration by ultraviolet sources.

Glass Ionomer Cements arise from the reaction of an acid with a glass. In some case resins are added to modify the physical characteristics. The basic constituents are:

1 Glasses

Most glass consists of three components, silica (SiO_2) and alumina (Al_2O_3) mixed in a flux of calcium fluoride (CaF_2). However, there are other elements which are included on occasions. For example, strontium or lanthanum can be used partly or wholly in place of calcium. Furthermore, different glass systems such as aluminoborate and zinc silicate have been developed. Every glass system has both

advantages and disadvantages. It has been shown that cements with aluminoborate have relatively poor hydrolytic properties (Braden et al, 1997). In glass ionomers the size of glass particles depends on the application. For example, filling materials have larger particles than lining materials (Craig et al., 1992; Davidsdson and Mjör, 1999)

2 Polyacid

Originally, aqueous solutions of polyacrylic acid in a concentration of about 50% were used as liquids. This liquid is very viscous and had the tendency to gel over time. Recently, acid in the form of a copolymer with itaconic, maleic, or tricarboxylic acid has been used. These added acids tend to increase the reactivity of the liquid, decrease the viscosity, and reduce the tendency for gelation. Some manufacturers have added tartaric acid to control the pH during the setting process, to improve the handling characteristics, and to increase the working time. However, additional tartaric acid tends to shorten the setting time (Crisp et al., 1979; Davidsdson and Mjör, 1999).

3 Resin component

Resin components have been added to conventional-glass ionomer to overcome their moisture sensitivity, weak early mechanical strength and acid erosion (Antonucci et al., 1988; Billington et al., 1992; Mitra, 1988; Mitra and Kedrowski, 1994). However, adding resin can result in less ionic reactivity between the glass ionomer and the tooth surface than is seen with conventional glass ionomer (Nakaseko et al., 1997). Hydroxyethyl methacrylate (HEMA) and bis-GMA are the most common resins applied in resin modified-GIC (Hse et al., 1999). Therefore, resin modified-GIC undertake both a polymerisation reaction and an acid base reaction as part of their setting (Mitra, 1994).

Wear Studies

Wear of dental hard tissue and materials has been studied in a number of different ways.

These include:

- clinical studies,
- *in vitro* studies using standard engineering wear instruments (eg pin and disc machines) or purpose-built wear machines
- indirect assessments based on the study of physical properties associated with wear

Hundreds of **clinical studies** of the wear of dental materials have been reported. Phillips et al. (1971, 1972, 1973) compared wear rates of a conventional composite resin with an amalgam at baseline, 1, 2, and 3 years in class II cavities using the USPHS method. After three years, composite resin restoration showed higher loss of anatomical form than amalgam. However, composites showed better marginal adaptation. A three-year clinical study of zinc and non-zinc amalgam by Ryge et al. (1974) showed no significant changes in anatomical form of restorations. In another clinical study Kusy and Leinfelder (1977) investigated the pattern of wear in posterior composite restorations using SEM. They concluded that wear was a result of thermo-mechanical fatigue caused by fine cracks at localized areas of stress concentration.

Many investigators have used **in vitro methods** to study wear. Because there is no “standard” test for wear resistance, a range of wear machines have been developed and used. For example, Peterson et al. (1966) used a mechanical tooth-brushing machine to determine the abrasion resistance of cylindrical specimens of composite resins. After 60 minutes brushing in slurry of extra heavy calcium carbonate, unfilled resins showed more abrasion than filled resins. As there are many types of abrasion, the data obtained by this method are indicative of the ability of the materials to withstand toothbrush abrasion but they can not predict the abrasion resistance in the presence of opposing teeth or food. Luggasy and Greener (1972) used a hydrolytic grinder to demonstrate higher wear rates for filled resins than for unfilled resins. Others (eg Rice et al., 1984) have used standard pin and disc machines used in engineering studies to investigate wear.

Each of the wear machines has its specific advantages and disadvantages associated with its design (Abe et al., 1997; Condon and Ferracane, 1996, 1997; Craig and Powers, 1976; Ratledges et al. 1994). As a result they provide data which is often specific for the narrow range of operating conditions considered and consequently it is difficult to compare results from different studies.

In addition to clinical and *in vitro* investigations, **mechanical properties** (such as hardness and coefficient friction) have been used to predict the wear resistance of materials. Tillitson et al. (1971) attempted to correlate friction and wear of dental materials and Koran et al. (1972) determined the coefficient of friction of prosthodontic tooth materials. Most studies have concluded that mechanical properties do not always correlate directly with wear but can give an indication of the effect of such variables as wear debris, load, sliding velocity, and environment on wear (Craig and Powers, 1976).

In one study (Jørgensen, 1980) a significant correlation between Wallace indentation hardness and abrasion in contact-free areas was demonstrated. In another *in-vitro* study of composite resin, a three-dimensional regression analysis found wear to decrease with decreasing Wallace indentation depth and increasing conversion (Peutzfeldt and Asmessen, 1996). However, this relationship is not always linear (Attin et al., 1996; Forss et al., 1991; McCabe and Smith, 1981). The complexities of these relationships is indicated by the fact that Yap et al. (1997) found no correlation between hardness and wear resistance of restorative materials.

Previous Experiments on Wear of Composite Resins and Glass Ionomer Cements

Since GIC's were originally introduced for use as a cement, early studies compared these materials with other cements such as dental silicate and polycarboxylate cements (Kent and Wilson, 1973; McCabe et al., 1979). As GIC's came to be considered as direct

restorative materials so recent studies have compared these materials with other direct restorative materials, particularly composite resins.

One study used 600-grit wet silicon carbide paper to show that a conventional-GIC was abraded three times as rapidly by volume than filled resin and showed a similar rate of abrasion as unfilled resin (Smales and Joyce, 1978). In a later two body wear study by Forss et al. (1991), a conventional-GIC from the range available at that time was abraded at only twice the rate of composite resin reflecting an improvement in properties compared with earlier materials.

Momoi et al. (1997) compared abrasion rates and surface roughness of the resin modified-GIC's, conventional-GIC's, composite resin, and amalgam subjected to toothbrush-dentifrice abrasion. Resin modified-GIC's showed the lowest abrasion resistance followed by conventional-GIC's, composite resin, and amalgam. This finding was confirmed by Peutzfeldt et al. (1997) who also showed that resin modified-GIC also showed lower hardness and wear resistance than conventional-GIC's which were in turn not as hard as compomer and composite resins respectively.

Some researchers have studied erosion of GIC's in acidic pH solutions. Conventional-GIC's have shown higher wear rates in acid pH than at neutral pH while resin modified-GIC seemed to be more resistance to acid erosion (Badrawy and McComb, 1998; Billington et al., 1992; Davidson and Mjör, 1999; De Gee and Pallav, 1994; Fukazawa et al., 1990)

Early and long-term wear of some restorative materials at different pH's were also compared using an ACTA machine which simulated occlusal. GIC's showed improved wear resistance over time, which may be due to long-term continuation of the acid-base reaction. However wear rates were still higher than for composite resin and amalgam. Additionally, at pH=5.0, the wear rate for GIC was greater than at pH=7.0 but at pH=6.0 the rate did not differ from that at pH=7.0 (De Gee et al., 1996).

Conclusion

Despite the amount of information published about wear of dental materials, it is difficult to develop of clear overview of the available data because of the diversity of materials, study designs (different loads, pH's, wear machines etc.) and analytical methods.

The general aim of this study was to derive wear information for a selection of commonly available aesthetic restorative materials subjected to wear over a range of loads and pH's. The derived data will facilitate comparisons between the performance of the materials under conditions that simulate a range of functional situations.

SECTION 2

MATERIALS AND METHODS

Chapter 6

Materials and Methods

Introduction

To date, numerous *in vivo* and *in vitro* experimental methods have been used to study wear of teeth and restorative materials. Even the best laboratory tests can not reflect the changes occurring *in vivo* (Mjör, 1987). However, *in vivo* experiments are expensive and involve economic and ethical problems. It is also very difficult to follow patients over an appropriate time period. As a result *in vitro* experiments that simulate *in vivo* conditions offer some advantages.

Wear Machine

In this study, an electromechanical tooth wear machine was used to simulate wear. This machine (Fig 6.1, 6.2) was designed and built by the Department of Mechanical Engineering at The University of Adelaide to investigate wear of enamel and dentine (Burak et al., 1999; Kaidonis et al., 1995; Partington et al., 1995).

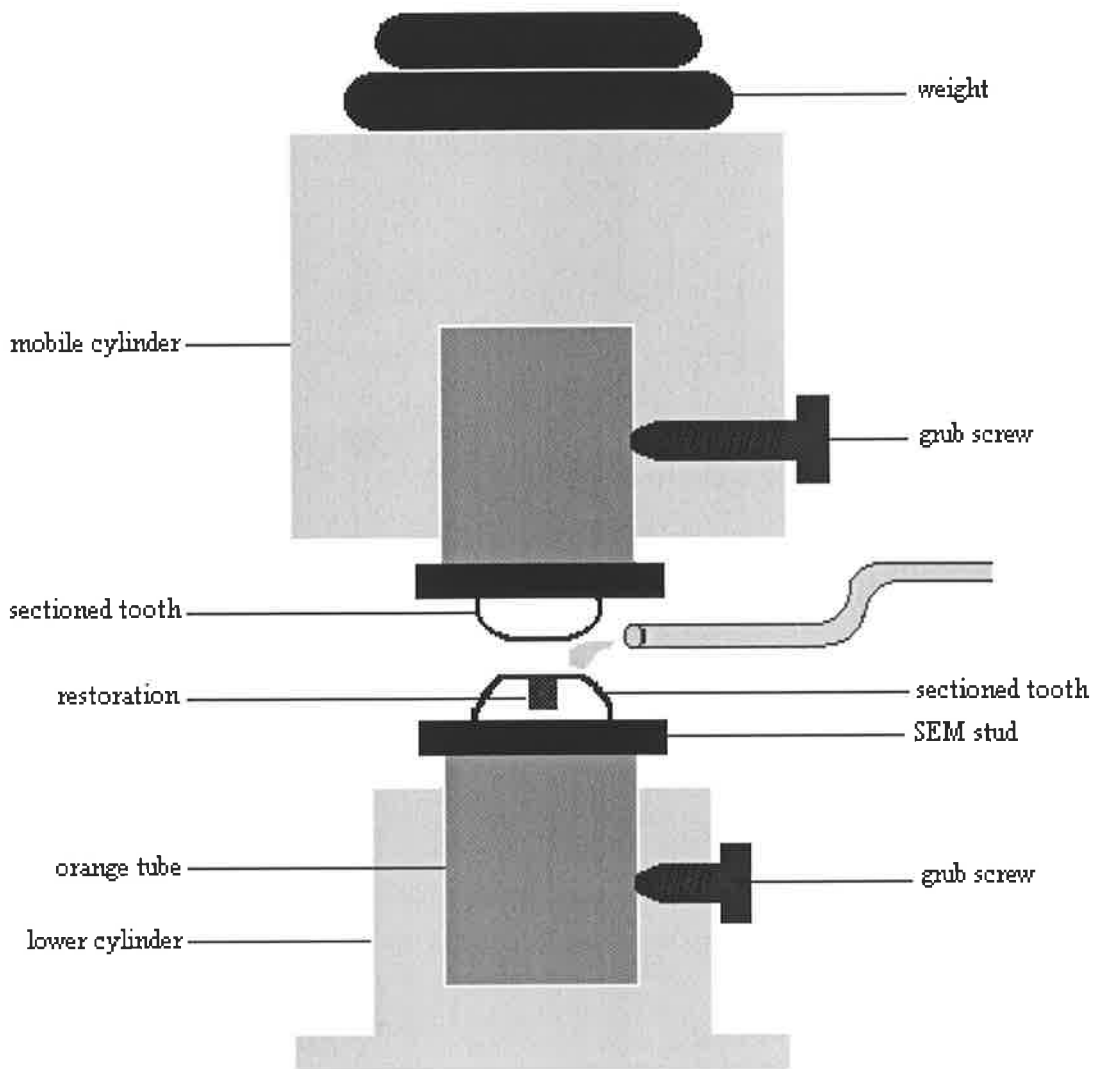


Figure 6.1 Schematic presentation of wear machine used in this study.

The apparatus consists of a stainless steel base and frame. A 75 watt D.C. electric motor drives the machine at variable speed. The motor powers a 10:1 reduction gear-box that moves a series of interchangeable cams controlling the movement of one of the two specimen holders. These cams can influence the position and consequently, the movement of the specimen holder in both the horizontal and vertical plane. Duration of contact between the opposite surfaces of specimen is controlled by adjustment of the cam in the horizontal plane. A magnetic counter attached to the gear-box, records the

number of cycles of the machine. This machine is capable of both uni-directional and bi-directional movements.

In these experiments a moving upper specimen was rubbed against a fixed lower specimen in one direction for a specified duration, after which the cam lifted the upper specimen and repositioned it at the beginning of the cycle.

Stainless steel cylinder holders were designed to mount specimens in the machine secured to the stationary base frame of the machine by screws. The upper specimen holder is an integral part of the moveable part of the machine that is controlled by the cam. The internal diameter of these holders is designed to accept the specimen cylinders. These are identified by a laterally-directed screw and tightly secured.

The upper mobile section of the machine was designed to support weights for applying loads to the specimens, giving an operating range of 0.25 kg to 16.2 kg. This machine can accept heavier loads, however, previous tests (Kaidonis, 1995) showed a high incidence of tooth fracture and complete tooth destruction above this operating range. Without the addition of load, the inherent weight of the upper movable component of the machine is 3.2 kg. To achieve loads below 3.2 kg, the upper movable component of the machine can be attached to a counter balanced overhead pulley system if desired.

Method of Lubrication

A gravity-fed drip system consisting of a plastic reservoir on an adjustable stand from which plastic tubing lead to a hypodermic needle. The end of the tubing was clamped to an adjustable stand to direct lubricant onto the crown without impinging upon the movement of the opposing tooth surface. The flow rate of the lubricant is fixed at 0.5 mL/min by adjusting a volume control device attached to the plastic tubing throughout the experiments. Lubricant running from the specimens is captured in a container and not reused.

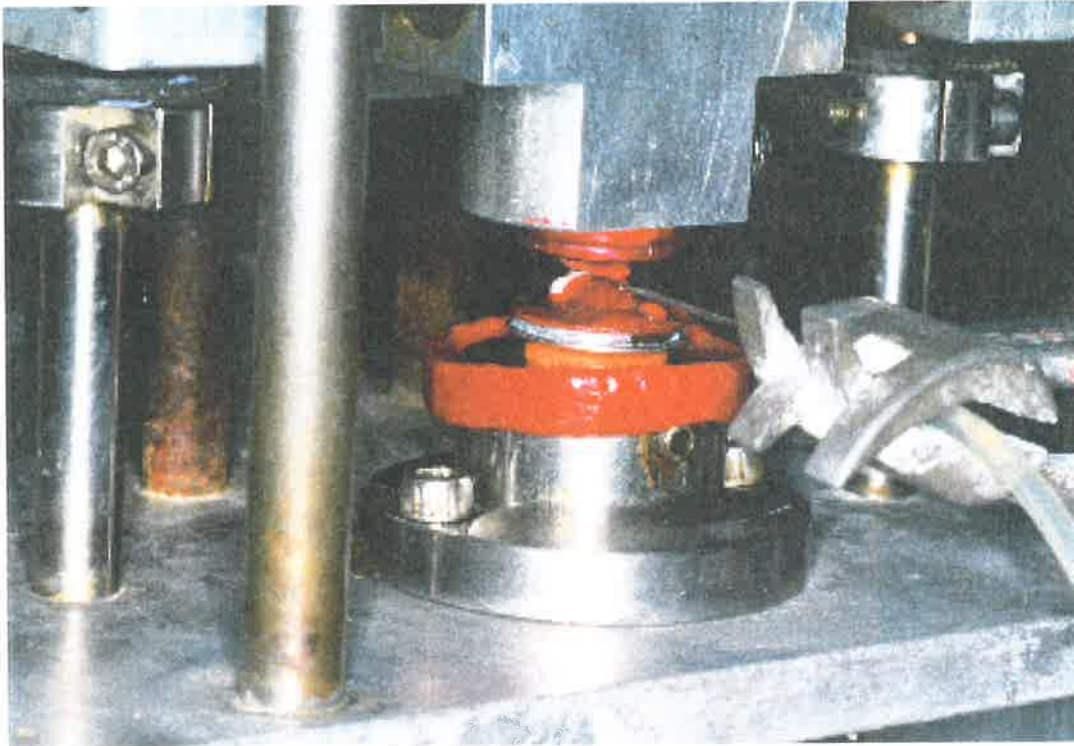


Figure 6.2 Close view of the tooth wear machine showing motor, pulley, gearbox, and the framework housing the upper moveable section controlled by the cam.

As the pH of oral cavity varies due to intake of food and drinks and diseases or deficiencies, it is desirable to investigate wear of tooth and restorative materials at different pH's. Following lubricant used for these experiments:

- Water (pH=7.0) resembling neutral pH.
- Acetic Acid (pH=3.3, 0.05 mol) resembling acidic diet.
- Hydrochloric acid (pH=1.2, 0.01 mol) resembling regurgitation acid.

Specimen Preparation

To simulate functional wear, enamel and restorative materials were abraded by opposing enamel. In addition, restorations needed to be surrounded by enamel to simulate the normal clinical situation in which these materials are used.

For this study, freshly-extracted intact molars were obtained as part of routine dental treatment in the Department of Dentistry at The University of Adelaide and from some private practices in Adelaide.

Each tooth was sectioned longitudinally by sectioning in a mesio-distal direction into halves using a Horico diamond disc. Sectioning was performed under a fountain of water in order to avoid excessive heat generation. The pulpal tissue was then removed, whilst the remaining portions of teeth were stored in water. They were then allowed to dry for at least one day. To control for variation in specimen hardness, in each experiment the two halves of a single tooth were randomly assigned as either the experimental specimen or the opposing abrading enamel.

Specimens were then prepared in following way:

- A scanning electron microscope stub was attached to a plastic cylinder (20 mm in length, 20 mm in diameter) using epoxy resin adhesive (Aradlite, CIBA-Geigy, Basel, Switzerland). The diameter of this cylinder was chosen to fit exactly into the upper and lower specimen holders of the tooth wear machine.
- Each half of the sectioned tooth was mounted in the center of the stub using epoxy resin.
- Two standard height reference points were defined on the surface of the SEM stub by including fragments of the water resistance plastic mounting (diameter, approximately 1mm) cylinder in the adhesive. These served to define the baseline height during measurement of specimen height changes during the experiments.
- After 24 hours the maximum strength of epoxy resin was achieved and the specimens were ready for further processing.
- To control fluctuation, the mounts and the adhesive were covered with non-soluble nail varnish one hour before mounting in the wear machine (Kaidonis, 1995).
- Initial facets were then established by 20,000 cycles of simulated wear using the wear machine.

- Two reference points were defined on the surface of each specimen.

This completed the preparation of specimens for the enamel experiments. For the experiments involving restorations, preparation continued in the following way:

- Each pair of specimens was then replaced in the wear machine to establish initial wear facets with a minimum diameter of 1 mm if necessary.
- A cavity (1 mm in diameter and 2 mm in depth) was prepared in the center of the facet of one of the pair of specimens.
- Restorations were placed in the cavities according to manufacturer's instructions.
- Specimens were stored in 100% humidity storage for one hour and then stored in water for 24 hours (Mitra, 1988).
- After 24 hours, restorations were polished according to the manufacturer's instructions and stored in water for one week prior to the experiments.

This completed the preparation of specimens for contact-area experiments. For the non-contact-area experiments, specimens were prepared following a similar protocol but no initial facet was produced.

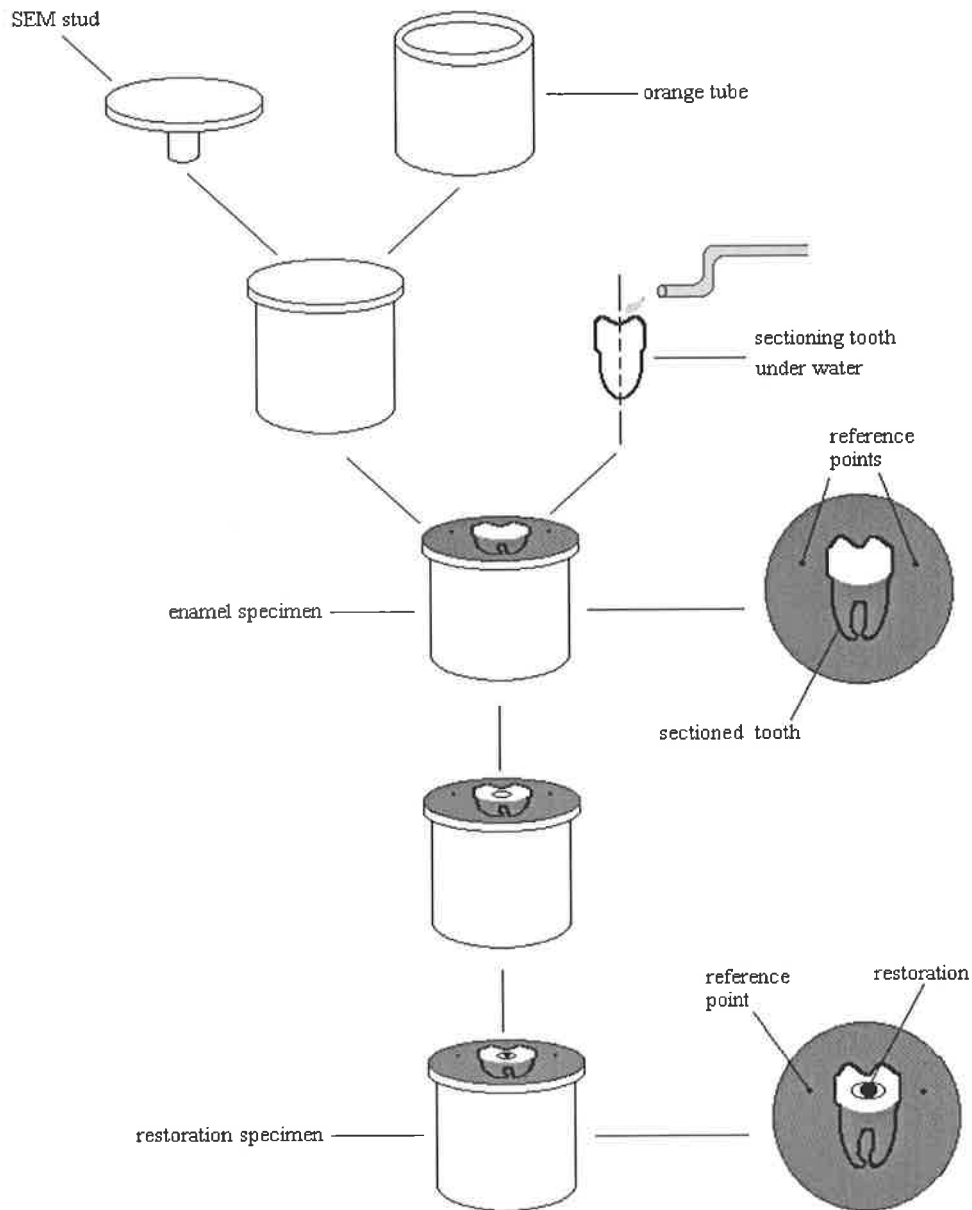


Figure 6.3 Schematic presentation of specimens preparation.

Materials

Three representative, commonly used materials were selected for consideration in this study. They were:

Composite Resin: composite resin (**Z100**, 3M CO, St. Paul, MN, USA) a hybrid composite resin containing, bis-GMA and TEGDMA; fused zirconia/silica with with average size of 0.6 μm , 75-85% Wt (Lot, 5905).

Conventional GIC: conventional-GIC (**Fuji IX**, GC CO, Tokyo, Japan) containing, fluoroaluminosilicate glass; polyacrylic acid, polybasic carboxylic acid, water (Lot, 181174).

Resin modified GIC: resin modified-GIC (**Fuji II LC**, GC CO, Tokyo, Japan) containing, fluoroaluminosilicate glass; polyacrylic acid, HEMA, catalyst (Lot, 271187).

Wear Measurement Methods

In this study, reduction in specimen height was used to quantify wear. To do this, a light microscope was modified by the connection of a depth gauge (Mercer, St. Albans, England) and used to measure the height of defined points. The microscope was modified in the following way:

- The body of the depth gauge was attached to the movable microscope stage with the pin aligned to contact a reference table attached to the microscope base (Fig 6.6). This allowed the height of the stage to be recorded over its range of positions. Individual heights of experimental specimens were recorded by focusing the microscope on a selected reference point on the specimen and recording the stage height.
- A standard specimen-mounting slide was constructed to facilitate the reproducible alignment of specimens during the measurement process. The mounting slide consisted of a glass microscope slide with an attached acrylic rod on one surface. The diameter of the rod corresponded to the internal diameter of the plastic tube

onto which the tooth specimens had been mounted. This ensured consistent placement of specimens in relation to the microscope slide and the microscope stage.

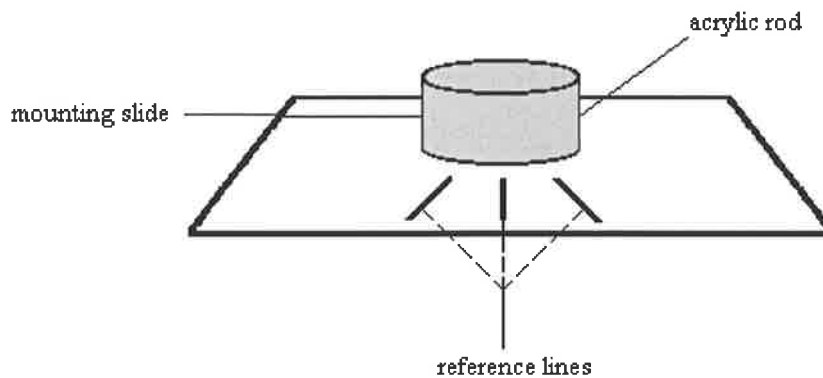


Figure 6.4 Mounting slide including acrylic rod and reference lines.

- Three reference lines were marked on the standard mounting slide surface adjacent to the acrylic rod. Specimens were rotated on the rod to orientate reference points on the specimen-mounting cylinder with the reference lines on the slide and ensure reproducible alignment.



Figure 6.5 Modified-light microscope showing light microscope, light source, depth gauge, and mounting slide with specimen.

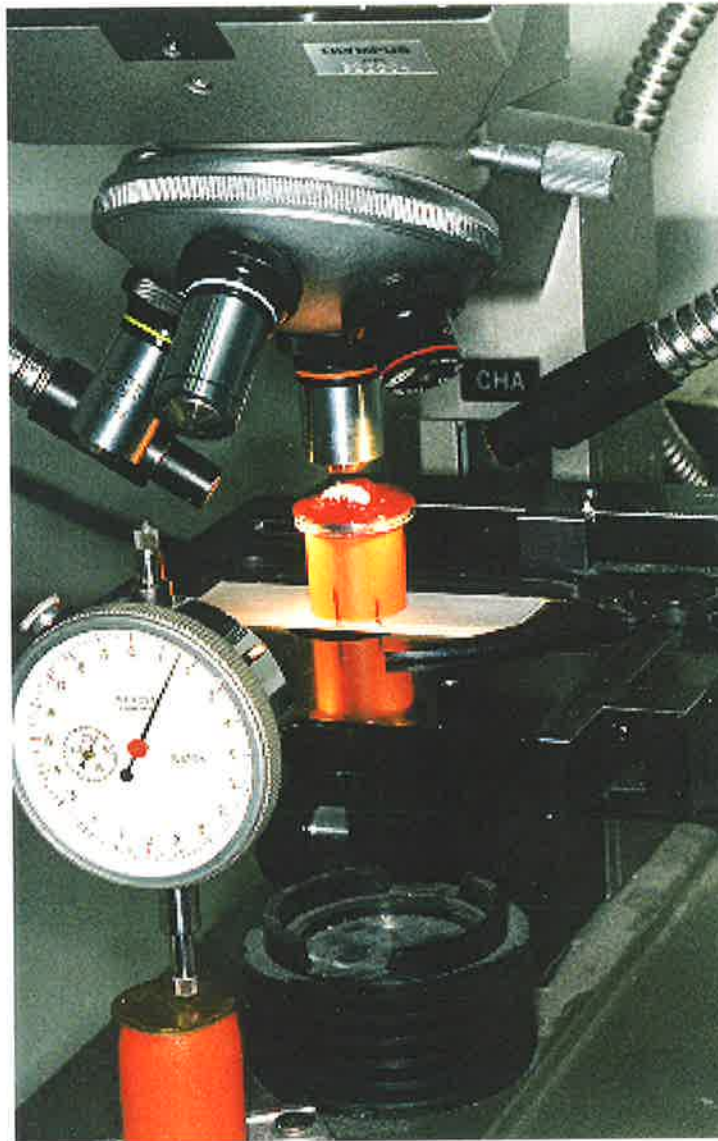


Figure 6.6 Closer view of modified-light microscope.

Initially the following procedure was followed to record the details of the specimen height prior to the commencement of the experiment.

- Each specimen was placed on acrylic rod of the standard specimen-mounting slide.
- The three reference lines on the standard mounting slide surface adjacent to the acrylic rod were aligned with the reference points on the specimen-mounting cylinder.

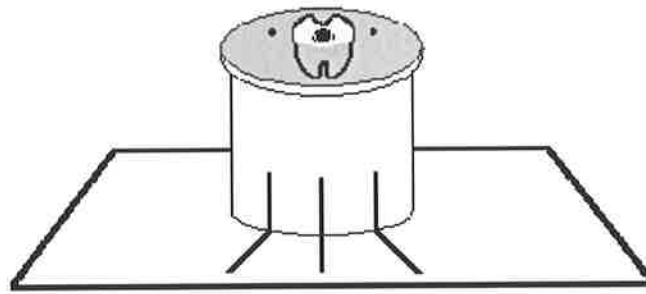


Figure 6.7 Schematic presentation of slide microscope with specimens.

- The microscope was focused on one of the standard height reference points and the height recorded.
- A transect was defined across the specimen between the two standard height reference points. The specimen heights were recorded at 0.5 mm intervals across the transect by the progressive displacement of the microscope stage across one of its axes of movement and the recording of specimen height from the dial gauge at each point.

For specimens involving restorations, measurements were done in a similar way and in addition the height of the center and margins adjacent to the areas of first and last contacts of restorations were measured.

Fabrication of specimen replicas

Before the commencement of each experiment and at each stage during the experiment epoxy resin replicas of the specimens were fabricated. At the completion of the height measurement procedure polyvinylsiloxane impressions (Extrude Injection, Kerr Corporation, USA) were made following the manufacturers instructions. Replicas were constructed in epoxy die material (Epoxy-Die, Ivoclar Pty. Ltd, USA) according to the

instructions. These replicas were available for subsequent visual and scanning electron microscopic examination.

Scanning Electron Microscope (SEM)

Scanning electron microscopy was used to examine surface and margin characteristics of enamel and restorative materials.

For each stage of each experiment, resin replicas were mounted on standard SEM stubs and gold-carbon coated for analysis using Phillips 20LX Scanning Electron Microscope. Initial observations of the overall specimen were made at low magnification with subsequent detailed observations of the wear facet details and of the body and margin of restorations being made at higher magnification (100 and 500 times). Images were stored and written to CD for subsequent comparison and analysis.

Statistical Methods

For each experiment, data were summarized in tabular form with load, pH, sample size, mean wear rates and their corresponding standard deviations. Mean wear rates for selected pairs of samples were compared using student's t-test for independent samples. Analysis of variance (ANOVA) was performed to assess the significance of observed differences between combinations of experimental groups.

Statistical analyses were performed using appropriate routines from Excel 97 (Microsoft Excel, Microsoft Corporation, USA) and Statview 512+ (Abacus Concepts, Inc). Statistical significance was set at the 0.05 probability level.

Chapter 7

Preliminary Experiments

Introduction

A series of preliminary experiments was undertaken to standardize the operating conditions for the wear machine and to assess the significance of a number of factors which might influence the design of the final experimental protocols.

- **Water uptake by specimens**

As these experiments were conducted using lubrication, it was necessary to test lubricant uptake by adhesive during the experiments to determine whether lubrication can influence height measurement. Therefore, the following experiments were undertaken:

To test the effect of water uptake by the adhesive on quantifying specimen height, four specimen mounts were prepared without bonding teeth to their surface. This allowed assessment of the dimensional changes of the mounting system alone. The whole surface of SEM stud and the adhesive (but not the acrylic standard height reference points) were covered with nail varnish. These specimen mounts were stored in water for a period of

16 hours. The height of each acrylic point was measured every four hours during the 16 hours of the experiment.

Table 7.1 Height of adhesive of four specimens stored in water recorded over 16 hours period.

Period (hours)	specimens				
	1	2	3	4	5
	Height (μm)	Height (μm)	Height (μm)	Height (μm)	Height (μm)
0 hour	2512	3695	1026	950	4865
4 hours	2510	3695	1026	950	4866
8 hours	2512	3695	1025	952	4866
12 hours	2512	3696	1026	952	4864
16 hours	2512	3698	1024	952	4865

Table 7.2. Change in height (μm) of adhesive of four specimens stored in water during indicated period.

Period (hours)	specimens					mean
	1	2	3	4	5	
	Height (μm)	Height (μm)	Height (μm)	Height (μm)	Height (μm)	
0 hour	0	0	0	0	0	0
4 hours	-2	0	0	0	+1	-0.2
8 hours	0	0	-1	+2	+1	+0.4
12 hours	0	+1	+1	+2	-1	+0.6
16 hours	0	+3	-2	+2	0	+0.6

The results on this analysis suggested that the contribution of changes in the mounting material during the course of the experiment were very small when compared with the total change in specimen height. The change in specimen height during experiments was of the order of $1\mu\text{m}$ for the conventional-GIC experiments under conditions associated with lowest wear (pH=3.3, load=0) and as great as $384\mu\text{m}$ for 10,000 cycles for experiments associated with high wear rates (pH=1.2, load=9.95 kg).

- **Effect of cycle rates on wear rates**

Previous experiments (Kaidonis, 1995) have established that the wear rate of enamel was not dependent on the operating rate of the wear machine. Changes in the operating rates in the range 80 and 160 cycles/min are not associated with differences in wear rate. In this study all experiments were conducted at 80 cycles/min to maintain consistency and to minimise the effect of impact stress.

- **Effect of type of movement (uni-directional and bi-directional)**

As the wear machine used in these experiments is capable of both uni-directional and bi-directional movements, it was necessary to test for any difference in wear rate between the two types of movements. Kaidonis (1995) showed no significant difference in average wear rates of enamel between the two movements. However, as this study involved some restorative materials, it was important to test whether the type of movement influenced the wear rate of restorative materials.

Wear rates for the composite resin used in this study (Z100, 3M CO, St Paul, MN, USA) were compared for both types of movement. This series of experiments was performed at pH=7.0 and under load of 9.95 and 6.7 kg.

Table 7.3. Mean wear rate ($\mu\text{m}/10^3$) of composite resin for uni-directional and bi-directional movements at pH=7.0 and under three different loads (kg) after 80,000 cycles.

Load	bi-directional	uni-directional	p-value	n	Mean	($\mu\text{m}/10^3$)	SD
	($\mu\text{m}/10^3$)	n	Mean		($\mu\text{m}/10^3$)	SD	
9.95	6	1.41	0.31	7	1.53	0.63	0.54
6.7	6	0.76	0.23	9	0.8	0.23	0.8
3.2	6	0.68	0.31	7	0.43	0.11	0.08

The results on this preliminary analysis showed no significant difference in average mean wear rates between two movements ($p>0.05$).

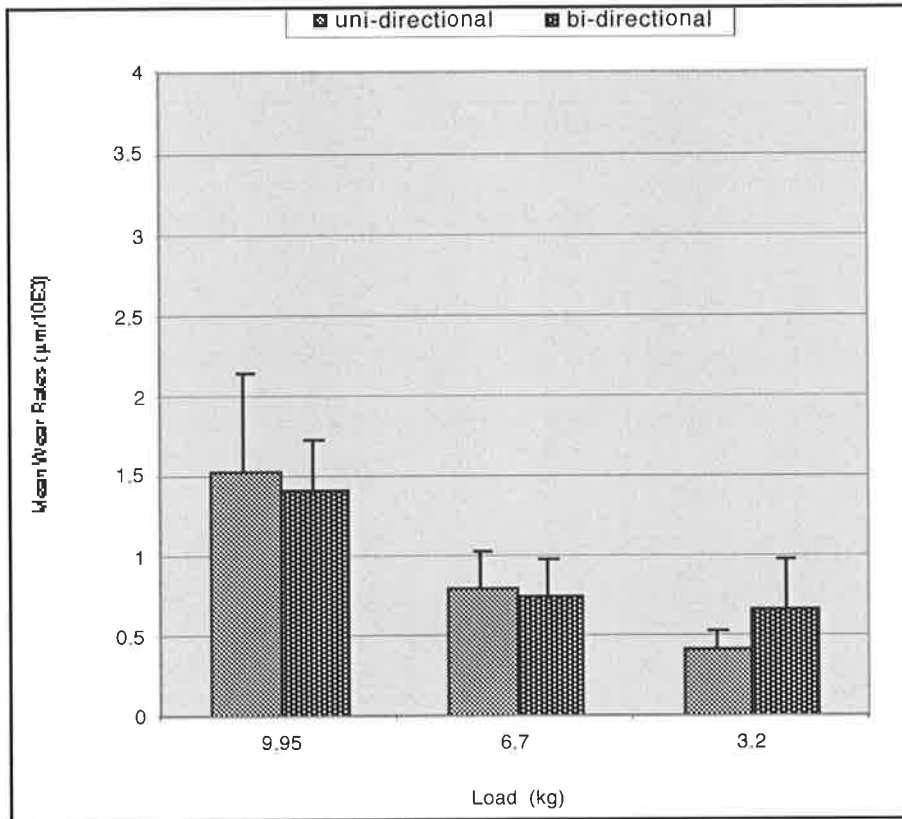


Figure 7.1. Mean wear rates ($\mu\text{m}/10^3$) of composite resin for uni-directional and bi-directional movements at different loads (kg) after 80,000 cycles.

• **Comparison of upper and lower specimens**

Difference between observed wear rates for the movable upper specimen and the fixed lower specimen was also possible. To compare the progress of enamel wear of upper and lower specimens, three samples (each of nine pairs) were worn at loads of 9.95, 6.7, and 3.2 kg for 80,000 cycles lubricating with water (pH=7.0).

Table 7.4 Mean wear rates ($\mu\text{m}/10^3$) of enamel for upper and lower specimens under different loads (kg) and after 80,000 cycles.

Load	upper			lower			p-value
	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)	
9.95	6	1.11	0.32	6	1.08	0.6	0.9
6.7	9	0.64	0.22	9	0.66	0.23	0.8
3.2	7	0.46	0.12	8	0.45	0.16	0.9

Unpaired t-tests showed no significant differences in mean enamel wear rates of upper and lower specimens under different loads ($p > 0.05$).

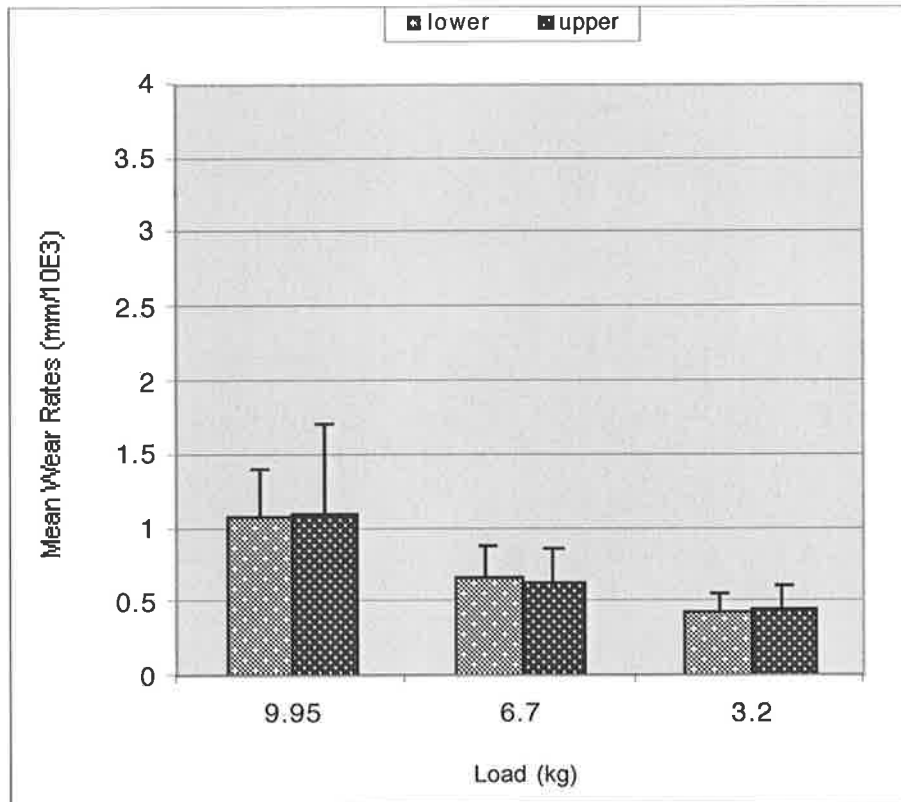


Figure 7.2 Mean wear rates ($\mu\text{m}/10^3$) of enamel for upper and lower specimens at different loads (kg) (with standard error bars).

- **Effect of area of contact**

As natural teeth with different size, shape, and hardness were used in this series of experiments, it was necessary to determine whether variation in these characteristics of the specimen teeth effected wear rates. To assess the effect of the area of the facet on the rate of wear, 10 enamel specimens were worn with water lubrication at a load of 9.95 kg. Wear facet areas for each specimen were measured from scanning electron microscope images after establishing an early facet by 5,000 cycles of wear (S1) and again after 40,000 cycles (S2). In addition, the change in height of the centre of the facet between the two stages was measured using the modified light microscope.

Table 7.5. Change in facet height, facet areas after 5000 cycles (S1) and 40,000 cycles (S2) of wear, and facet area ratios.

specimens	Facet height change (μm)	Facet area at S1 (μm^2)	Facet area S2 (μm^2)	RatioS2/S1
1	151	1.65	2.99	1.81
2	95	1.60	2.50	1.56
3	80	0.81	1.76	2.17
4	100	1.040	1.63	1.16
5	90	1.65	2.97	1.8
6	50	0.36	0.43	1.1
7	20	1.47	2.79	1.9
8	60	0.81	1.78	2.1
9	70	0.61	1.06	1.73
10	80	0.31	0.88	2.83

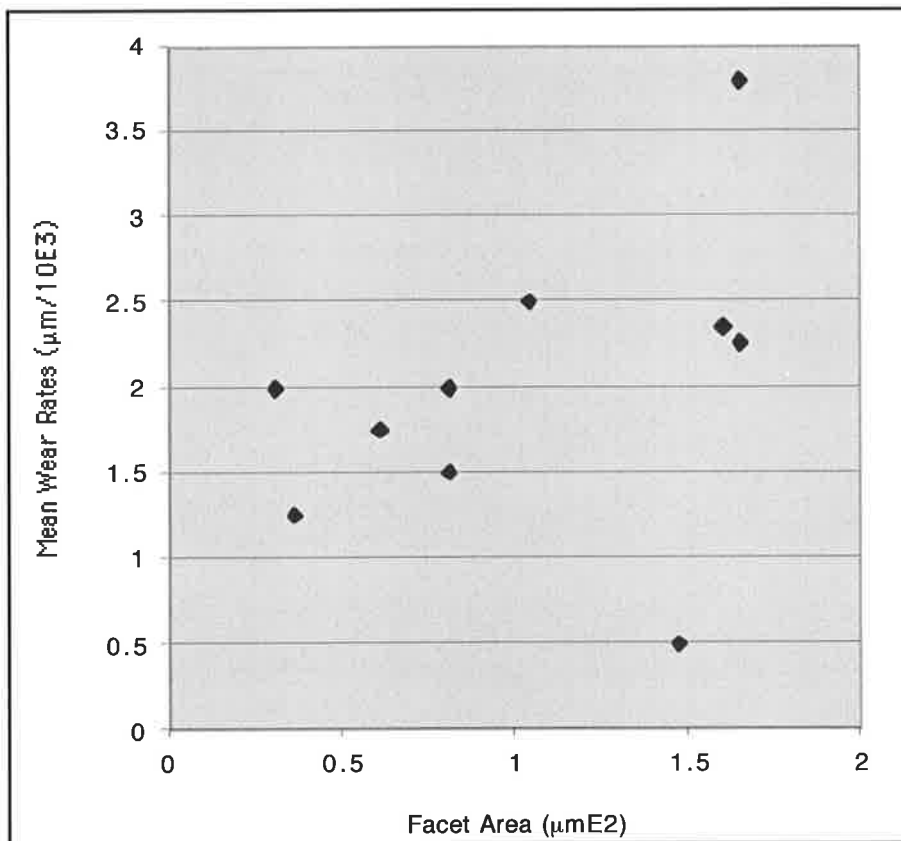


Figure 7.3 The relationship between the initial facet area and mean wear rates ($\mu\text{m}/10^3$) of enamel.

The relationship between the initial facet area (S1) and the facet height reduction is illustrated in Figure 7.3.

The low correlation between the initial area and the change in height ($r=0.37$) indicates that there is no significant relationship ($p>0.05$) between facet area and wear rate assessed from measurements of facet height.

- **Duration of experiments**

Previous experiments by Kaidonis (1995) showed two phases of enamel wear, an initial or primary phase and a secondary phase. Significant differences in wear rate between the two phases were also evident. Kaidonis found that the rate of enamel wear in the primary phase was approximately five times that observed in the secondary phase.

In this study all experiments at pH of 7.0 and 3.3 were conducted during the secondary phase. However, the experiments at pH of 1.2 were run for shorter duration due to the high rate of enamel loss. And as a result the initial part of these experiments were conducted during the primary wear phase.

- **Reproducibility of measurement techniques**

The reproducibility of height measurements obtained using the modified light microscope were determined by comparing a series of repeated measurements of the standard height reference points, the restoration margins and the center of the restorations for a series of 20 specimens.

In each case mean differences between first and second measurements were small and did not differ significantly from zero ($p<0.05$) indicating that there were no systematic differences between the first and second measurement.

The error variance (Se^2) calculate as:

$$Se^2 = (\text{sum } (x_1 - x_2)^2) / 2n \quad (\text{Dahlberg, 1940})$$

Based on the estimates of the error variance derived by Dahlberg's method, errors contributed between 0.8 percent and 4.2 percent to the total observed variation. The largest errors involved the margins of the restoration at the area of first contact and the smallest errors involving the margin in the area of final contact during the wear cycle.

This information established the height assessment method was sufficiently reproducible for the purposes of this study.

Conclusion

The results of these preliminary experiments provided the basis for the development of the final experimental protocol.

Chapter 8

Experimental Protocols

Introduction

Information from the preliminary studies provided the basis for the design of the main experiments in this study where observations of wear rates for enamel and restorative materials were made under following conditions:

- Contact-area experiments, which were conducted with restorations placed in the wear facets generated during initial periods of wear. These experiments assessed the rate of loss of enamel and restorative materials during two- and three-body wear processes in contact areas.
- Non-contact-area experiments which were designed to assess the loss of enamel and restorative materials in non-loaded areas due to chemical processes alone.

Contact-area experiments

These experiments were conducted under following loads and pH's:

Experiment Series A: Lubricating with water (pH=7.0)

These experiments were conducted at pH of 7.0 and three different loads. They were subdivided into:

A3. These experiments were conducted under a load of 9.95 kg for 80,000 cycles. Height of defined sites was measured before and after wear. The difference in height was divided by the number of cycles to determine the wear rate in μm of enamel and restorative material loss per 1000 cycles ($\mu\text{m}/10^3$ cycles). Finally, mean wear rates and standard deviations were calculated at each load.

A2. This series of experiments was conducted under a load of 6.7 kg and for 80,000 cycles. The methodology for this series of experiments was identical to experiments A1.

A1. These experiments were conducted under load of 3.2 kg for 80,000 cycles. The methodology for this series of experiments was identical to experiments A1.

Experiment Series B: lubricating with acetic acid (0.05 mol, pH=3.3)

These experiments were conducted at pH of 3.3 and under three different loads. They were subdivided into:

B3. Experiments under load of 9.95 kg and for 80,000 cycles.

B2. Experiments under load of 6.7 kg and for 80,000 cycles.

B1. Experiments under load of 3.2 kg and for 80,000 cycles.

The methodology for this series of experiments was identical to experiments A.

Experiments C: lubricating with hydrochloric acid (0.01 mol, pH=1.2).

These experiments were conducted at pH of 1.2 and under three different loads. As enamel is dissolved at this pH, these series of experiments were conducted for shorter time. They were subdivided into:

C3. Experiments under load of 9.95 kg and for 10,000 cycles.

C2. Experiments under load of 6.7 kg and for 10,000 cycles.

C1. Experiments under load of 3.2 kg and for 10,000 cycles.

Heights of defined sites were measured before and after wear. The difference in height was divided by the number of cycles to determine the wear rate in μm of enamel and restorative material loss per 1000 cycles ($\mu\text{m}/10^3$ cycles). Finally, mean wear rate and standard deviations were calculated for each load.

Table 8.1 Numbers of specimens for contact-area experiments at different conditions.

pH	Load (kg)	Cycles	Materials	Numbers
7.0	9.95	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
	6.7	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
	3.2	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
3.3	9.95	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
	6.7	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
	3.2	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
1.2	9.95	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
	6.7	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10
	3.2	80,000	enamel	10
			Z100	10
			Fuji IX	10
			Fuji II LC	10

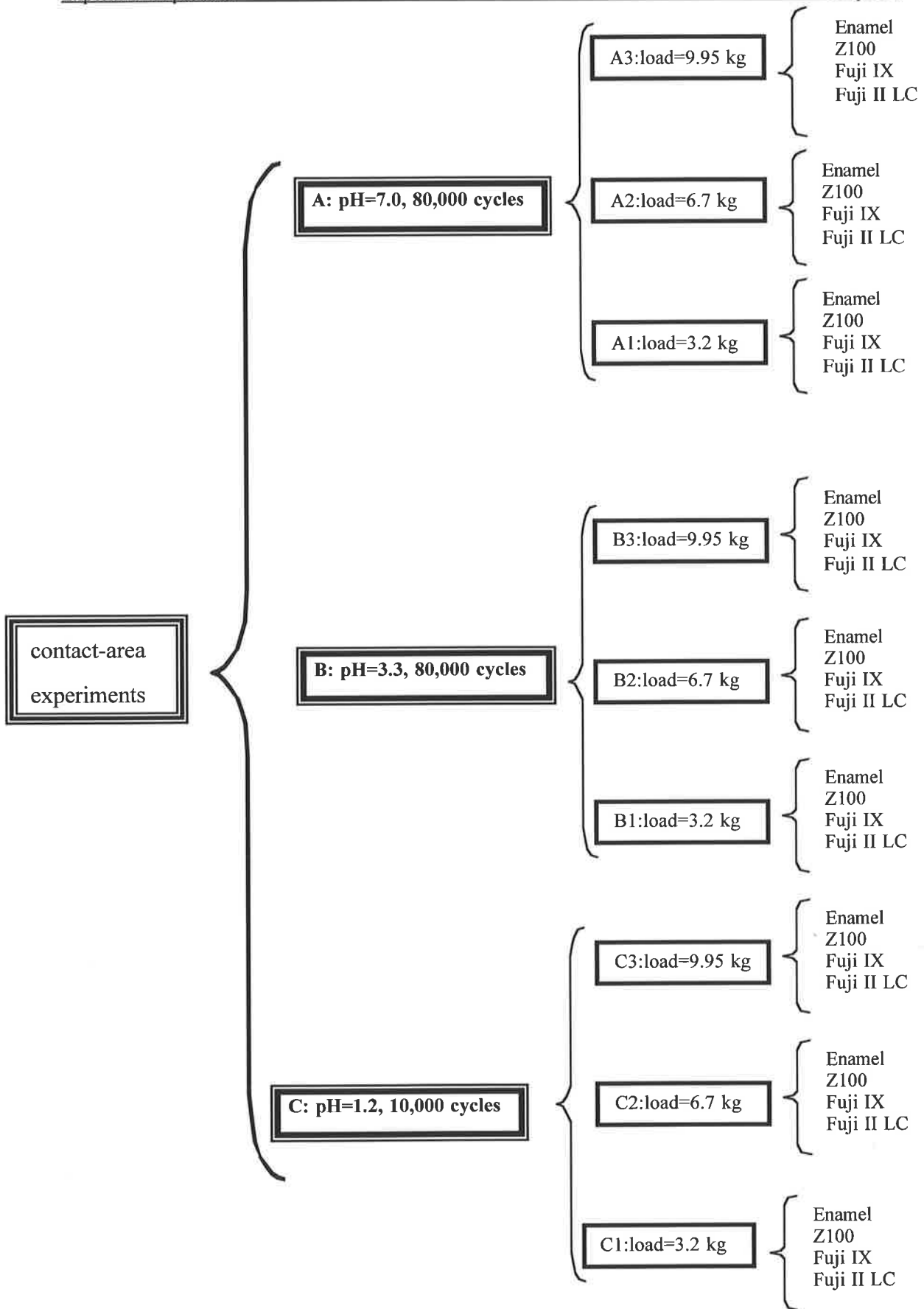


Diagram 8.1 Design of contact-area experiments.

Non-contact-area experiments

As these experiments were designed to simulate changes in non-contact-areas, no load was applied during these experiments. Experiments were conducted at the following pH's:

Experiment Series A0: lubricating with water (pH=7.0)

These experiments were conducted at pH=7.0 and specimens were stored in containers with tap water for 16 hours (approximating the duration of contact area experiments conducted over 80,000 cycles). Height of defined sites (center of restoration and margins of restoration) was measured before and after the experiment using the modified-light microscope. Before the commencement and at the completion of each experiment polyvinylsiloxane impressions (Extrude Injection, Kerr Corporation, USA) were made following the manufacturers instructions. Replicas were constructed in epoxy die material (Epoxy-Die, Ivoclar Pty. Ltd, USA) according to the instructions. These replicas were available for subsequent visual and scanning electron microscopic examination.

Experiment Series B0: lubricating with acetic acid (0.05 mol, pH=3.3)

These experiments were conducted at pH of 3.3. Again specimens were stored in containers with acetic acid for 16 hours (corresponding to the duration for 80,000 cycles of wear). The methodology for this series of experiments was identical to experiments A0.

Experiment Series C0: lubricating with hydrochloric acid (0.01 mol, pH=1.2)

These experiments were conducted at pH of 1.2 and specimens were stored in container with hydrochloric acid for 2 hours (almost equal to time for 10,000 cycles). The methodology for this series of experiments was identical to experiments A0.

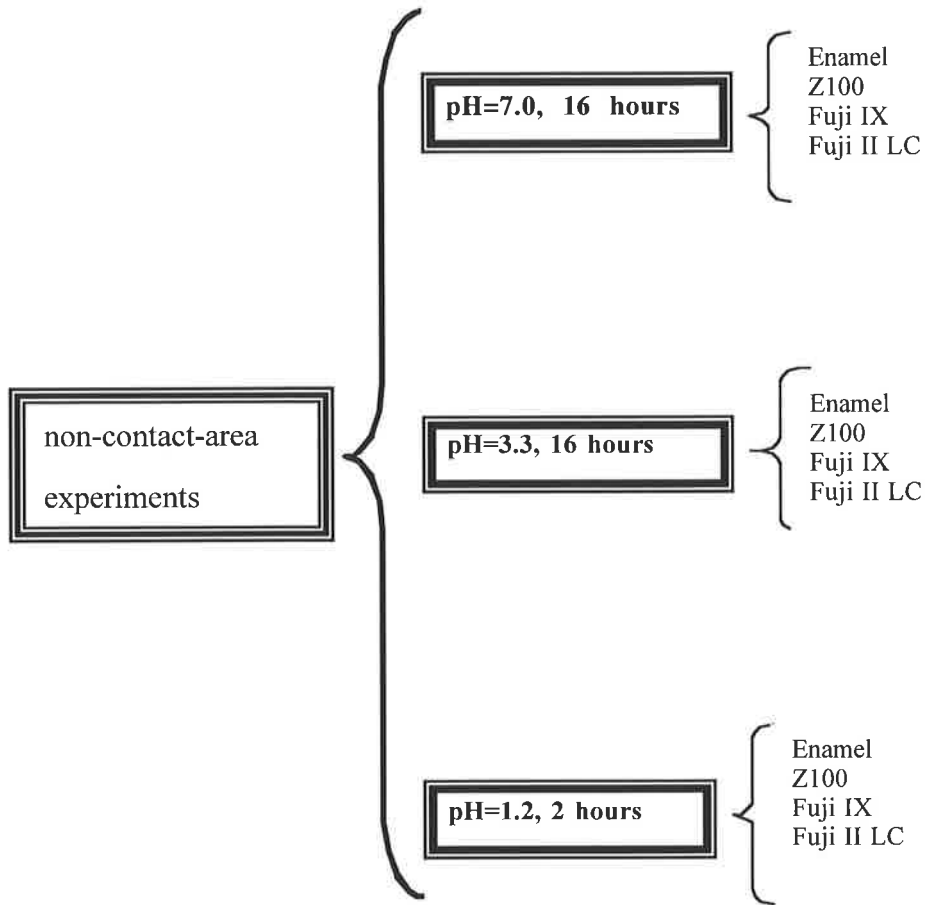


Diagram 8.2 Design of non-contact-area experiments.

Table 8.2 Numbers of specimens for non-contact-area experiments at different conditions.

pH	Period (hours)	Material	numbers
7.0	16	Enamel	10
		Z100	10
		Fuji IX	10
		Fuji II LC	10
3.3	16	Enamel	10
		Z100	10
		Fuji IX	10
		Fuji II LC	10
1.2	2	Enamel	10
		Z100	10
		Fuji IX	10
		Fuji II LC	10

Special Considerations

During these experiments, variables were controlled as follows:

- All teeth were sectioned mesio-distally which allowed the buccal aspect of each tooth to wear in contact with its own lingual aspect. This overcame to some extent the variability that may exist between teeth from different individuals.
- The surface of the mounting adhesive was always sealed by nail varnish to prevent any lubricant uptake.
- The duration of contact between specimens was kept constant. It was achieved by setting the lateral displacement of the upper, moveable part of the machine at 3 mm to ensure both upper and lower specimens remained in contact throughout the movement.
- As preliminary experiments showed no significant difference in wear rate between uni-directional and bi-directional movements, uni-directional movement was used exclusively for this series of experiments.
- The operating speed of the machine was set at 80 cycles per minute. Although preliminary experiments showed slightly greater amount of wear at 160 cycles per minute due to impact stress imparted into the grinding cycle, cycle speed at which specimens were worn did not affect the wear rate. Therefore, it was decided to run machine at 80 cycles per minute to minimise the effect of impact stress.
- The modified-light-microscope was kept on a free-standing table with no vibration at all times.
- The standard mounting slide was cleaned between uses to remove any debris and minimise errors from misalignment.
- The surface of the mounting tubes which were in contact with the standard mounting slide was cleaned and polished to allow stability of specimens before each measurement.

SECTION 3

RESULTS

Results

Introduction

In this section, wear data (quantitative results) and descriptions of SEM images (qualitative results) derived from contact-area and non-contact-area experiments conducted over the selected ranges of pH and load are presented as:

- **Enamel Wear Results**
- **Composite Resin (Z100) Wear Results**
- **Conventional-GIC (Fuji IX) Wear Results**
- **Resin Modified-GIC (Fuji II LC) Wear Results**

Chapter 9

Enamel Wear Results

Quantitative Results

Information about the wear rate of enamel was derived from a series of experiments representing each of the conditions described in Chapter 8. Results of these experiments are subdivided into three main groups:

Enamel Experiments Series A (pH=7.0)

Enamel Experiments Series B (pH=3.3)

Enamel Experiments Series C (pH=1.2)

Enamel Experiments Series A (pH=7.0)

These experiments were conducted with lubrication at pH=7.0 under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and under no load for non-contact-area experiments. The results for this series of experiments are summarized as part of Figure 9.1. They were subdivided into the following groups:

Enamel A3 (pH=7.0, load=9.95 kg)

At pH=7.0 and under load=9.95 kg, mean wear rates across the facet were of the order of $1.1 \mu\text{m}/10^3$ cycles. While wear tended to be more rapid in the area of the last contact, the differences across the facet were not statistically significant ($p>0.05$).

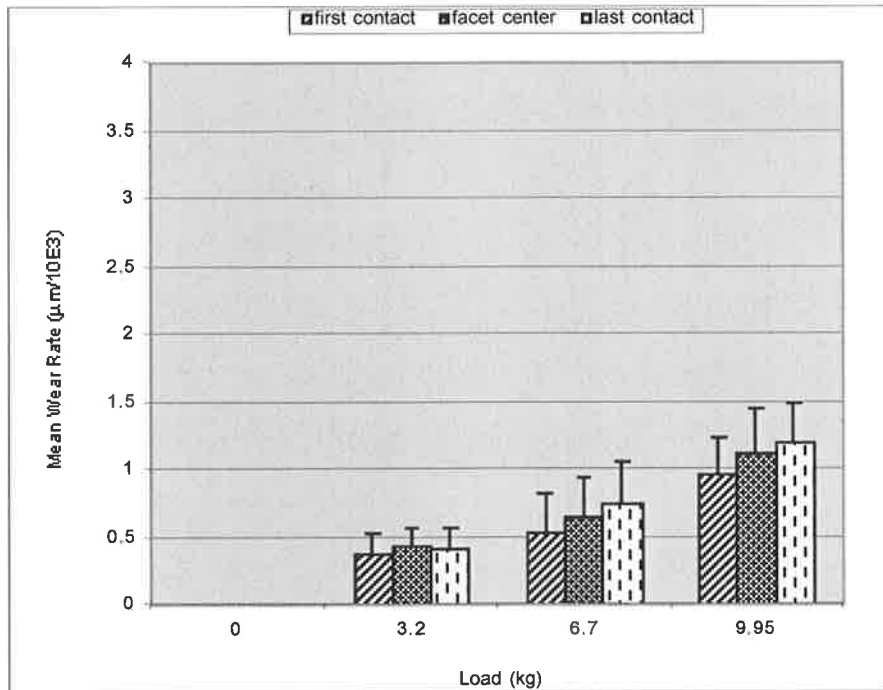


Figure 9.1 Mean wear rates ($\mu\text{m}/10^3$ cycles) of enamel at pH=7.0 and under different loads (kg) measured for the area of first contact, area of facet center, and area of last contact.

Enamel A2 (pH=7.0, load=6.7 kg)

Mean wear rates for experiments conducted at pH=7.0 and under load of 6.7 kg were significantly less than mean wear rates of those under load of 9.95 kg and at the same pH ($p<0.05$). Mean wear rates were of the order of $0.64 \mu\text{m}/10^3$ cycles. Although wear rates tended to be more rapid in the area of last contact paralleling the pattern seen in high load (9.95 kg) these differences were not statistically significant ($p>0.05$).

Enamel A1 (pH=7.0, load=3.2 kg)

Mean wear rates at pH=7.0 and under load of 3.2 kg were significantly lower than of mean wear rates of those experiments under load of 9.95 kg and at the same pH ($p < 0.05$). Wear rates of the area of last contact compared to the area of first contacts were not as rapid as that for experiments under loads of 9.95 and 6.7 kg. Under this load, the mean wear rates were of the order of $0.39 \mu\text{m}/10^3$ cycles.

Enamel A0 (pH=7.0, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) in lubricant at pH=7.0, no enamel loss was recorded.

Enamel Experiments Series B (pH=3.3)

These series of experiments were performed with lubricant at pH=3.3 under three different loads (9.95, 6.7, and 3.2 kg) for contact-area experiments and under no load for non-contact-area experiments. The results for this group of experiments are shown as part of Figure 9.2. They were subdivided into following groups:

Enamel B3 (pH=3.3, load=9.95 kg)

The mean wear rates at pH=3.3 and under load of 9.95 kg were of the order of $2.73 \mu\text{m}/10^3$ cycles. While wear seemed to be more rapid in the area of the last contact, these differences across the facet were not statistically significant ($p > 0.05$).

Mean wear rates of experiments at pH=3.3 and under load of 9.95 kg were significantly higher than mean wear rates of those experiments at pH=7.0 and under at the same load ($p < 0.05$).

Enamel B2 (pH=3.3, load=6.7 kg)

Mean wear rates for experiments conducted at pH=3.3 and under load of 6.7 kg were significantly less than wear rates of those experiments under load of 9.95 kg and at the

same pH ($p < 0.05$). Mean wear rates of this group of experiments were of the order of $2.1 \mu\text{m}/10^3$ cycles.

Wear rates tended not to be more rapid in the area of last contact paralleling the pattern seen in high load (9.95 kg) and at the same pH.

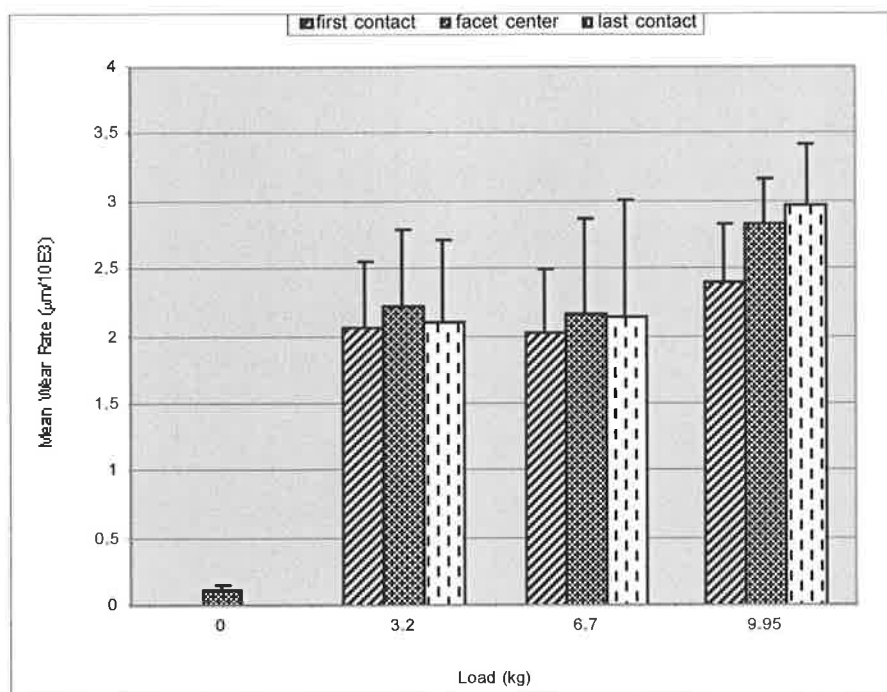


Figure 9.2 Mean wear rates ($\mu\text{m}/10^3$ cycles) of enamel at pH=3.3 and under different loads measured for the area of first contact, area of facet center, and area of last contact.

Enamel B1 (pH=3.3, load=3.2 kg)

Mean wear rates in the area of facet centre tended to be more rapid than other areas but these differences were not significant ($p > 0.05$). Mean wear rates under these conditions were of the order of $2.1 \mu\text{m}/10^3$ cycles, which was similar to that for experiments under load of 6.7 kg and at same pH. Mean wear rates of this group of experiments were significantly lower than mean wear rates of those at load of 9.95 kg and at the same pH ($p < 0.05$).

Mean wear rates of the experiments at pH=3.3 and load of 3.2 kg were significantly higher than those experiments at pH=7.0 and the same load ($p < 0.05$).

Enamel B0 (pH=3.3, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) storage in lubricant at pH=3.3, enamel loss was equivalent to $0.12 \mu\text{m}/10^3$ cycles which was significantly lower than that for corresponding contact-area-experiments ($p < 0.05$).

Enamel Experiments Series C (pH=1.2)

These series of experiments were performed at pH=1.2 under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and under no load for non-contact-area experiments. The results for this series of experiments are shown as part of Figure 9.3. They were subdivided into following group:

Enamel C3 (pH=1.2, load=9.95 kg)

Under these conditions the mean wear rates across the facet were of the order of $37.6 \mu\text{m}/10^3$ cycles. The differences across the facet were not statistically significant ($p > 0.05$). Mean wear rates for this group of experiments were significantly more rapid than those experiments at higher pH's (7.0, 3.3) and at the same load ($p < 0.05$).

Enamel C2 (pH=1.2, load=6.7 kg)

At pH=1.2 and under load of 6.7 kg, mean wear rates tended to be more rapid in the area of last contact but these differences were not significant ($p > 0.05$) reflecting a similar pattern to that which was evident at a load of 9.95 kg. The mean wear rates across the facet were of the order of $37.6 \mu\text{m}/10^3$ cycles.

Mean wear rates for this group of experiments were significantly higher than mean wear rates of experiments at higher pH's (7.0, 3.3) and at the same loads.

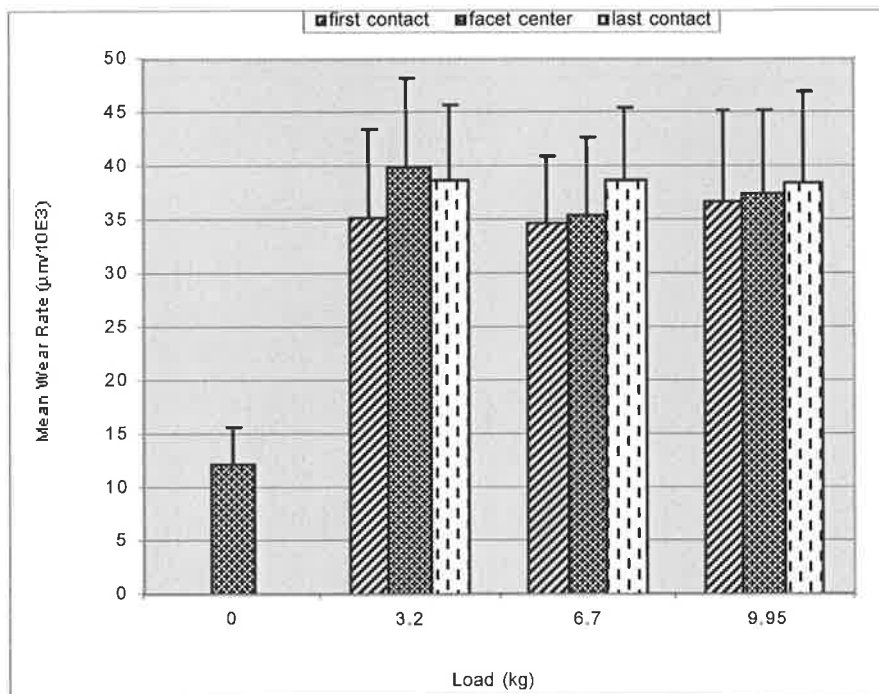


Figure 9.3 Mean wear rates ($\mu\text{m}/10^3$ cycles) of enamel at $\text{pH}=1.2$ and under three defined loads (kg) measured for the area of first contact, area of facet center, and area of last contact.

Enamel C1 ($\text{pH}=1.2$, load=3.2 kg)

Although mean wear rates of experiments at $\text{pH}=1.2$ and at a load of 3.2 kg tended to be more rapid for the area of facet center, these differences across the facets were not significant ($p>0.05$). The mean wear rates across the facet were of the order of $38.0 \mu\text{m}/10^3$ cycles.

Unlike wear rates derived from experiments at higher pH 's (7.0, 3.3), where the rate of wear was lower at lighter loads, the results of this series of experiments suggested that wear rates did not differ significantly with load with lubrication of $\text{pH}=1.2$. Mean wear rates of this group were significantly higher than mean wear rates of those experiments at higher pH 's (7.0, 3.3) and at the same load ($p<0.05$).

Enamel C0 (pH=1.2, load=0.0 kg)

After two hours storage (corresponding to the duration of the 10,000 cycles of wear in the contact-area experiments) in lubricant at pH=1.2, enamel loss was equivalent to $12.22 \mu\text{m}/10^3$. This amount of enamel loss was significantly lower than those for contact-area experiments ($p < 0.05$).

Overview of Quantitative Results

Table 9.1 summarizes the mean wear rates of enamel at three different pH's and under three different loads for three defined points across the wear facet.

Table 9.1 Quantitative results of enamel wear under experimental conditions including pH, load (kg), site, number of specimens (n), mean wear rate and standard deviation (SD).

Experiments	pH	Load (kg)	Site	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)
Enamel A3	7.0	9.95	First	6	0.96	0.21
			Center	6	1.13	0.32
			Last	6	1.2	0.28
Enamel A2	7.0	6.7	First	8	0.53	0.33
			Center	8	0.64	0.29
			Last	8	0.75	0.30
Enamel A1	7.0	3.2	First	5	0.37	0.12
			Center	5	0.41	0.13
			Last	5	0.4	0.15
Enamel A0	7.0	0.0	Center	10	0.0	0.0
Enamel B3	3.3	9.95	First	10	2.39	0.42
			Center	10	2.84	0.33
			Last	10	2.97	0.45
Enamel B2	3.3	6.7	First	8	2.01	0.48
			Center	8	2.16	0.70
			Last	8	2.14	0.88
Enamel B1	3.3	3.2	First	8	2.06	0.49
			Center	8	2.23	0.57
			Last	8	2.05	0.70
Enamel B0	3.3	0.0	Center	9	0.12	0.03
Enamel C3	1.2	9.95	First	9	36.83	8.28
			Center	9	37.54	7.71
			Last	9	38.43	8.61
Enamel C2	1.2	6.7	First	9	34.83	6.14
			Center	9	35.56	7.26
			Last	9	38.73	6.68
Enamel C1	1.2	3.2	First	9	35.33	8.07
			Center	9	39.92	8.42
			Last	9	38.72	7.13
Enamel C0	1.2	0.0	Center	10	12.22	3.58

ANOVA analysis

A series of statistical analyses were undertaken to assess the significance of the observed differences in wear rates. Initially, differences between wear rates in the contact-area experimental groups under various conditions for the three analyzed sites (area of first contact, facet center, area of last contact) across each facet were assessed. The results are included in Table 9.2.

Table 9.2 Two-way ANOVA analysis of wear rate of enamel for contact-area experiments by pH, load, and contact site including degree of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	63965.86	31982.93	1432.661	1.0E ⁻⁴
Load (B)	2	22.062	11.031	.494	.6109
AB	4	25.157	6.289	.282	.8896
Site (C)	2	45.662	22.831	1.023	.3616
AC	4	65.925	16.481	.738	.567
BC	4	17.786	4.446	.199	.9386
ABC	8	43.57	5.446	.224	.9818
Error	189	4219.263	22.324		

The results of this analysis for the experiments under load suggest that effect of pH was statistically significant on enamel wear rate while enamel wear rate did not differ significantly with load or site.

As the variation in wear rate did not differ significantly with site (ie between the area of first contact, the center of the facet, and the area of final contact) in either of these analyses, site was not included in the subsequent ANOVA.

Table 9.3 Two-way ANOVA analysis of wear rate of enamel for both contact-area and non-contact-area experiments by pH, and load including degrees of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	15537.435	7768.718	391.303	1.0E ⁻⁴
Load (B)	3	34.94	11.647	0.587	0.6255
AB	6	1202.532	200.422	10.095	1.0E ⁻⁴
Error	80	1588.276	19.853		

ANOVA results for both contact-area and non-contact-area experiments also demonstrated the significant effect of pH on wear rate. In addition, combination of pH and load significantly effected the mean wear rate of enamel indicating that the effect of load was more significant at some pH's on mean wear rate of enamel.

Qualitative Results

Results obtained from SEM analysis of enamel wear in each of the experimental groups are shown to illustrate surface characteristics under different conditions. The results for specimens from each series of experiments are presented with the area of first contact to the right of the image and at two enlargements. The lower magnification being of the order of 20-30 times and the higher magnifications being in the range 300-400 times.

Enamel Experiments Series A (pH=7.0)

Enamel A3 (pH=7.0, load=9.95 kg)

At pH=7.0 at a load of 9.95 kg the microscopic appearance was consistent across the facet with the predominant appearance suggesting surface breakdown of the type associated with adhesive wear. The higher magnification image showed significant surface roughness.

Enamel A2 (pH=7.0, load=6.7 kg)

At pH=7.0 and under load of 6.7 kg surface roughness was less marked than at the higher load. The center of the facet showed evidence of surface breakdown but the areas of first and final contact showed a tendency to be less rough.

Enamel A1 (pH=7.0, load=3.2 kg)

At pH of 7.0 and under load of 3.2 kg the facet appearance was significantly different that at higher loads. The wear facet was generally consistent in appearance with little evidence of surface roughness. At higher magnification the surface was characterized by a generally smooth appearance with areas of surface pitting and chipping. These pits

were of the order of 5 μm in diameter and occurred either in isolation or in aggregates of 10-20 μm .

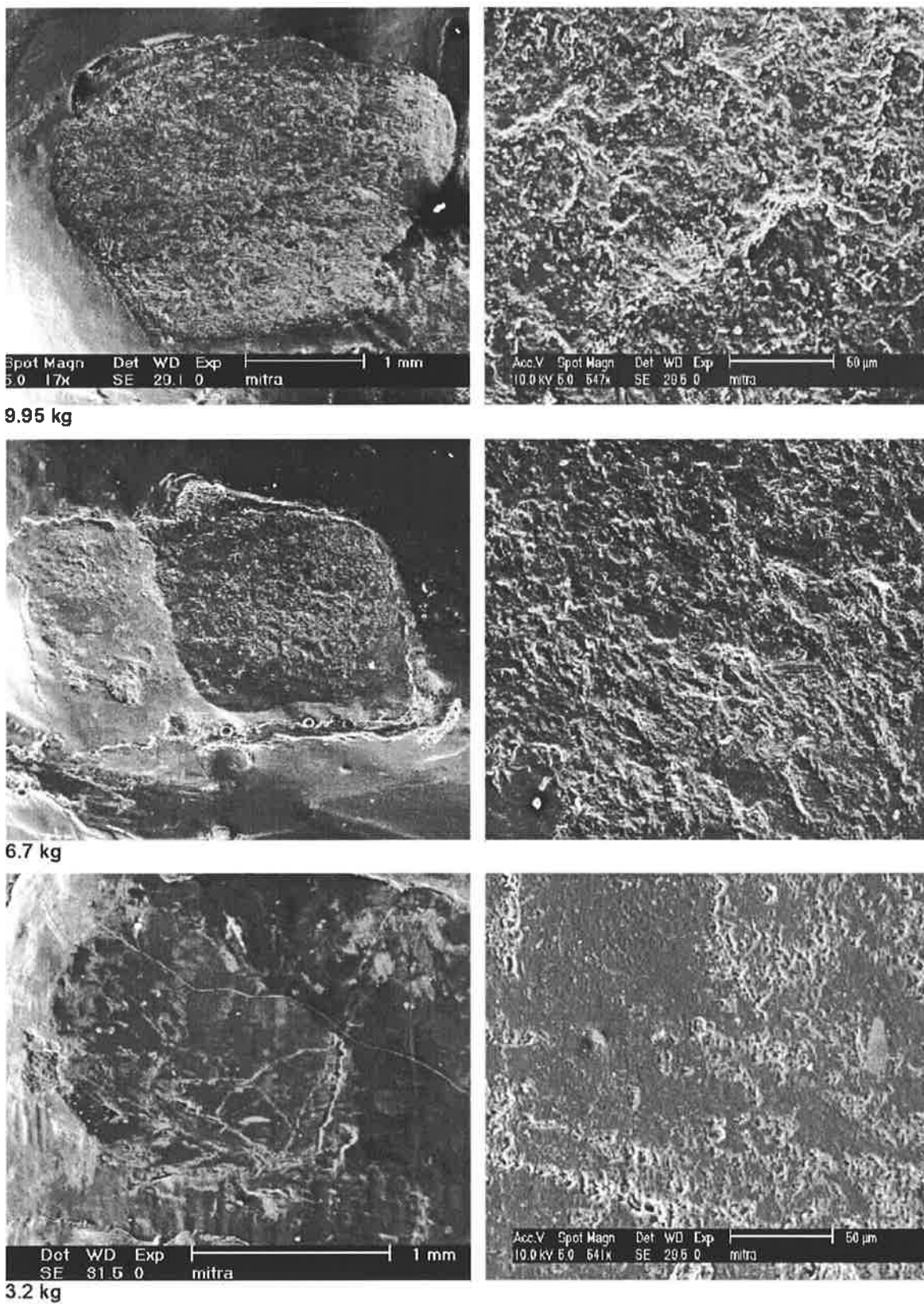


Figure 9.4 SEM results of enamel at pH=7.0 and under different loads (kg).

Enamel Experiments Series B (pH=3.3)

For the series of experiments conducted at pH=3.3 the predominant pattern of wear appeared to reflect the effects of the acid. The extent of acid destruction is evident in the in the lower magnification images where clear facet margins were not evident and enamel microstructure was accentuated in non-contact areas.

Enamel B3 (pH=3.3, load=9.95 kg)

Under these conditions the “etched” appearance of the enamel was consistent across the facets. There was, however, a qualitative difference in the appearance of the etching between specimens subjected to wear at 9.95 kg and the known appearance of etched, unworn enamel. The worn specimens showed evidence of damage to exposed enamel prisms and evidence of wear striations across the etched surface.

Enamel B2 (pH=3.3, load=6.7 kg)

The overall pattern of wear under these conditions was similar to that seen at the higher load except that there was little evidence of damage to the etched enamel prisms and no evidence of wear striations. The micro-morphology of the wear occurring under these conditions was consistent across the facet.

Enamel B1 (pH=3.3, load=3.2 kg)

At high magnification, the appearance of wear appeared very similar to that occurring at load=6.7 kg with a similar pattern of etching across the facet.

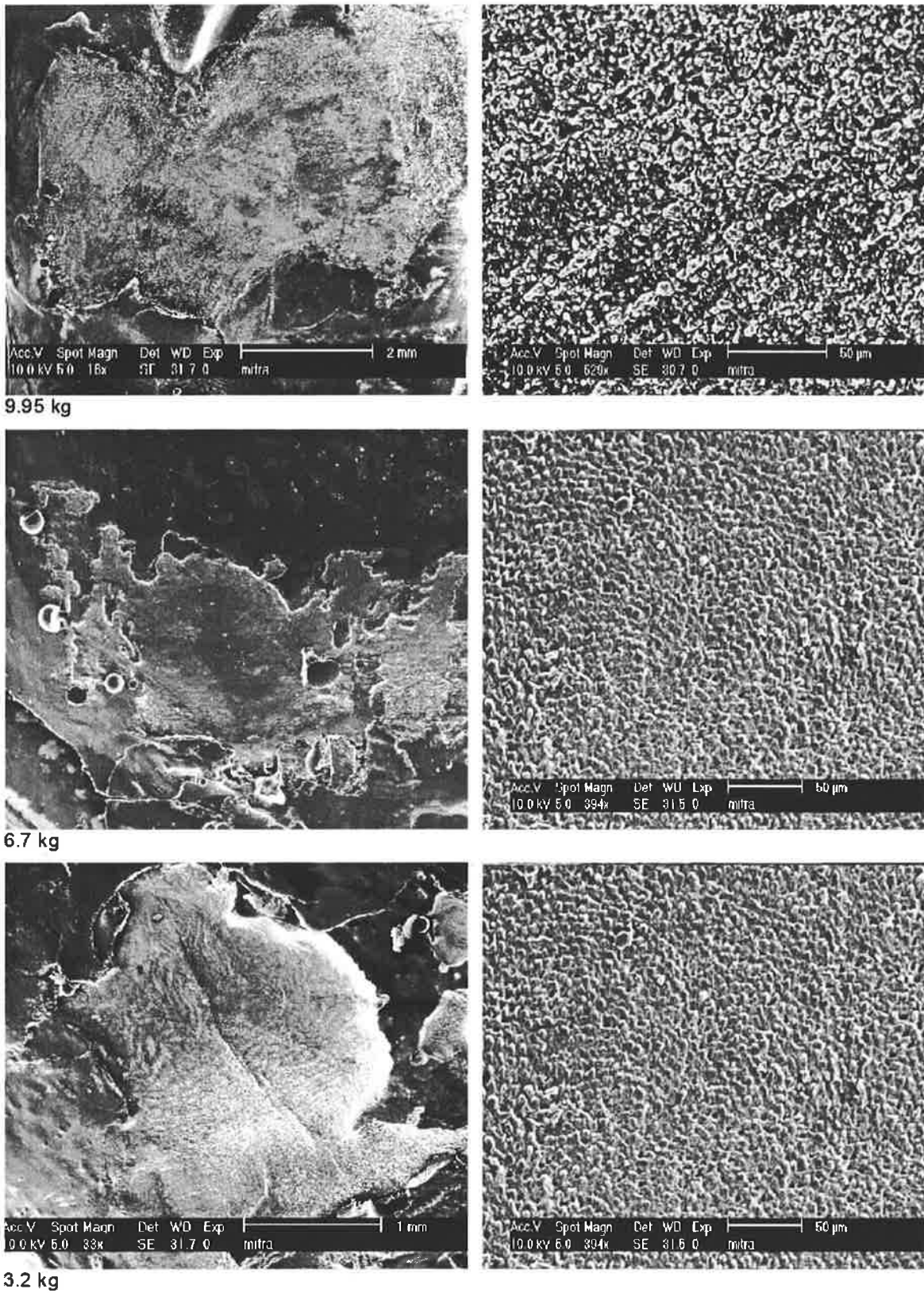


Figure 9.5 SEM results of enamel at pH=3.3 and under different loads (kg).

Enamel Experiments Series C (pH=1.2)

Lubrication of specimens with acid at pH=1.2 resulted in extensive destruction of exposed enamel.

Enamel C3 (pH=1.2, load=9.95 kg)

Under these conditions there were no apparent differences in the appearance of the wear across the facet, with similar appearances in the areas of first and final contact and in the center of the facet. At higher magnification acid etching and the superimposed wear revealed the prism structure of the enamel with the end of the exposed rods showing evidence of flattening associated with the concurrent wear.

Enamel C2 (pH=1.2, load=6.7 kg) andEnamel C1 (pH=1.2, load=3.2 kg)

The resultant appearance the enamel did not appear to differ significantly between specimens subjected to wear under these conditions. They showed extensive destruction and little remaining evidence of the original enamel micro-anatomy.

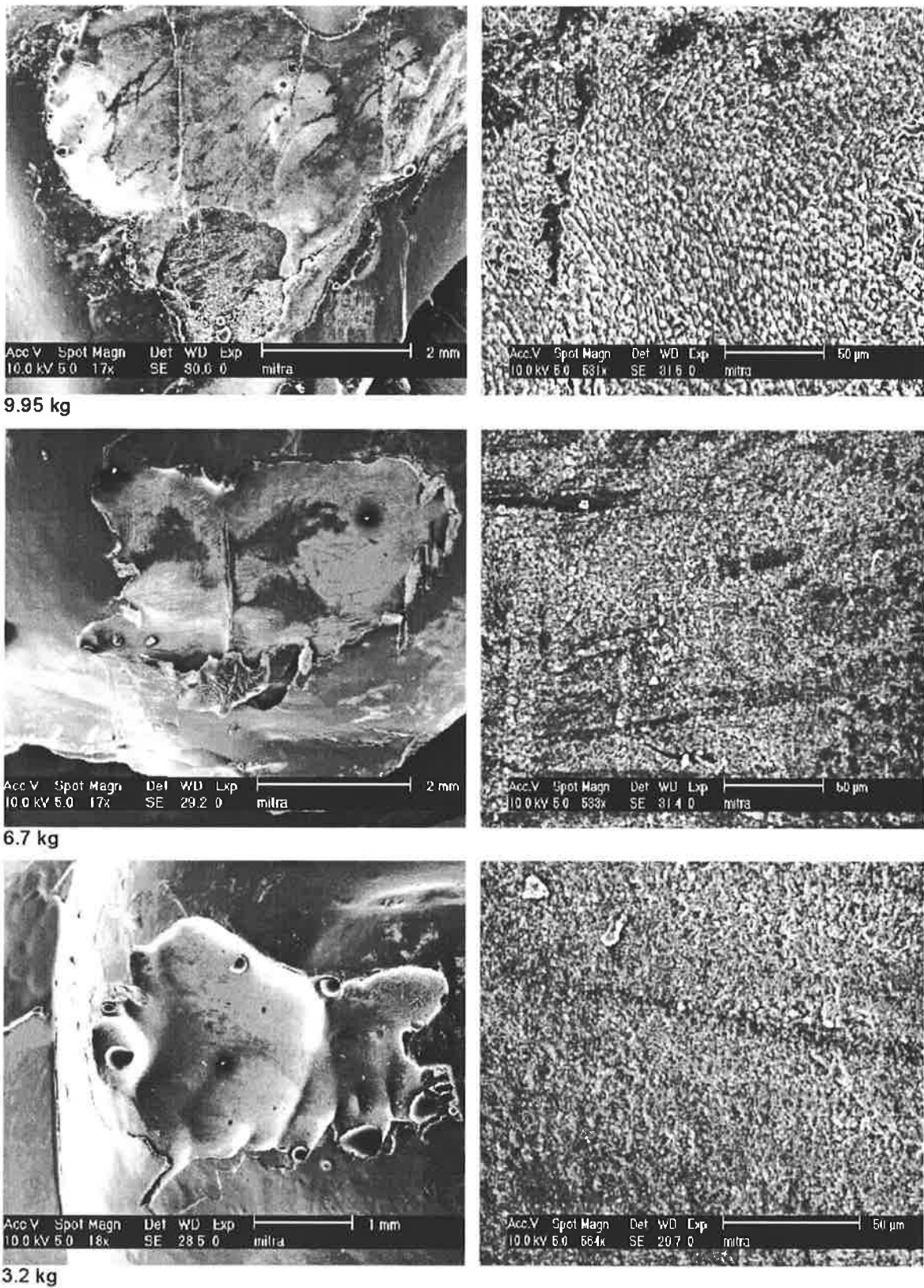


Figure 9.6 SEM results of enamel at pH=1.2 and under different loads (kg).

Non-Contact Experiments

Enamel Experiments Series A0, B0, C0 (pH=7.0, pH=3.3, pH=1.2)

Enamel Experiments Series A0 (pH=7.0, load=0.0 kg)

At pH=7.0 there was no loss of enamel and no changes to the micro-morphology of the surface.

Enamel Experiments Series B0 (pH=3.3, load=0.0 kg)

At pH=3.3 there was evidence of chemical damage reflecting the effects of the acid. Surface of enamel looked rough with some relief of the order of 1-5 μm in diameter.

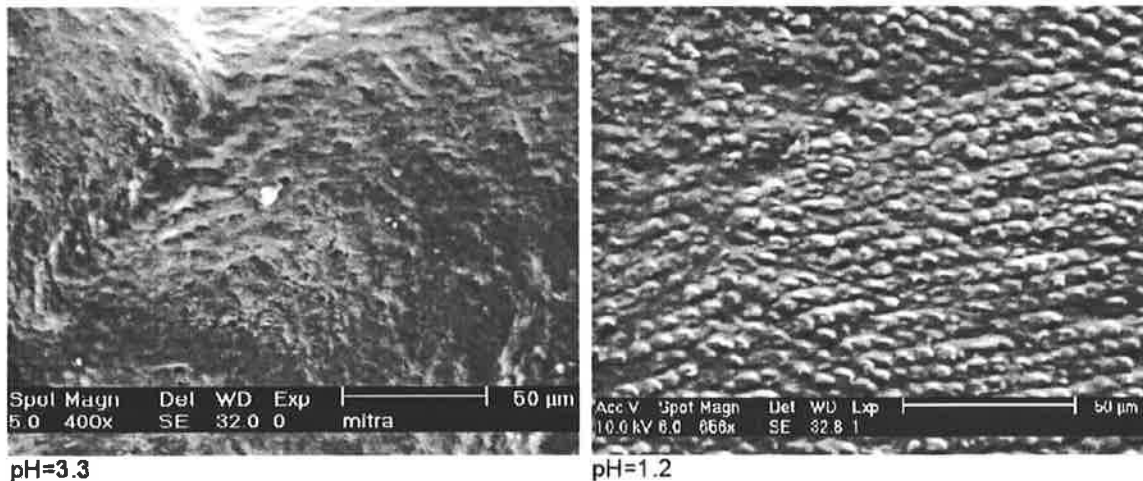


Figure 9.7 SEM results of enamel for non-contact-area experiments.

Enamel Experiments Series C0 (pH=1.2, load=0.0 kg)

Lubrication of specimens with acid at pH=1.2 resulted in “acid etched” appearance showing evidence of the original enamel micro-anatomy. There was no evidence of surface breakdown.

Conclusion

In conclusion, the qualitative and quantitative results obtained in this part of the study are presented in Figure 9.8 and Table 9.4.

At higher pH's (7.0, 3.3) mean wear rates of enamel were proportional to load with significantly higher wear rates at higher loads (9.95, 6.7 kg) than those under low load of 3.2 kg ($p < 0.05$).

Mean wear rates of enamel at low pH (1.2) were significantly higher than those higher pH's (7.0, 3.3) ($p < 0.05$).

Mean wear rates of enamel loss under no load were significantly lower than those of under loads ($p < 0.05$).

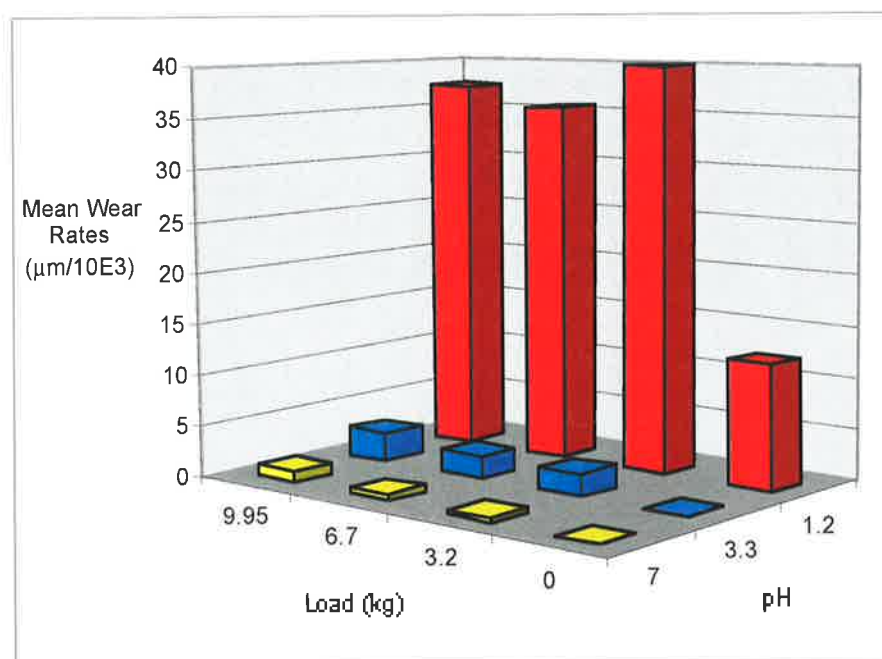


Figure 9.8 Mean wear rates ($\mu\text{m}/10^3$) of enamel at different pH's and under different loads (kg).

Table 9.4 Summary of quantitative and qualitative results of enamel experiments at different pH's and under different loads (kg).

Load (kg)	pH		
	7.0	3.3	1.2
9.95	Low wear rate ($1.13\mu\text{m}/10^3$ cycles), extensive surface breakdown	Moderate wear rate ($2.84\mu\text{m}/10^3$ cycles), etched and worn surface	Extreme wear rate ($37.54\mu\text{m}/10^3$ cycles), extensive etching with superimposed wear
6.7	Very low wear rate ($0.64\mu\text{m}/10^3$), some surface breakdown	Moderate wear rate ($2.16\mu\text{m}/10^3$), etched surface	Extreme wear rate ($35.56\mu\text{m}/10^3$), surface destruction
3.2	Very low wear rate ($0.41\mu\text{m}/10^3$), generally smooth surface	Moderate wear rate ($2.23\mu\text{m}/10^3$), etched surface	Extreme wear rate ($39.92\mu\text{m}/10^3$), surface destruction
0.0	No enamel loss	Lowest wear rate ($0.12\mu\text{m}/10^3$) eroded surface	Very high wear rate ($12.2\mu\text{m}/10^3$) expose of enamel rods

CHAPTER 10

Composite Resin Wear Results

Introduction

In this chapter, wear data (quantitative results) and descriptions of SEM images (qualitative results) derived from experiments with composite resin (**Z100**, 3M, St. Paul, MN) conducted over the selected ranges of pH and load are presented.

Quantitative Results

Information about the wear rates of composite resin was derived from a series of experiments representing each of the conditions described in Chapter 8. Results of these experiments are subdivided into three main groups:

Composite Resin Experiments Series A (pH=7.0)

Composite Resin Experiments Series B (pH=3.3)

Composite Resin Experiments Series C (pH=1.2)

Composite Resin Experiments Series A (pH=7.0)

These experiments were conducted with lubrication at pH=7.0 and under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and under no load for non-contact-

area experiments. The results for this series of experiments are summarized as part of Figure 10.1. They were subdivided into following groups:

Composite Resin A3 (pH=7.0, load=9.95 kg)

At pH=7.0 and under load=9.95 kg, mean wear rates across the facet were of the order of $1.48 \mu\text{m}/10^3$ cycles. Although mean wear rates tended to be more rapid in the margin adjacent to the area of first contact than other areas, the differences cross the restorations were not statistically significant ($p>0.05$).

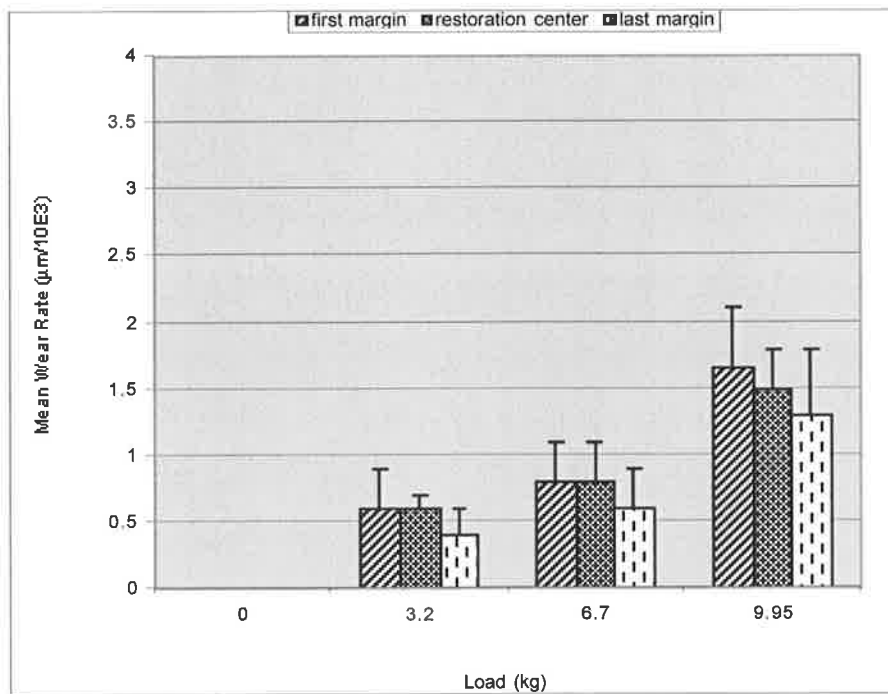


Figure 10.1 Mean wear rates ($\mu\text{m}/10^3$ cycles) of composite resin at pH=7.0 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact.

Composite Resin A2 (pH=7.0, load=6.7 kg)

Mean wear rates for experiments conducted at pH=7.0 and under load=6.7 kg were significantly less than wear rates of those under load of 9.95 kg ($p<0.05$). Under load of 6.7 kg, mean wear rates were of the order of $0.73 \mu\text{m}/10^3$ cycles. Wear rates tended to be

more rapid for the margin adjacent to the area of first contact than other areas but these differences were not statistically significant ($p>0.05$).

Composite Resin A1 (pH=7.0, load=3.2 kg)

Under load=3.2 kg, mean wear rates were of the order of $0.53 \mu\text{m}/10^3$ cycles. Wear rates tended to be more rapid in the margin adjacent to the area of first contact paralleling the pattern seen at load=6.7 kg but again these differences were not significant ($p>0.05$).

Mean wear rates were significantly lower than mean wear rates under load=9.95 kg at the same pH ($p<0.05$). Although mean wear rates tended to be lower than mean wear rate of those under load of 6.7 kg, these difference were not significant ($p>0.05$).

Composite Resin A0 (pH=7.0, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) in lubricant at pH=7.0, no composite resin loss was recorded.

Composite Resin Experiments Series B (pH=3.3)

These series of experiments were performed with lubricant at pH=3.3 under three different loads (9.95, 6.7, and 3.2 kg) for contact-area experiments and under no load for non-contact-area experiments. The results for this group of experiments are shown as part of Figure 10.2. They were subdivided into following groups:

Composite Resin B3 (pH=3.3, load=9.95 kg)

At pH=3.3 and under load=9.95 kg, mean wear rates across the restorations were of the order of $0.8 \mu\text{m}/10^3$ cycles. While wear appeared to be more rapid in the margin adjacent to the area of first contact, these differences cross the restorations were not statistically significant ($p>0.05$). Mean wear rates of experiments at pH=3.3 and under load=9.95 kg were significantly lower than mean wear rate of experiments at pH=7.0 and at the same load ($p<0.05$).

Composite Resin B2 (pH=3.3, load=6.7 kg)

Under load of 6.7 kg, mean wear rates were of the order of $0.6 \mu\text{m}/10^3$ cycles. No significant differences were found between mean wear rates for different contact areas across the facets ($p>0.05$). Mean wear rates of this group of experiments tended to be less rapid than that for those under load of 9.95 kg and at the same pH but these differences were not significant ($p>0.05$).

No significant differences were found between mean wear rates for this group of experiments and those at higher pH (7.0) at the same load ($p>0.05$).

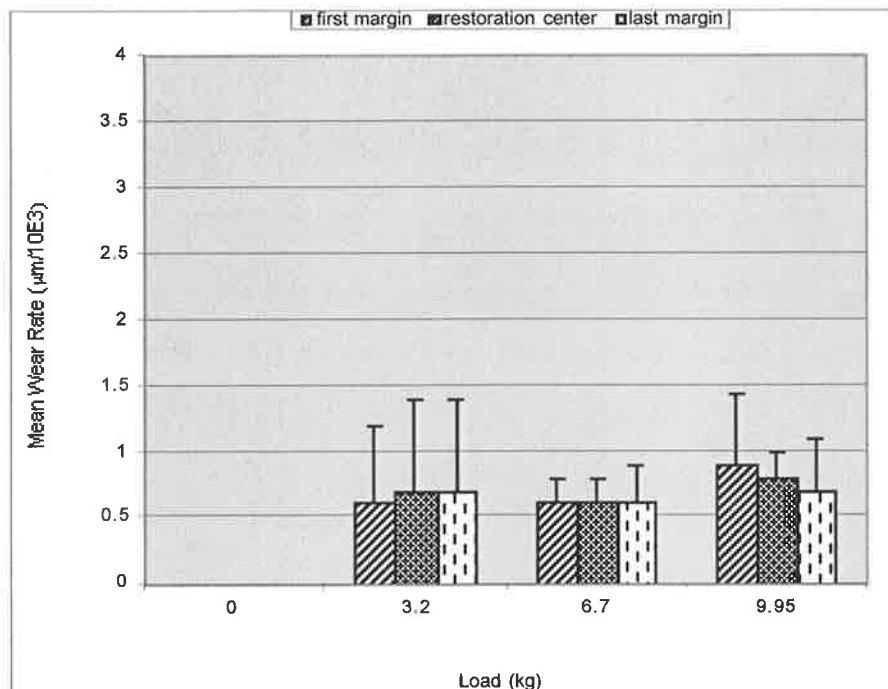


Figure 10.2 Mean wear rates ($\mu\text{m}/10^3$ cycles) of composite resin at pH=3.3 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact.

Composite Resin B1 (pH=3.3, load=3.2 kg)

Wear pattern for the experiments at pH=3.3 and under load=3.2 kg was different from those experiments under higher loads (9.95, 6.7 kg) at the same pH. Mean wear rates of the margin adjacent to the area of last contact tended to be more rapid than other areas

but these differences were not statistically significant ($p>0.05$). Mean wear rates were of the order of $0.66 \mu\text{m}/10^3$ cycles which tended to be higher than mean wear rates of those experiments under load of 6.7 kg and at the same pH but again these differences were not statistically significant ($p>0.05$).

Composite Resin B0 (pH=3.3, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) in lubricant at pH=3.3, no composite resin loss was recorded.

Composite Resin Experiments Series C (pH=1.2)

These series of experiments were performed at pH=1.2 under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and under no load for non-contact-area experiments. The results for this series of experiments are shown as part of Figure 10.3. They were subdivided into three following groups:

Composite Resin C3 (pH=1.2, load=9.95 kg)

At pH=1.2 and under load of 9.95 kg, mean wear rates across the restorations were of the order of $6.02 \mu\text{m}/10^3$ cycles. Mean wear rates of last margins adjacent to the area of last contact tended to be more rapid than other areas although these differences were not statistically significant ($p>0.05$).

Mean wear rates for this group of experiments were significantly higher than mean wear rates of those experiments at higher pH's (7.0,3.3) and at the same load ($p<0.05$).

Composite Resin C2 (pH=1.2, load=6.7 kg)

At pH=1.2 and under load of 6.7 kg, mean wear rates tended to be more rapid in the area of restoration centers than other areas but these differences were not statistically significant ($p>0.05$). The mean wear rates across the restorations were of the order of $2.43 \mu\text{m}/10^3$ cycles. Mean wear rates of this group were significantly higher than mean

wear rates of experiments at higher pH's (7.0, 3.3) and at the same load ($p < 0.05$). Mean wear rates were also significantly higher than mean wear rate of those experiments load of 9.95 kg and at the same pH ($P < 0.05$).

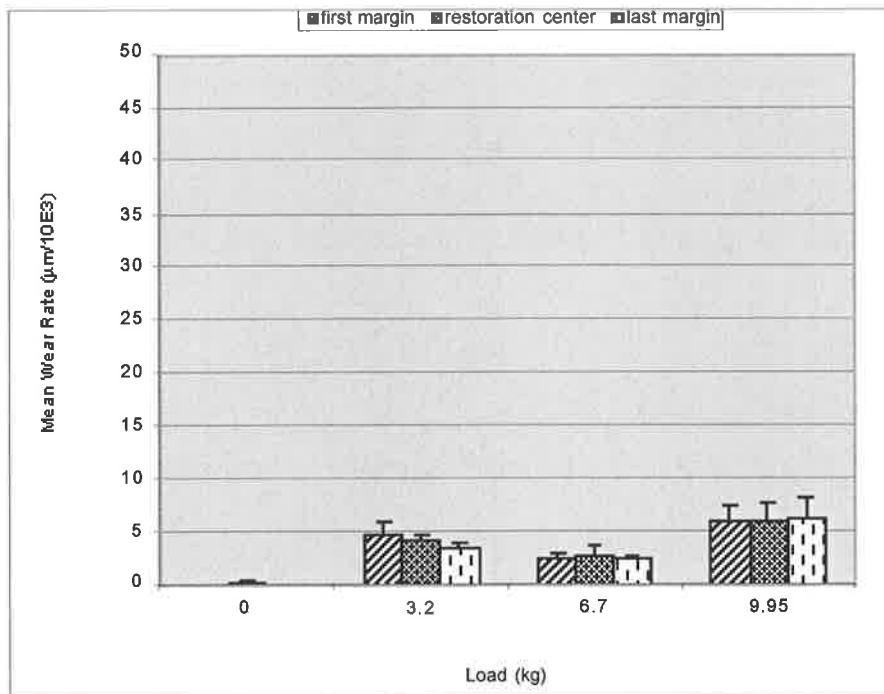


Figure 10.3 Mean wear rates ($\mu\text{m}/10^3$ cycles) of composite resin at pH=1.2 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact.

Composite Resin C1 (pH=1.2, load=3.2 kg)

Mean wear rates of experiments at pH=1.2 and under load=3.2 kg were significantly more rapid for the margins adjacent to the area of first contact area than other areas but these differences were not significant ($p > 0.05$). Mean wear rates of this group of experiments were of the order of $4 \mu\text{m}/10^3$ cycles which was significantly higher than mean wear rates of those experiments at higher pH's (7.0, 3.3) and at the same load ($p < 0.05$).

Composite Resin C0 (pH=1.2, load=0.0 kg)

After 2 hours (corresponding to the duration of the 10,000 cycles of wear in the contact-area experiments) in lubricant at pH=1.2, composite resin loss was $0.2 \mu\text{m}/10^3$.

Overview of Quantitative Results

Table 10.1. summarized the mean wear rates of composite resin with their standard deviations at three different pH's and under three different loads for three defined points.

Table 10.1 Quantitative results of composite resin (CR) wear under experimental conditions including pH, load (kg), site, number of specimens (n), mean wear rate ($\mu\text{m}/10^3$), and standard deviation ($\mu\text{m}/10^3$), (SD).

Experiments	pH	Load (kg)	Site	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)
CR A3	7.0	9.95	First	5	1.65	0.5
			Center	5	1.5	0.3
			Last	5	1.3	0.5
CR A2	7.0	6.7	First	5	0.8	0.3
			Center	5	0.8	0.3
			Last	5	0.6	0.3
CR A1	7.0	3.2	First	6	0.6	0.3
			Center	6	0.6	0.1
			Last	6	0.4	0.2
CR A0	7.0	0.0	Center	10	0.0	0.0
CR B3	3.3	9.95	First	6	0.9	0.5
			Center	6	0.8	0.2
			Last	6	0.7	0.4
CR B2	3.3	6.7	First	5	0.6	0.2
			Center	5	0.6	0.2
			Last	5	0.6	0.3
CR B1	3.3	3.2	First	5	0.6	0.3
			Center	5	0.7	0.3
			Last	5	0.7	0.3
CR B0	3.3	0.0	Center	10	0.0	0.0
CR C3	1.2	9.95	First	5	5.8	1.5
			Center	5	6.0	1.7
			Last	5	6.2	2.0
CR C2	1.2	6.7	First	6	2.3	0.6
			Center	6	2.7	0.9
			Last	6	2.3	0.4
CR C1	1.2	3.2	First	5	4.8	1.2
			Center	5	4.0	0.8
			Last	5	3.3	0.5
CR C0	1.2	0.0	Center	10	0.2	0.1

ANOVA Results

An analysis of variance was undertaken to assess the statistical significance of the observed differences in wear rates among experimental groups under various conditions for the three analyzed sites (margin adjacent to the area of first contact, area of restoration center, margin adjacent to the area of last) across each restoration. The results are shown in Table 10.2.

The results suggest that the effect of pH, load, and combination of load and pH were statistically significant while mean wear rate of composite resin did not differ significantly with contact site.

Table 10.2 Two-way ANOVA analysis of wear rates of composite resin in contact-area experiments by pH, load, type of material, and contact site including degrees of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	336.849	168.425	321.775	1.0E ⁻⁴
Load (B)	2	56.629	28.314	54.095	1.0E ⁻⁴
AB	4	54.392	13.598	25.979	1.0E ⁻⁴
Site (C)	2	1.398	0.699	1.336	0.2671
AC	4	0.656	0.164	0.313	0.8685
BC	4	1.606	0.402	0.767	0.5488
ABC	8	4.39	0.549	1.049	0.4044
Error	114	59.67	0.523		

As the variation in wear rate did not differ significantly with site (ie between the margin adjacent to the area of first contact, the restoration center, and the margin adjacent to the area of last contact) in either of these analyses, site was not included in the subsequent ANOVA.

Table 10.3 Two-way ANOVA analysis of wear rates of composite resin for both contact-area and non-contact-area experiments by pH, load, type of material, and contact site including degrees of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	85.851	42.925	118.027	1.0E ⁻⁴
Load (B)	3	18.787	6.262	17.218	1.0E ⁻⁴
AB	6	25.925	4.321	11.88	1.0E ⁻⁴
Error	56	20.367	0.364		



Analysis of variance for both the combined data suggests that the effect of pH, load, and the combination of load and pH were statistically significant on the wear rate.

Qualitative Results

Results obtained from SEM of the composite resin experimental groups are shown to illustrate surface and marginal characteristics of these restorations under different conditions. These results are presented with the margin adjacent to the area of first contact to the right of the image and the margin adjacent to the area of last contact to the left of the image. The surface characteristics of restorations are also shown at higher magnification. The lower magnification being of the order of 20-30 times and higher magnifications being in the range 300-400 times.

Composite Resin Experiments Series A (pH=7.0)

Composite Resin A3 (pH=7.0, load=9.95 kg)

At pH=7.0 and under load=9.95 kg, there was evidence of the same type of enamel breakdown evident in the experiments involving enamel alone particularly in the area of final contact. In addition, there was evidence of more extensive margin breakdown in margins adjacent to the area of first contact where defects of up to 80 μm were evident.

The surface of the restorations was generally smooth with evenly distributed surface irregularities of the order of 1-3 μm in diameter.

Composite Resin A2 (pH=7.0, load=6.7 kg)

Under these conditions cavity margins showed less marginal fracture in the area of first margin contact although there was evidence of breakdown of adjacent enamel for some restorations. Enamel adjacent to the area of last margin contact was generally smooth

with less evidence of surface breakdown than in experiments under similar conditions with enamel alone.

There was less evidence of surface breakdown of composite resin restorations under these conditions under higher loads with up to 50 percent of the restoration appearing smooth and surface irregularities being localized in other areas.

Composite Resin A1 (pH=7.0, load=3.2 kg)

At pH=7.0 and under load of 3.2 kg, there was evidence of some enamel surface breakdown adjacent to the margin in the area of first contact. The enamel surfaces in the areas of final contact were generally smooth. Most of restorations showed no evidence of marginal breakdown and the surfaces of the restorations look much smoother with less surface breakdown than those restorations under higher loads (9.95, 6.7 kg).

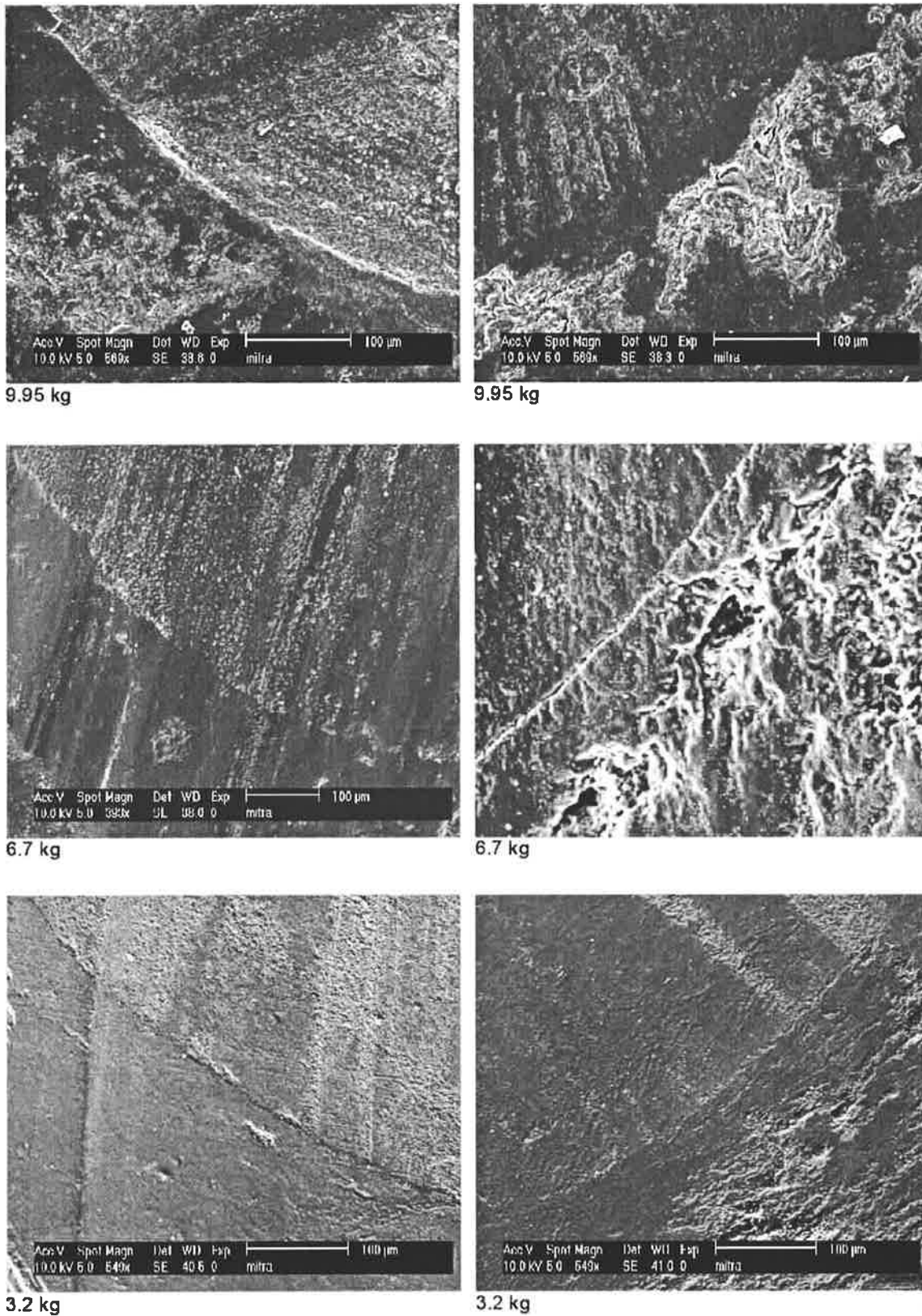


Figure 10.4 SEM results of composite resin at pH=7.0 and under different loads (kg).

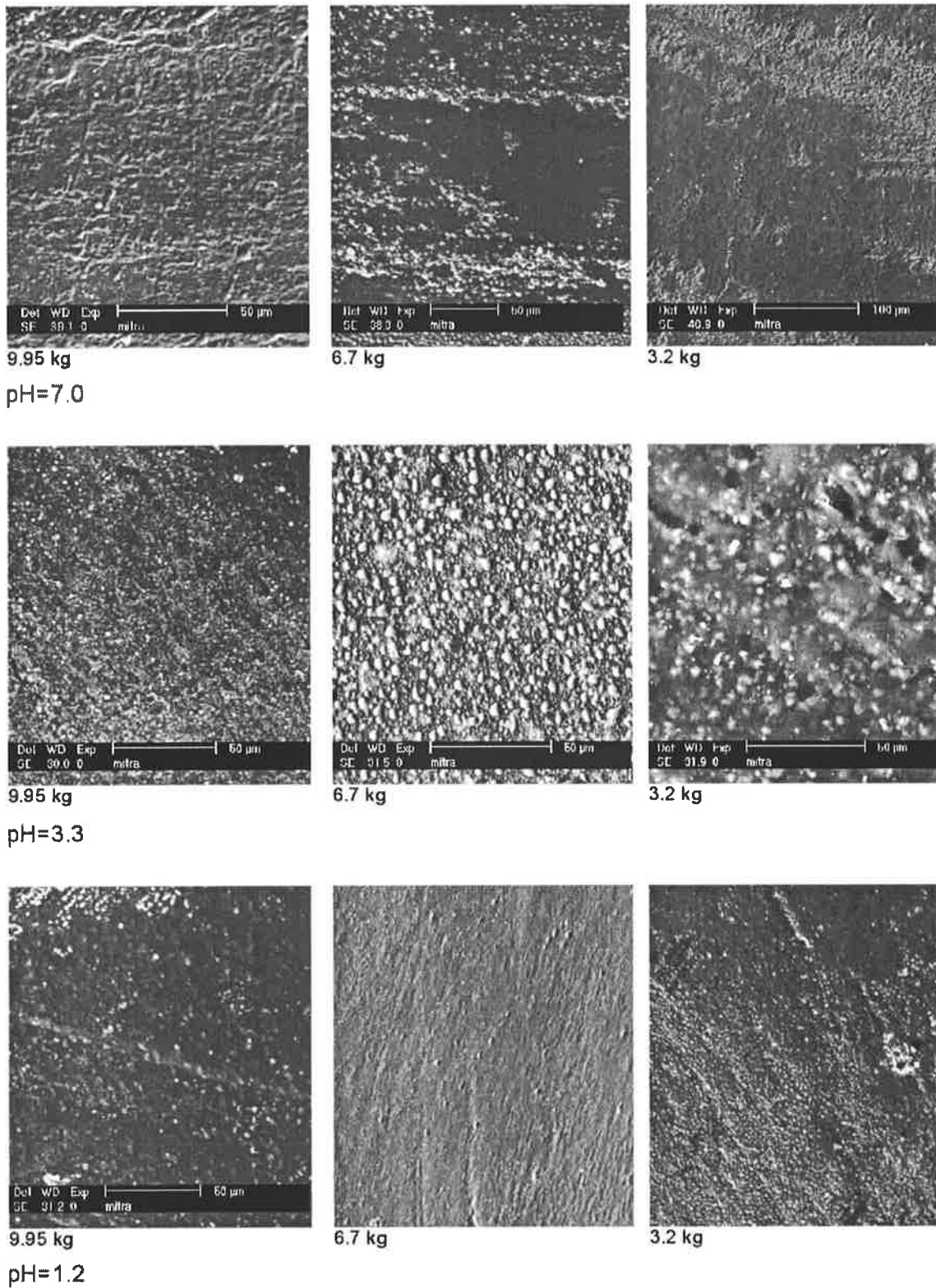


Figure 10.5 SEM results of composite resin at different pH's and under different loads (kg) with high magnification.

Composite Resin Experiments Series B (pH=3.3)

Composite Resin B3 (pH=3.3, load=9.95 kg)

Under these conditions there was clear evidence of erosion corresponding to the enamel changes seen in the corresponding series of experiments.

Because of the relatively high rate of chemical destruction, composite restoration margins were exposed and unsupported by enamel with a step up of the order of 50 μ m from the enamel to the restoration surface. There was some evidence of fracture of the exposed composite margins but the enamel-composite margins were generally intact. Areas of restoration surface breakdown were evident particularly in the areas of initial contact where the surface features were not obviously different to those described at load=9.95 kg and pH=7.0.

Composite Resin B2 (pH=3.3, load=6.7 kg)

The appearance of the enamel in specimens subjected to wear under these conditions was similar to that seen at the higher load with evidence of chemical erosion predominating. This high rate of chemical destruction resulted in exposure of the composite margins in the same way as occurred in experiments at 9.95 kg. The restoration surface was relatively consistent in appearance with exposed filler particles evident across the restoration.

Composite Resin B1 (pH=3.3, load=3.2 kg)

In this series of experiments the enamel surface adjacent to the restorations showed less evidence of the exposed, "etched" appearance evident in the enamel specimens worn under the corresponding conditions

Compared with the restorations worn at higher loads in this series, the restoration surfaces at load=3.2 kg were relatively smooth with less evidence of exposed filler particle and little evidence of surface breakdown.

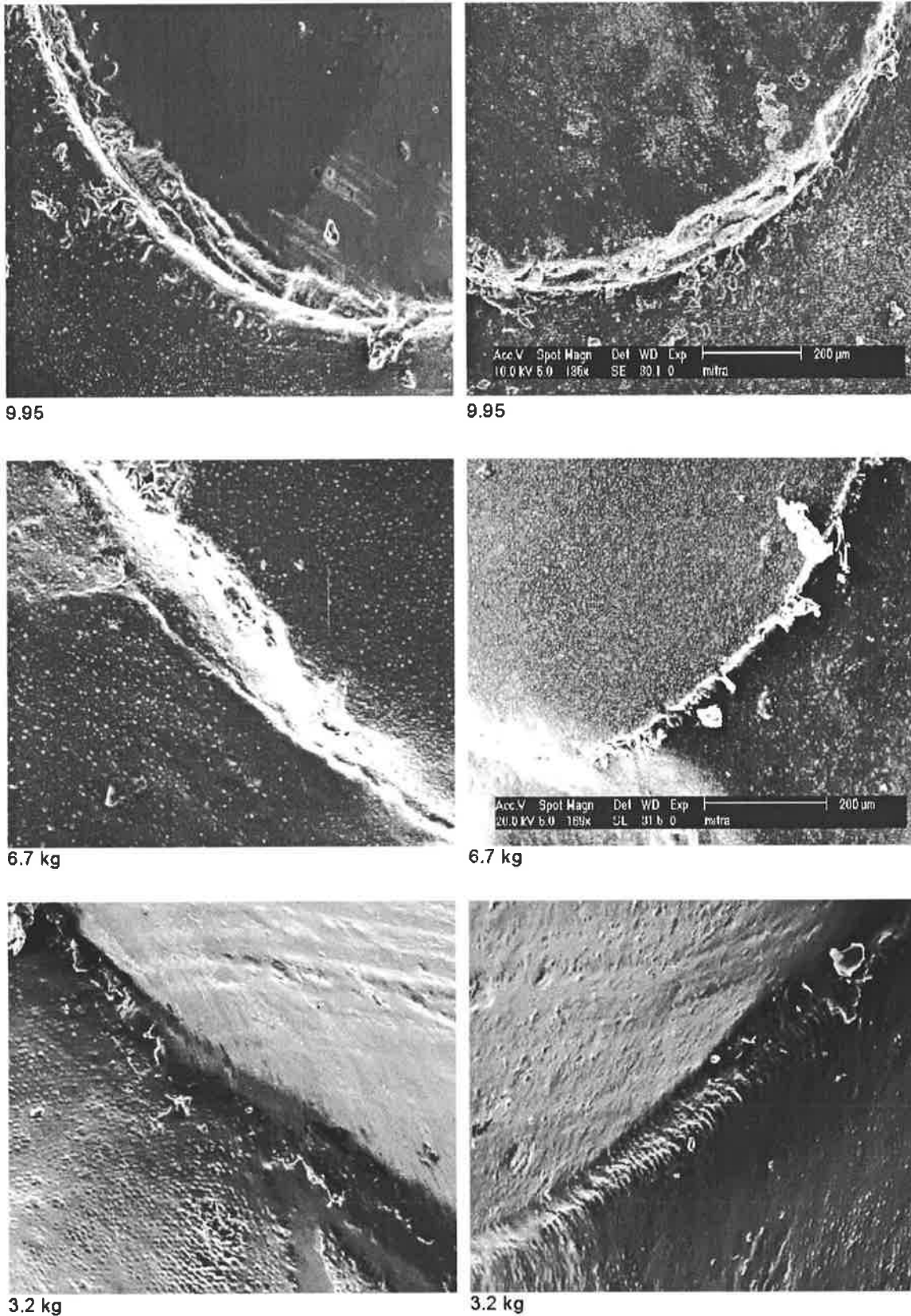


Figure 10.6 SEM results of composite resin at pH=3.3 and under different loads (kg).

Composite Resin Experiments Series C (pH=1.2)

In this series of experiments there was evidence of extensive loss of enamel similar to the changes seen under corresponding conditions for enamel alone. The consistent appearance included extensive enamel erosion with 100-200 μm of restoration left unsupported by enamel.

Composite Resin C3 (pH=1.2, load=9.95 kg)

Under these conditions, in addition to the relatively high rate of chemical destruction and the exposure of composite restoration margins there was also evidence of fracture of the exposed composite margins with damaged enamel-composite junction in the area of first margin contact.

The restoration surfaces showed no significant evidence of breakdown.

Composite Resin C2 (pH=1.2, load=6.7 kg)

Composite Resin C1 (pH=1.2, load=3.2 kg)

Under these conditions the appearance of the enamel in specimens subjected to wear was similar to that seen at the higher load with evidence of chemical erosion predominating. There was less evidence of marginal fracture affecting either the restoration or the enamel at these loads compared with specimens subjected to wear at load of 9.95 kg.

The restoration surfaces were relatively consistent in appearance and generally smooth. While there were some signs of exposed filler particles evident across the restoration, this was much less evident than for specimens subjected to wear at corresponding loads and pH=3.3.

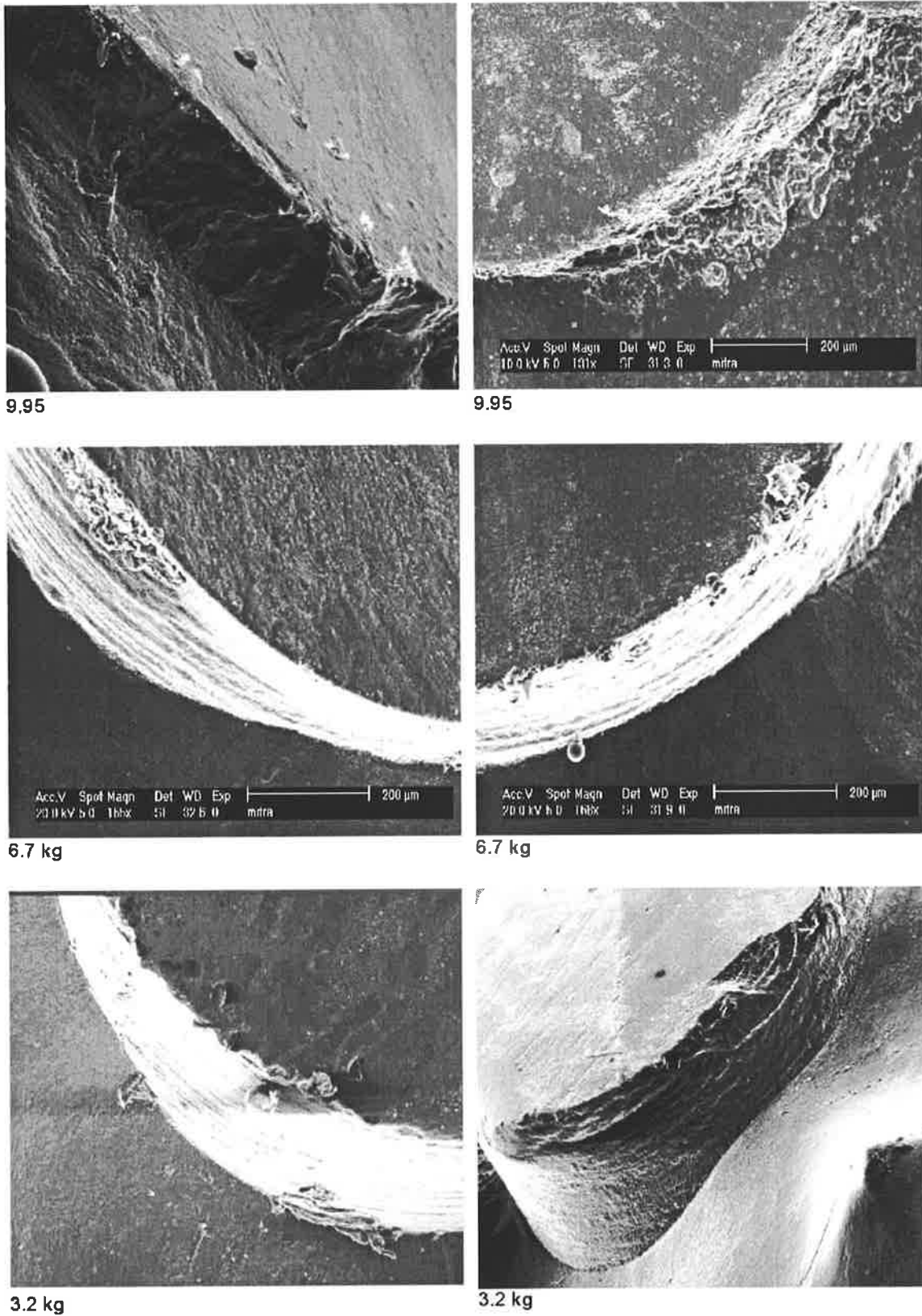


Figure 10.7 SEM results of composite resin at pH=1.2 and under different load (kg).

Non-Contact Experiments

Enamel Experiments Series A0, B0, C0 (pH=7.0, pH=3.3, pH=1.2)

Composite Resin A0 (pH=7.0, load=0.0 kg)

At pH=7.0 there was no loss of composite resin and no changes to the micro-morphology of the surface.

Composite Resin B0 (pH=3.3, load=0.0 kg)

At pH=3.3, because of the higher chemical wear of enamel, composite restoration margins were exposed and unsupported by enamel with a step up of the order of 5-10 μm from the enamel to the restoration surface exposure of composite restoration margins. There was no evidence marginal fracture and enamel-restoration junctions were also intact. Surface of restorations seemed to be smooth with no evidence of breakdown or chemical destruction.

Composite Resin C0 (pH=1.2, load=0.0 kg)

Under this condition, in spite of high chemical erosion of enamel and exposure of restoration margins of the order of 100 μm , there was no evidence of marginal fracture or failure of the enamel-restoration bond.

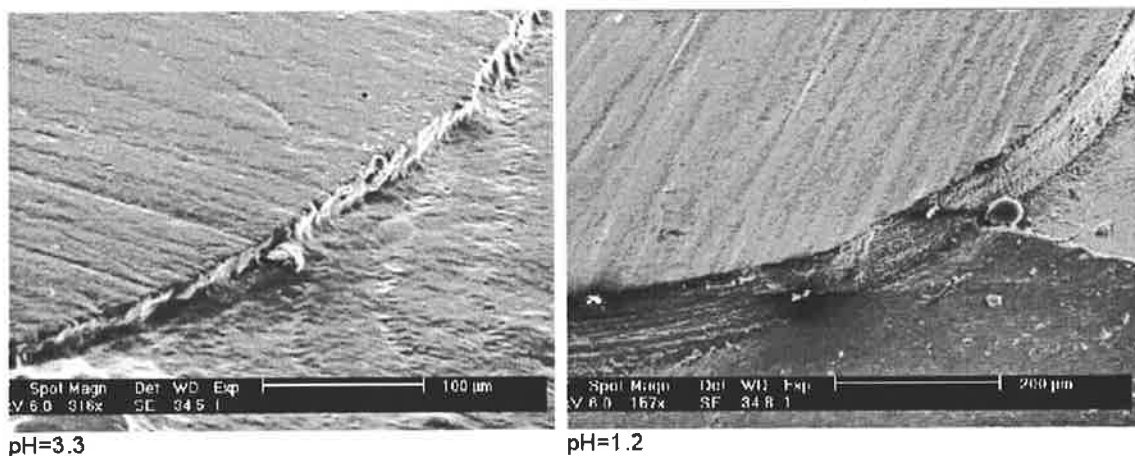


Figure 10.8 SEM results of composite resin at pH's of 3.3 and 1.2 and under no load.

The surface of restorations were relatively consistent in appearance and generally smooth with no sign of chemical destruction.

Conclusion

The qualitative and quantitative results obtained from this part of the study are presented in Figure 10.9 and Table 10.4.

At pH=7.0 mean wear rates of composite resin under high load (9.95 kg) were significantly higher than those under lower loads (6.7, 3.2 kg). At pH=3.3 mean wear rates of composite resin did not differ significantly with load ($p>0.05$) while at low pH (1.2) mean wear rates increased significantly with loads ($p<0.05$). At low pH (1.2) mean wear rates of composite resin were significantly greater than those at higher pH (7.0, 3.3) ($p<0.05$). Mean wear rates of composite resin under no load were significantly lower than those of under loads ($p<0.05$).

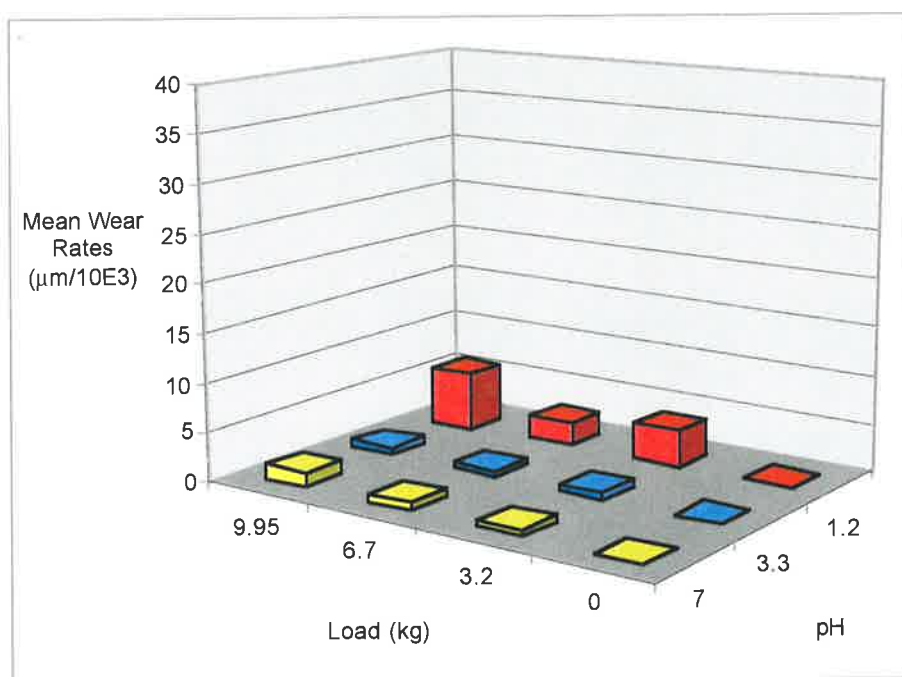


Figure 10.9 Mean wear rates ($\mu\text{m}/10^3$) of composite resin at different pHs and under different loads (kg).

Table 10.4 Summary of qualitative and quantitative results of enamel experiments at different pH and under different loads.

Load (kg)	pH		
	7.0	3.3	1.2
9.95	Low wear rate ($1.5\mu\text{m}/10^3$) smooth surface with evenly distributed irregularities	Lowest wear rate ($0.8\mu\text{m}/10^3$) margins exposed with some evidence of fracture, areas of surface breakdown evident in areas of initial contact, surface generally smooth	High wear rate ($6.0\mu\text{m}/10^3$) margins exposed, restoration surfaces showed no significant evidence of breakdown.
6.7	Lowest wear rate ($0.8\mu\text{m}/10^3$) less surface breakdown with approx. 50 percent appearing smooth	Lowest wear rate ($0.6\mu\text{m}/10^3$) margins exposed, exposed filler particles evident across the restoration	Moderate wear rate ($2.7\mu\text{m}/10^3$) margins exposed, generally smooth, some signs of exposed filler particles
3.2	Lowest wear rate ($0.6\mu\text{m}/10^3$) generally smooth surfaces	Lowest wear rate ($0.7\mu\text{m}/10^3$) margins exposed, relatively smooth surface with little evidence of surface breakdown or exposure of filler particles.	High wear rate ($4.0\mu\text{m}/10^3$) margins exposed, generally smooth, some signs of exposed filler particles
0.0	No material loss, generally smooth surface	No material loss, generally smooth surface	lowest wear rate ($0.2\mu\text{m}/10^3$) relatively smooth surface

CHAPTER 11

Conventional-GIC Wear Results

Introduction

In this Chapter, wear data (quantitative results) and descriptions of SEM images (qualitative results) derived from experiments with conventional-GIC (**Fuji IX**, GC CO, Tokyo, Japan) conducted over the selected ranges of pH and load are presented.

Quantitative Results

Information about the wear rates of conventional-GIC derived from a series of experiments representing each of the conditions described in Chapter 8. Results of these experiments are subdivided into three main groups:

Conventional-GIC Experiments Series A (pH=7.0)

Conventional-GIC Experiments Series B (pH=3.3)

Conventional-GIC Experiments Series C (pH=1.2)

Conventional-GIC Experiments Series A (pH=7.0)

These experiments were conducted with lubrication at pH=7.0 under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and under no load for non-contact-

area experiments. The results for this series of experiments are shown as part of Figure 11.1. They were subdivided into following groups:

Conventional-GIC A3 (pH=7.0, load=9.95 kg)

Mean wear rates of experiments at pH=7.0 and under load of 9.95 kg across the restorations were of the order of $1.78 \mu\text{m}/10^3$ cycles. Although mean wear rates tended to be more rapid in the margin adjacent to the area of first contact than other areas, these differences across the restorations were not statistically significant ($p>0.05$).

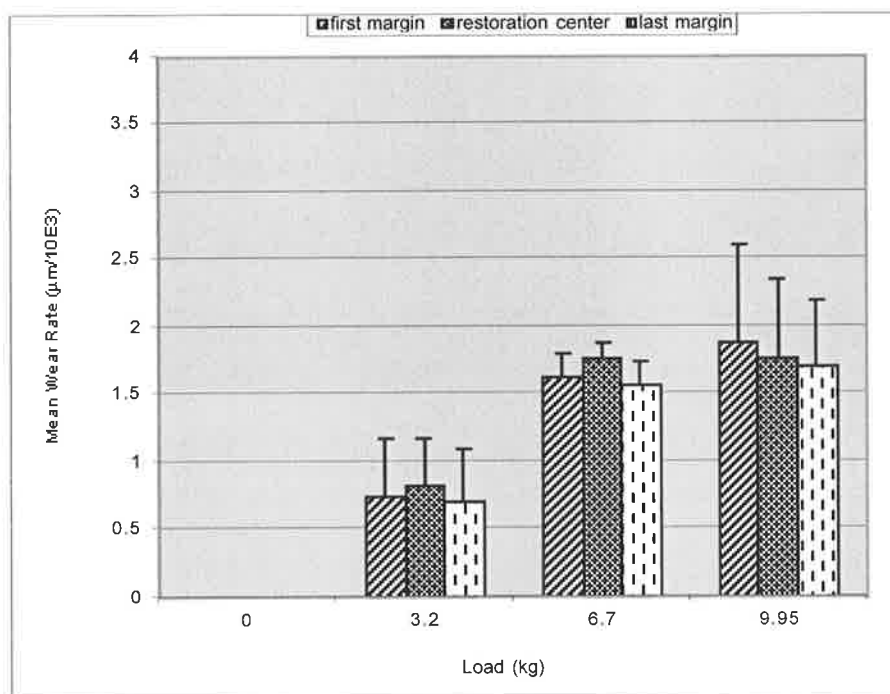


Figure 11.1 Mean wear rates ($\mu\text{m}/10^3$ cycles) of conventional-GIC at pH=7.0 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact.

Conventional-GIC A2 (pH=7.0, load=6.7 kg)

Under these conditions, mean wear rates tended to be more rapid in the area of the restoration center, however these differences were not significant across the restorations ($p>0.05$). Mean wear rates were of the order of $1.64 \mu\text{m}/10^3$ cycles. The wear pattern in

these experiments was different from those experiments under load of 9.95 kg and at the same pH but no significant differences were found ($p>0.05$).

Conventional-GIC A1 (pH=7.0, load=3.2 kg)

At pH=7.0 and under load of 3.2 kg, mean wear rates were of the order of $0.75 \mu\text{m}/10^3$ cycles. Wear rates tended to be more rapid in the area of the restoration center paralleling the pattern seen in load of 6.7 kg but these differences were not significant ($p>0.05$). Although mean wear rates were significantly lower than mean wear rates of those experiments under load of 9.95 kg ($p<0.05$), no significant difference was found between mean wear rates at loads of 6.7 and 3.2 kg ($p>0.05$).

Conventional-GIC A0 (pH=7.0, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) in lubricant at pH=7.0, no conventional-GIC loss was recorded.

Conventional-GIC Experiments Series B (pH=3.3)

These series of experiments were performed with lubricant at pH=3.3 under three different loads (9.95, 6.7, and 3.2 kg) for contact-area experiments and with no load for non-contact-area experiments. The results for experiments at pH=3.3 and under load of 9.95 kg are shown as part of Figure 11.2. They were subdivided into following groups:

Conventional-GIC B3 (pH=3.3, load=9.95 kg)

Under these conditions the mean wear rates across the restoration are of the order of $2.29 \mu\text{m}/10^3$ cycles. Mean wear rates appeared to be greater in the area of the restoration center but the differences across the restorations were not statistically significant ($p>0.05$). Mean wear rates of experiments at pH=3.3 and load of 9.95 kg were significantly higher than wear rate of those experiments at pH=7.0 and under the same load ($p<0.05$).

Conventional-GIC B2 (pH=3.3, load=6.7 kg)

Mean wear rates of experiments at pH=3.3 and load of 6.7 kg were of the order of $1.73 \mu\text{m}/10^3$ cycles. Mean wear rates tended to be greater for the margin adjacent to the area of last contact than other areas but these differences were not statistically significant ($p>0.05$). Wear patterns were different from wear pattern seen at high load (9.95 kg) at the same pH however, no significant differences were found between these two groups of experiments ($p>0.05$). Mean wear rates in experiments at pH=3.3 and load of 6.7 kg tended to be greater than those for experiments at pH=7.0 and at the same load while these differences were not significant ($p>0.05$).

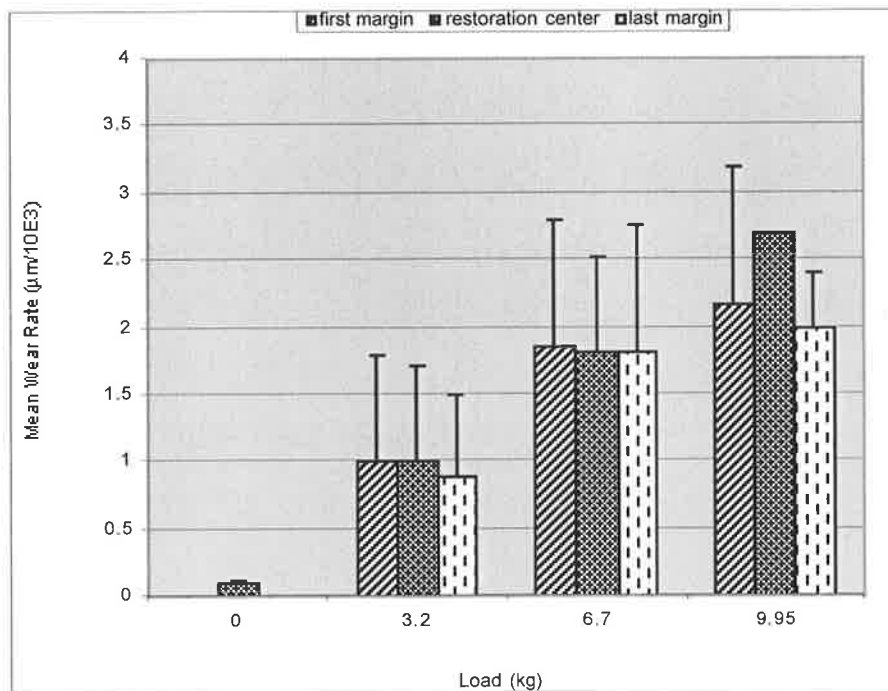


Figure 11.2 Mean wear rates ($\mu\text{m}/10^3$ cycles) of conventional-GIC at pH=3.3 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact.

Conventional-GIC B1 (pH=3.3, load=3.2 kg)

Mean wear rates of the experiments at pH=3.3 and load of 3.2 kg were of the order of $0.96 \mu\text{m}/10^3$ cycles. Mean wear rates of the margins adjacent to the area of first contact and restoration center tended to be greater than in the margin adjacent to the area of last

contact but these differences were not significant ($p>0.05$). Mean wear rates for the experiments conducted under these condition were significantly less than mean wear rate of those under load of 9.95 kg and at the same pH ($p<0.05$). Mean wear rates at pH=3.3 and load of 3.2 kg appeared to be less than mean wear rate at pH=7.0 at the same load however, these difference were not significant ($p>0.05$).

Conventional-GIC B0 (pH=3.3, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) in lubricant at pH=7.0, conventional-GIC loss was of the order of $0.1 \mu\text{m}/10^3$ which are significantly less than of at loads (9.95, 6.7, 3.2 kg) and at the same pH ($p<0.05$).

Conventional-GIC Experiments Series C (pH=1.2)

These series of experiments were performed with lubricant at pH=1.2 under three different loads (9.95, 6.7, and 3.2 kg) for contact-area experiments and under no load for non-contact-area experiments. The results for this series of experiments are summarized as part of Figure 11.3. They were subdivided into the following groups:

Conventional-GIC C3 (pH=1.2, load=9.95 kg)

At pH=1.2 and under load of 9.95 kg, mean wear rates across the restorations were of the order of $24.5 \mu\text{m}/10^3$ cycles. Mean wear rates at the margin adjacent to the area of first contact were significantly greater than those for the margins adjacent to the area of last contact but these differences were not significant ($p<0.05$). the mean wear rates under this condition are significantly greater than mean wear rate of those experiments at higher pH's (7.0, 3.3) and at the same load ($p<0.05$).

Conventional-GIC C2 (pH=1.2, load=6.7 kg)

At pH=1.2 and under load of 6.7 kg, mean wear rates were greater in the margins adjacent to the area of first contact than other areas while these differences were not statistically significant ($p>0.05$). The wear rates across the restorations were of the

order of $23.1 \mu\text{m}/10^3$ cycles which was significantly higher than mean wear rates of those experiments at higher pH's (7.0, 3.3) and at the same load ($p < 0.05$). Mean wear rates across the restorations tended to be lower than mean wear rates of those experiments under load of 9.95 kg but these differences were not significant ($p > 0.05$).

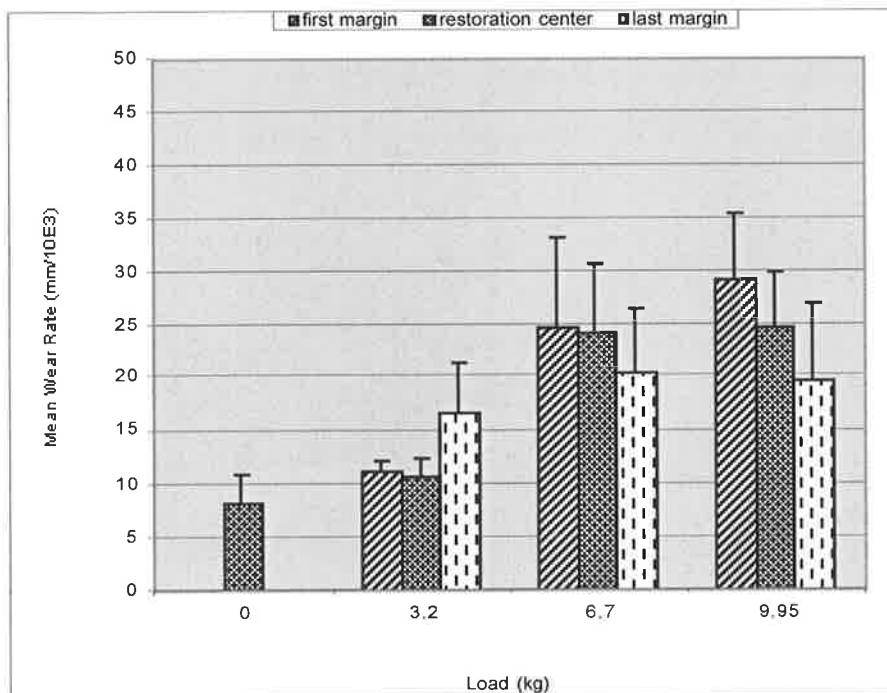


Figure 11.3 Mean wear rates ($\mu\text{m}/10^3$ cycles) of conventional-GIC at pH=1.2 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact.

Conventional-GIC C1 (pH=1.2, load=3.2 kg)

Mean wear rate of experiment at pH=1.2 and under load of 3.2 kg tended to be greater for the margins adjacent to the area of last than other areas but these differences were not statistically significant ($p < 0.05$). Mean wear rates across the restoration were of order of $12.8 \mu\text{m}/10^3$ cycles which was significantly lower than mean wear rates of those experiments at loads of 9.95 and 6.7 kg at the same pH ($p < 0.05$).

Mean wear rates for this group of experiments was significantly higher than mean wear rates of those experiments at higher pH's (7.0, 3.3) at the same load ($p < 0.05$).

Conventional-GIC C0 (pH=1.2, load=0.0 kg)

After 2 hours (corresponding to the duration of the 10,000 cycles of wear in the contact-area experiments) in lubricant at pH=1.2, conventional-GIC loss was of the order of $8.12 \mu\text{m}/10^3$. Mean wear rates for this group of experiments were significantly higher than those under loads (9.95, 6.7, 3.2 kg) and at the same pH ($p < 0.05$).

Overview of Quantitative Results

Table 11.1. summarize the mean wear rates of conventional-GIC at three different pH's and under four different loads for three defined points.

Table 11.1. Quantitative results of conventional-GIC wear under experimental conditions including pH, load (kg), site, number of specimens (n), mean wear rate ($\mu\text{m}/10^3$) and standard deviation (SD) ($\mu\text{m}/10^3$).

Experiments	pH	Load	Site	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)
C-GIC A3	7.0	9.95	First	6	1.89	0.71
			Center	6	1.76	0.59
			Last	6	1.69	0.5
C-GIC A2	7.0	6.7	First	5	1.61	0.18
			Center	5	1.76	0.11
			Last	5	1.57	0.16
C-GIC A1	7.0	3.2	First	7	0.75	0.5
			Center	7	0.82	0.53
			Last	7	0.70	0.48
C-GIC A0	7.0	0	Center	10	0.00	0.0
C-GIC B3	3.3	9.95	First	5	2.18	1.03
			Center	5	2.7	0.6
			Last	5	2	0.4
C-GIC B2	3.3	6.7	First	5	1.7	1.1
			Center	5	1.7	0.9
			Last	5	1.8 ³	1.2
C-GIC B1	3.3	3.2	First	5	1	0.8
			Center	5	1	0.7
			Last	5	0.9	0.6
C-GIC B0	3.3	0	Center	10	0.1	0.01
C-GIC C3	1.2	9.95	First	7	29.3	6.1
			Center	7	24.6	5.3
			Last	7	19.8	7.0
C-GIC C2	1.2	6.7	First	6	24.8	8.5
			Center	6	24.3	6.4
			Last	6	20.4	6.1
C-GIC C1	1.2	3.2	First	5	11.2	1.0
			Center	5	10.8	1.7
			Last	5	16.6	4.8
C-GIC C0	1.2	0	Center	10	8.22	2.47

ANOVA analysis

An analysis of variance was undertaken to assess the statistical significant of the observed differences in wear rates between experimental groups under various conditions. Initially, differences between wear rates in the contact-area experimental groups under various conditions for the three analyzed sites (margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact) across each facet were assessed. The results are included in Table 11.2.

Table 11.2 Two-way ANOVA analysis of wear rate of conventional-GIC for contact-area experiments by pH, load, type of material, and contact site including degrees of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	11070.648	5535.324	423.038	1.0E ⁻⁴
Load (B)	2	602.325	301.162	23.016	1.0E ⁻⁴
AB	4	671.69	167.922	12.833	1.0E ⁻⁴
Site (C)	2	19.202	9.601	0.734	0.4822
AC	4	35.789	8.947	0.684	0.6045
BC	4	133.532	33.383	2.551	0.0426
ABC	8	249.186	31.148	2.381	0.0204
Error	120	1570.165	13.085		

The pH, load, and combination of load and pH had a significant effect on mean wear rate of conventional-glass ionomer while conventional-GIC wear rate did not differ with site.

As ANOVA results showed no significant effect of site on wear rate of conventional-glass ionomer wear rate (ie between the margin adjacent to the area of first contact, the restoration center, and the margin adjacent to the area of last contact) in either of these analyses, site was not included in the subsequent ANOVA.

Table 11.3 Two-way ANOVA analysis of wear rate of conventional-GIC for both contact-area and non-contact-area experiments by pH, and load including degrees of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	2972.545	1486.273	193.295	1.0E ⁻⁴
Load (B)	3	318.592	106.197	13.811	1.0E ⁻⁴
AB	6	626.644	104.441	13.583	1.0E ⁻⁴
Error	60	461.35	7.689		

Two-way ANOVA analysis (Table 11.3) for both contact-area and non-contact-area experiments suggests the significant effect of pH, load, and combination of pH and load on wear rate of conventional-GIC.

Qualitative Results

SEM analysis of surface characteristics of conventional-GIC restorations experimental groups under different conditions are shown as:

Conventional-Glass Ionomer Experiments Series A (pH=7.0)

Conventional-GIC A3 (pH=7.0, load=9.95 kg) and

Conventional-GIC A2 (pH=7.0, load=6.7 kg)

Under these conditions although there was evidence of the same type of enamel breakdown evident in the experiments involving enamel alone, particularly in the area of final contact, there was no evidence of major breakdown of restoration margins. Enamel-restoration junctions were still intact. The surfaces of the restorations were relatively rough with some evidence of porosity.

Conventional-GIC A1 (pH=7.0, load=3.2 kg)

At pH=7.0 and under load of 3.2 kg, enamel adjacent to the area of first margin contact was generally smooth but with evidence of 10-30 μm wide wear striations parallel to the direction of wear. There was less evidence of enamel wear at this load than at higher loads. There was no evidence of margin breakdown in the area of first contact while there were signs of breakdown in the margins adjacent to the area of last contact. The surface of restorations were relatively smoother and with less evidence of breakdown under these conditions than under higher loads with up to 50 percent of the restoration appearing smooth and small surface irregularities (5-10 μm) localized in other areas.

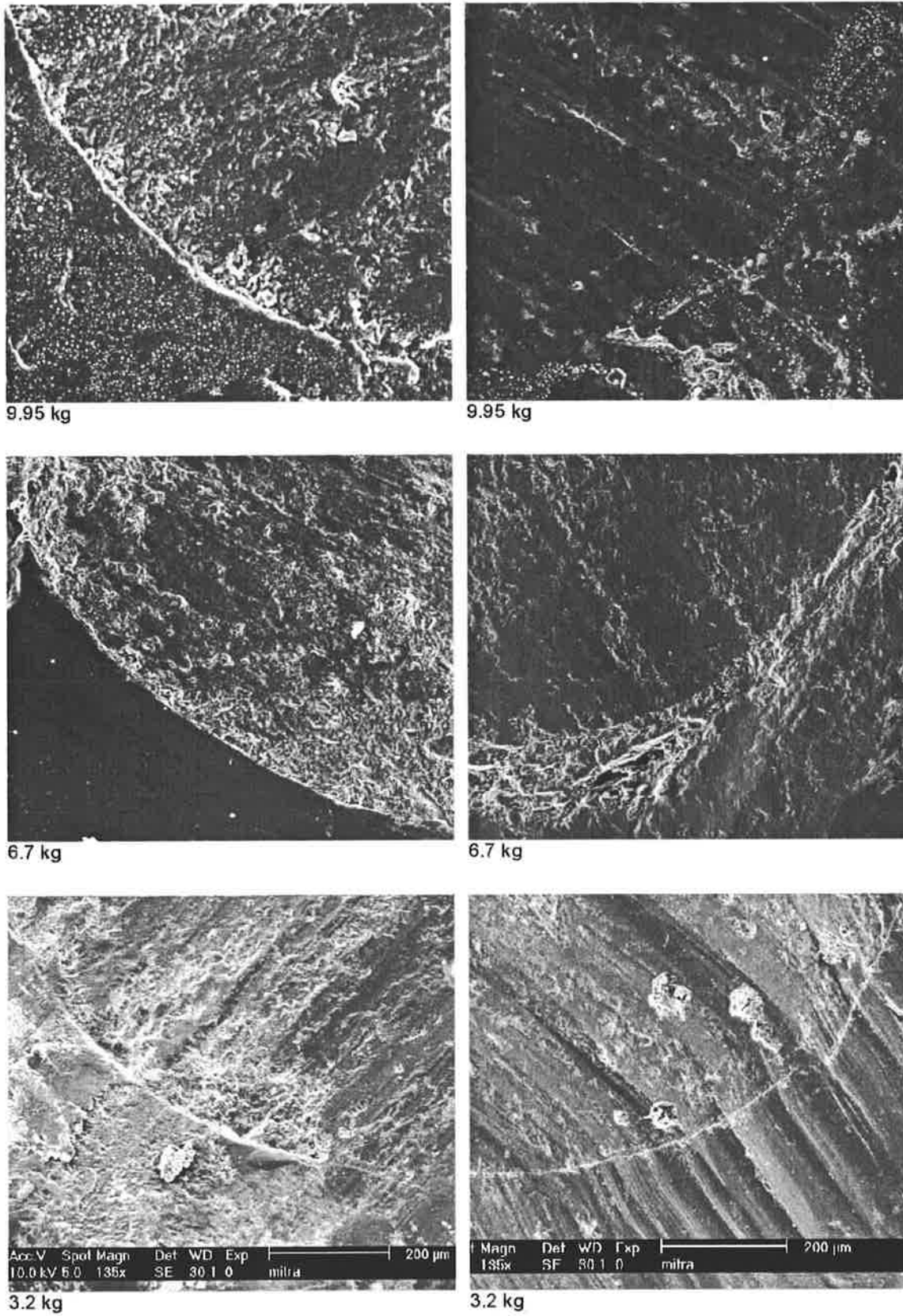


Figure 11.4 SEM results of conventional-GIC at pH=7.0 and under different loads (kg).

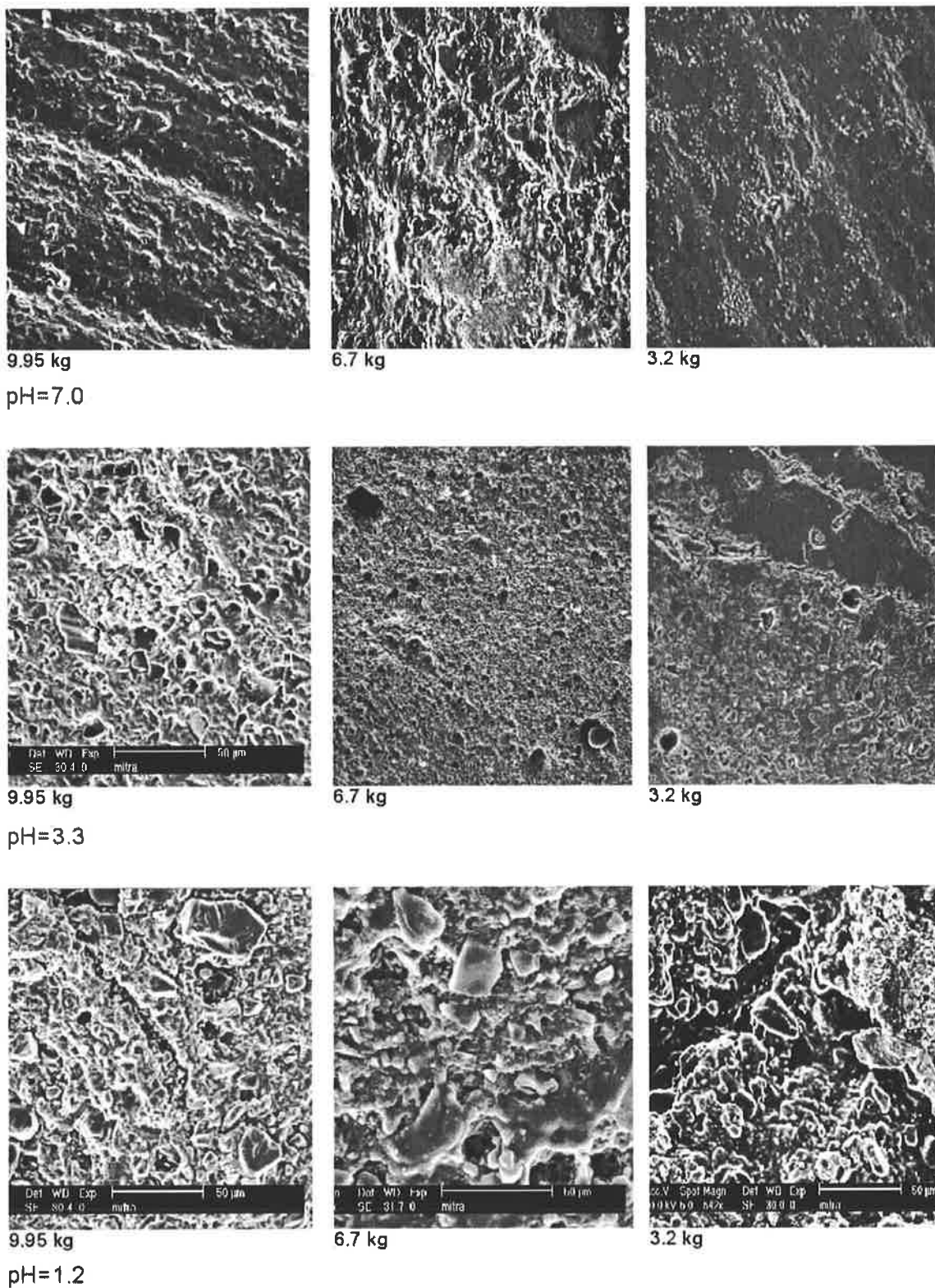


Figure 11.5 SEM results of conventional-GIC at different pH's and under different loads (kg) with high magnification.

Conventional-GIC Experiments Series B (pH=3.3)

Conventional-GIC B3 (pH=3.3, load=9.95 kg)

At pH=3.3 and under load of 9.95 kg, there was clear evidence of extensive chemical destruction of the enamel similar to that seen in experiments with enamel alone. Although there were areas of marginal breakdown, enamel-restoration junctions were still intact.

The surfaces of the restorations were generally rough with very significant chemical destruction with surface defects of the order of 300 μm in diameter.

Conventional-GIC B2 (pH=3.3, load=6.7 kg)

Under these conditions, there were similar chemical effects to that seen for the experiments involving enamel alone. There was no evidence of marginal fracture in spite of the chemical destruction of restorations and adjunct enamel.

Surface of restorations appeared rough and sponge-like with evidence of porosities of 10-20 μm in diameter.

Conventional-GIC B1 (pH=3.3, load=3.2 kg)

Conventional-glass ionomer restorations under load of 3.2 kg showed less surface destruction than was evident in experiments at higher loads (9.95, 6.7 kg). There was no evidence of marginal fracture of the restorations even when enamel breakdown in area of last contact had occurred.

The surfaces of restorations were less rough than in corresponding experiments at higher load but still showed some porosity.

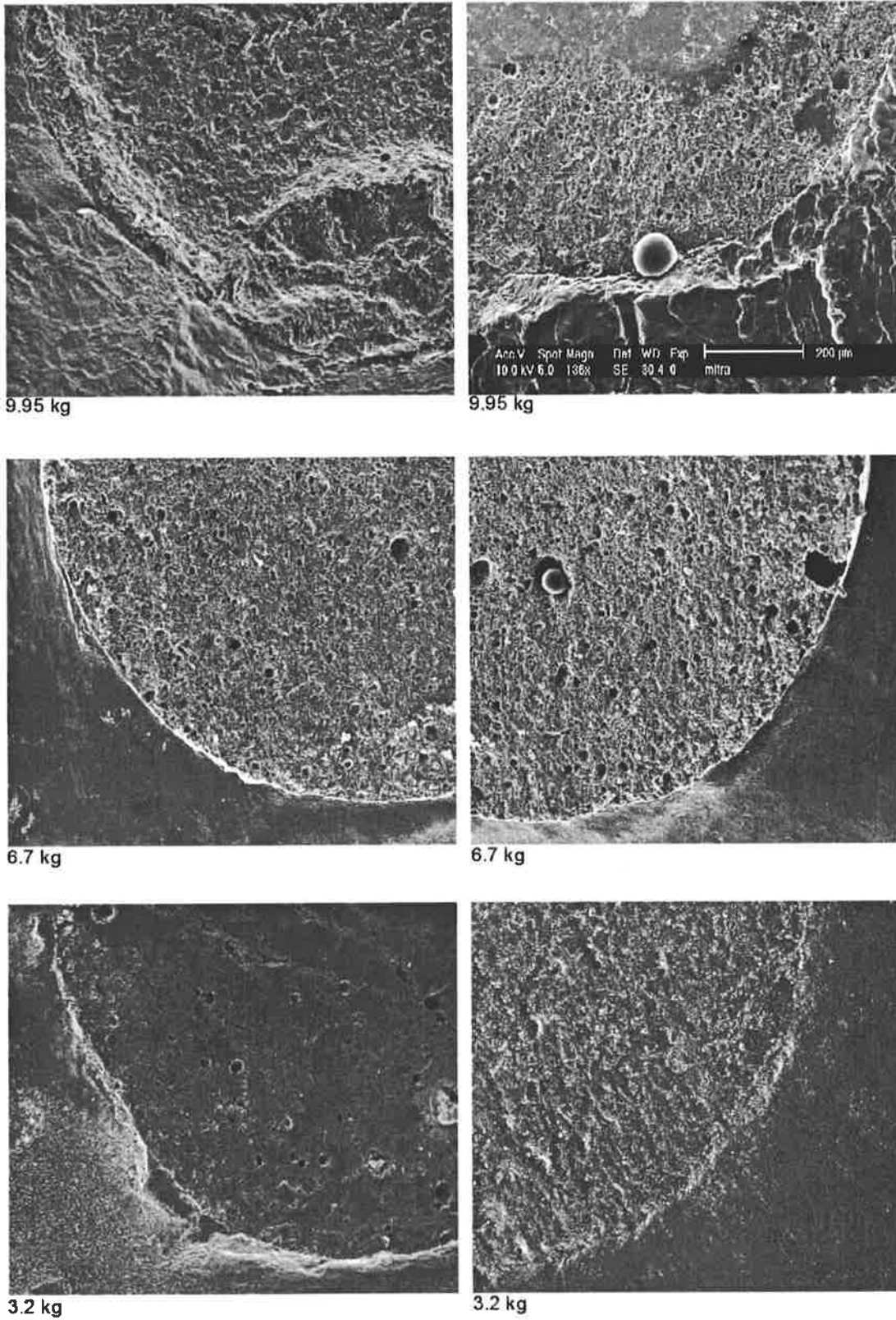


Figure 11.6 SEM results of conventional-GIC at pH=3.3 and under different loads (kg).

Conventional-Glass Ionomer Experiments Series C (pH=1.2)

Conventional-GIC C3 (pH=1.2, load=9.95 kg)

Conventional-GIC C2 (pH=1.2, load=6.7 kg)

Conventional-GIC C1 (pH=1.2, load=3.2 kg)

In this series of experiments there was evidence of extensive loss of enamel corresponding to the changes seen under corresponding conditions or enamel alone. All of restorations showed very significant chemical destruction and associated surface roughness.

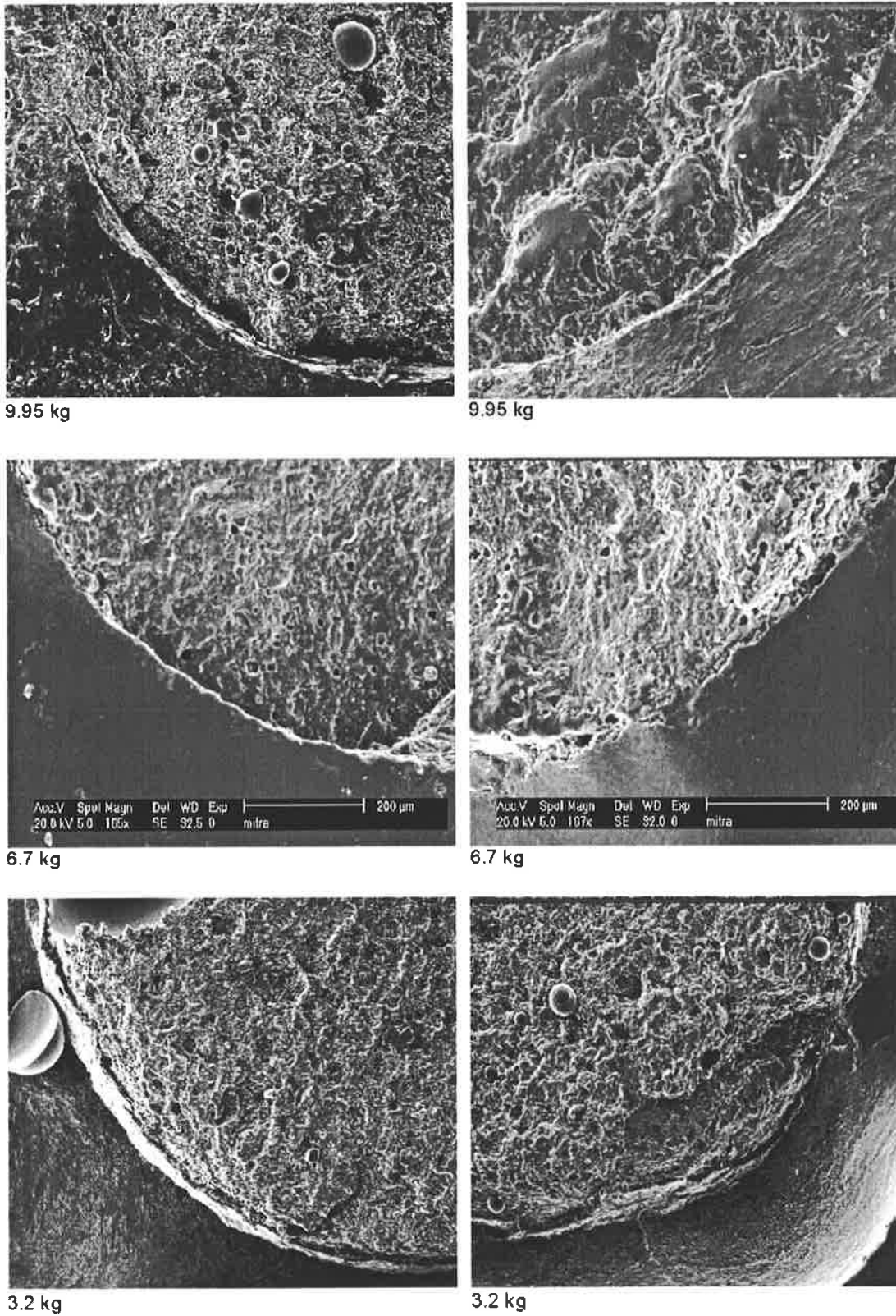


Figure 11.7 SEM results of conventional-GIC at pH=1.2 and under different loads (kg).

Non-Contact-Area Experiments

Conventional-Glass Ionomer Experiments Series A0, B0, C0 (pH=7.0, pH=3.3, pH=1.2)

Conventional-GIC A0 (pH=7.0, load=0.0 kg)

No surface changes were evident following exposure of GIC restorations to lubricant at pH=7.0.

Conventional-GIC B0 (pH=3.3, load=0.0 kg)

Under this condition, although there was evidence of corrosion of both enamel and restorations, there was no sign of marginal fracture. Enamel-restoration junctions seemed to be intact.

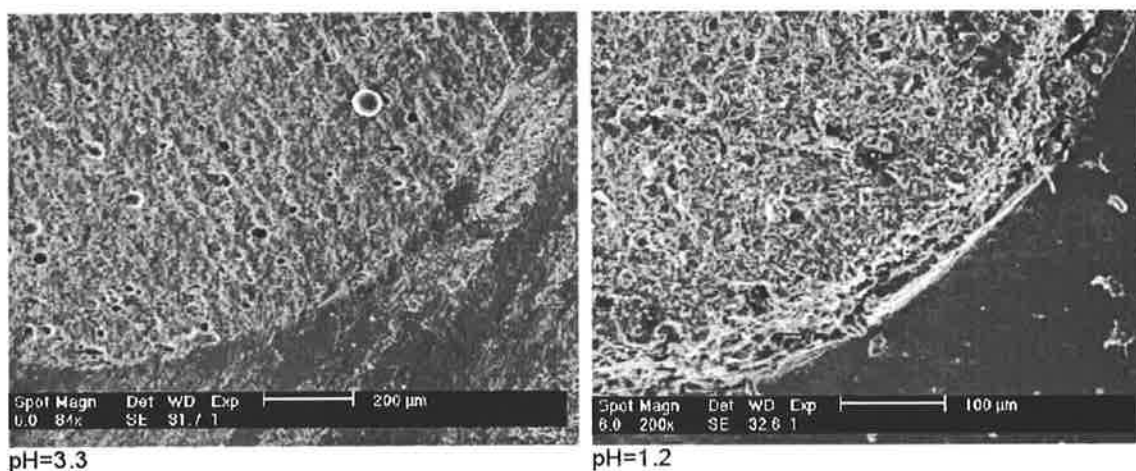


Figure 11.8 SEM results of conventional-GIC for non-contact-area experiments.

Conventional-GIC C0 (pH=1.2, load=0.0 kg)

At pH=1.2, there was massive chemical destruction of both enamel and restorations. Surfaces of restorations generally appeared rough.

Conclusion

The qualitative and quantitative data obtained in this part of the study are shown in Figure 11.9. and Table 11.4.

At pH=7.0, mean wear rates under loads of 9.95 and 6.7 kg were significantly higher than those of under load of 3.2 kg ($p<0.05$).

At pH=3.3, mean wear rates under load of 9.95 kg were significantly higher than those of under load of 3.2 kg ($p<0.05$). At this pH, mean wear rates of those under no load were significantly lower than those of under different loads ($p<0.05$).

Mean wear rates at pH=1.2 were significantly higher than at pH's 7.0 and 3.3 ($p<0.05$).

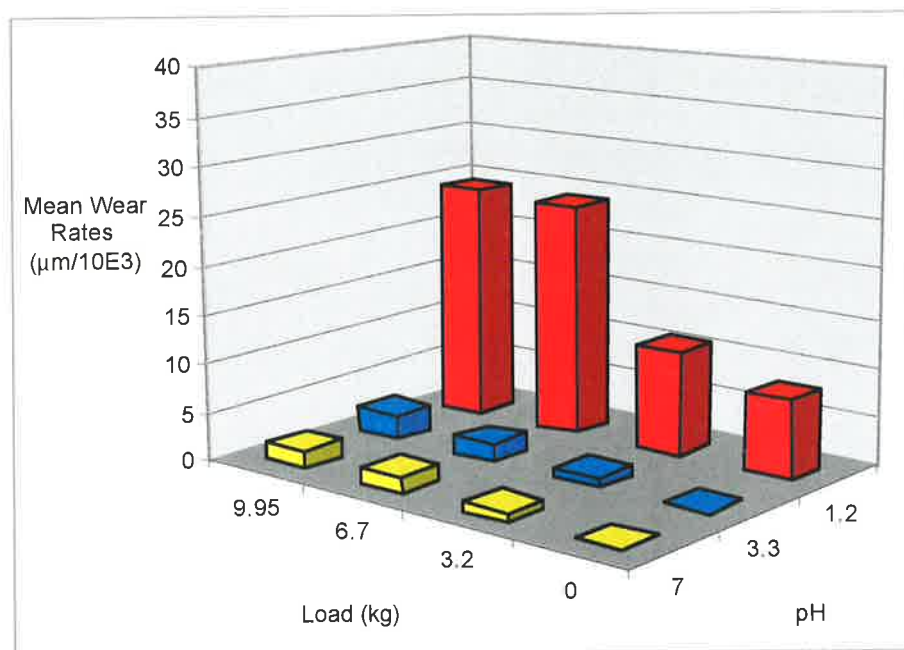


Figure 11.9 Mean wear rates ($\mu\text{m}/10^3$) of conventional-GIC at different pH's and under different loads (kg).

Table 11.4 Summary of quantitative and qualitative results of conventional-GIC at different pH's and under different loads.

Load (kg)	pH		
	7.0	3.3	1.2
9.95	Low wear rate (1.76µm/10 ³ cycles) Intact enamel-restoration bond, relatively rough surface with evenly some evidence of porosity.	Low wear rate (2.7µm/10 ³ cycles) intact enamel-restoration bond, generally rough surfaces with very significant chemical destruction with surface defects of the order of 300 µm in diameter.	Extreme wear rate (24.6 µm/10 ³ cycles) very significant chemical destruction and associated surface roughness.
6.7	Lowest wear rate (1.76µm/10 ³ cycles) Intact enamel-restoration bond, relatively rough surface with evenly some evidence of porosity.	Low wear rate (1.7µm/10 ³ cycles) chemical destruction, rough and sponge-like surface appearance with evidence of porosities of 10-20 µm in diameter	Extreme wear rate (24.3µm/10 ³ cycles) very significant chemical destruction and associated surface roughness.
3.2	Lowest wear rate (0.82µm/10 ³ cycles) ,relatively smoother surface with less evidence of breakdown irregularities (5-10 µm) localized in other areas.	Low wear rate (1.0µm/10 ³ cycles) relatively less surface destruction than evident in experiments at higher loads (9.95, 6.7 kg)	Extreme wear rate (10.8µm/10 ³ cycles) very significant chemical destruction and associated surface roughness.
0.0	No material loss No surfaces changes	Lowest wear rate (0.1 µm/10 ³) evidence of chemical wear	High wear rate (8µm/10 ³) massive chemical destruction, generally rough surfaces

CHAPTER 12

Resin Modified-GIC Wear

Introduction

In this Chapter, wear data (quantitative results) and descriptions of SEM images (qualitative results) derived from contact-area and non-contact-area experiments with resin modified-GIC (**Fuji II LC**, GC CO, Tokyo, Japan) conducted over the selected ranges of pH and load is presented.

Quantitative Results

Information about the wear rate was derived from a series of experiments representing each of the conditions described in Chapter 8. Results of these experiments are subdivided into three main groups:

Resin Modified-GIC Experiments Series A (pH=7.0)

Resin Modified-GIC Experiments Series B (pH=3.3)

Resin Modified-GIC Experiments Series C (pH=1.2)

Resin Modified-GIC Experiments Series A (pH=7.0)

These experiments were conducted with lubrication at pH=7.0 under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and under no load for non-contact-

area experiments. The results for this series of experiments are shown as part of Figure 12.1. They were subdivided into following groups:

Resin Modified-GIC A3 (pH=7.0, load=9.95 kg)

At pH=7.0 and under load of 9.95 kg, mean wear rates across the restorations were of the order of $1.71 \mu\text{m}/10^3$ cycles. Mean wear rates tended to be more rapid in the margin adjacent to the area of first contact than other areas but these differences across the restorations were not statistically significant ($p>0.05$).

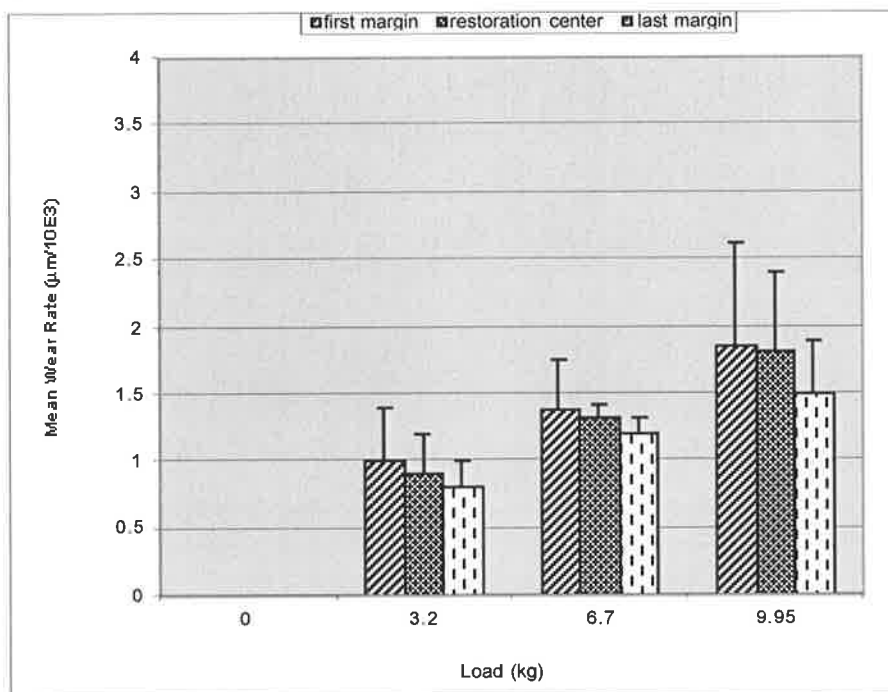


Figure 12.1 Mean wear rates ($\mu\text{m}/10^3$ cycles) of resin modified-GIC at pH=7.0 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and the margin adjacent adjacent to the area of last contact.

Resin Modified-GIC A2 (pH=7.0, load=6.7 kg)

Mean wear rates of the experiments conducted at pH=7.0 and under load of 6.7 kg tended to be more rapid in the margin adjacent to the area of first contact paralleling wear pattern seen in load of 9.95 kg but these differences were not significant ($p>0.05$). Mean wear rates across the restorations were of the order of $1.2 \mu\text{m}/10^3$ cycles.

Resin Modified-GIC A1 (pH=7.0, load=3.2 kg)

Under these conditions, mean wear rates were of the order of $0.9 \mu\text{m}/10^3$ cycles. Again wear rates tended to be more rapid in the margins adjacent to the area of first contact area paralleling the pattern seen in loads of 9.95 and 6.7 kg. Mean wear rates were significantly lower than those under load of 9.95 kg ($p < 0.05$).

Resin Modified-GIC A0 (pH=7.0, load=0.0 kg)

After 16 hours (corresponding to the duration of the 80,000 cycles of wear in the contact-area experiments) in lubricant at pH=7.0, no material loss was recorded.

Resin Modified-GIC Experiments Series B (pH=3.3)

These series of experiments were performed with lubricant at pH=3.3 under three different loads (9.95, 6.7, and 3.2 kg) for contact-area experiments and with no load for non-contact-area experiments. The results for this group of experiments are shown as part of Figure 12.2. They were subdivided into following groups:

Resin Modified-GIC B3 (pH=3.3, load=9.95 kg)

At pH=3.3 and under load of 9.95 kg, mean wear rate across the restoration were of the order of $2.29 \mu\text{m}/10^3$ cycles. While wear appeared to be more rapid in the margins adjacent to the area of first contact, these differences across the restorations were not statistically significant ($p > 0.05$).

Mean wear rates of experiments under these conditions were significantly higher than those at pH=7.0 and at the same load ($p < 0.05$).

Resin Modified-GIC B2 (pH=3.3, load=6.7 kg)

Mean wear rates of experiments at pH=3.3 and under load of 6.7 kg were of the order of $1.6 \mu\text{m}/10^3$ cycles. Mean wear rates at the restoration center tended to be more rapid than in other areas but these differences were not significant ($p > 0.05$). The wear pattern

was different from that seen at load of 9.95 kg and the same pH however, no significant differences were found between these two groups of experiments ($p>0.05$).

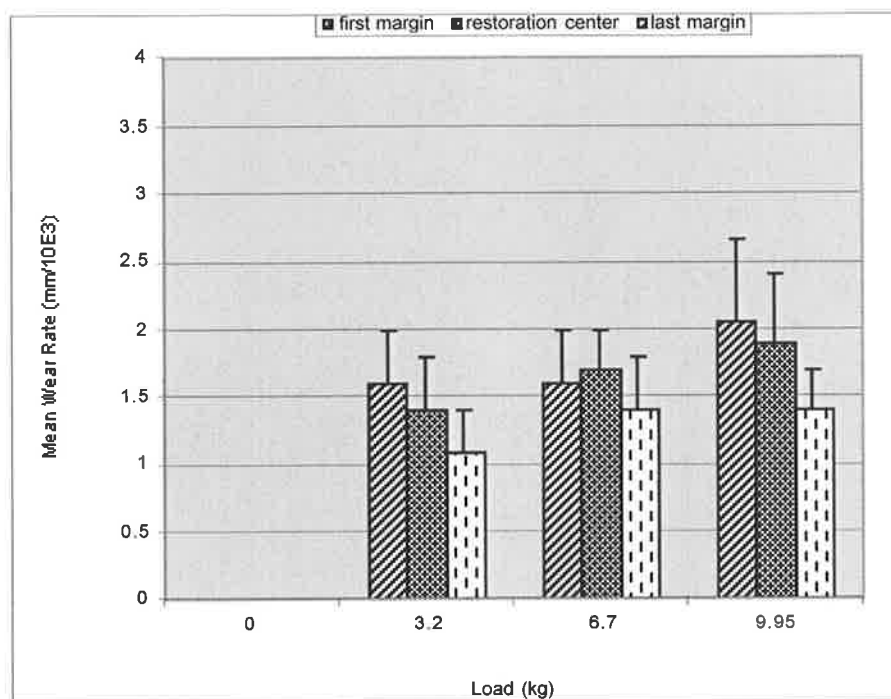


Figure 12.2 Mean wear rates ($\mu\text{m}/10^3$ cycles) of resin modified-GIC at pH=3.3 and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and the margin adjacent adjacent to the area of last contact.

Resin Modified-GIC B1 (pH=3.3, load=3.2 kg)

At pH=3.3 and load of 3.2 kg, mean wear rates of the experiments were of the order of $1.36 \mu\text{m}/10^3$ cycles. Mean wear rates of the margins adjacent to the areas of first contact tended to be more rapid than other areas paralleling seen in experiments under load of 9.95 kg however, these differences were not significant ($p>0.05$). The mean wear rate for the experiments conducted under this condition tended to be lower than those experiments under loads of 9.95 and 6.7 kg but again the differences were not significant ($p>0.05$).

Resin Modified-GIC B0 (pH=3.3, load=0.0 kg)

At pH=3.3 and after 16 hours (corresponding to the duration of the 80, 000 cycles of wear in the contact-area experiments), no material loss was recorded.

Resin Modified-GIC Experiments Series C (pH=1.2)

These series of experiments were performed at pH=1.2, under three different loads (9.95, 6.7, 3.2 kg) for contact-area experiments and with no load for non-contact-area experiments. The results for this series of experiments are shown as part of Figure 12.3. They were subdivided into three following group:

Resin Modified-GIC C3 (pH=1.2, load=9.95 kg)

Under these conditions, mean wear rates across the restorations were of the order of $13.1 \mu\text{m}/10^3$ cycles. Mean wear rate of the margins adjacent to the area of first contact tended to be more rapid than the margins adjacent to the area of last contact but these differences were not significant ($p < 0.05$).

Mean wear rates of these experiments were significantly higher than those at higher pH's (7.0, 3.3) and the same load ($p < 0.05$).

Resin Modified-GIC C2 (pH=1.2, load=6.7 kg)

At pH=1.2 and under load of 6.7 kg, mean wear rates tended to be more rapid in the margin adjacent to the area of first contact than the margin adjacent to the area of last contact paralleling seen under load of 9.95 kg and the same pH ($p > 0.05$).

The wear rates across the restorations were of the order of $10.6 \mu\text{m}/10^3$ cycles which was significantly higher than those at higher pH's (7.0, 3.3) and the same load ($p < 0.05$).

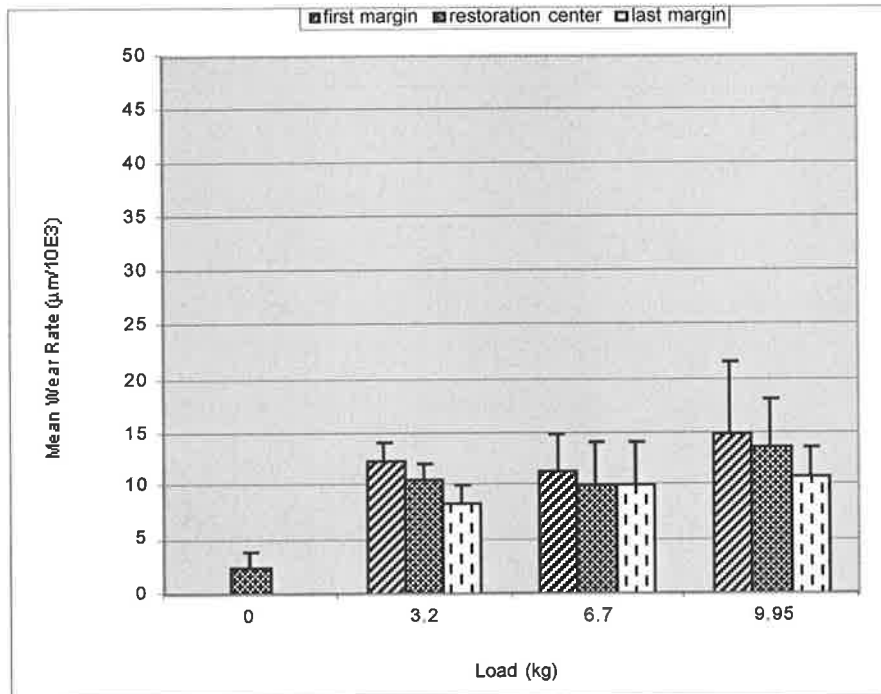


Figure 12.3 Mean wear rates ($\mu\text{m}/10^3$ cycles) of resin modified-GIC at $\text{pH}=1.2$ and under different loads (kg) measured for the margin adjacent to the area of first contact, area of restoration center, and the margin adjacent adjacent to the area of last contact

Resin Modified-GIC C1 (pH=1.2, load=3.2 kg)

Mean wear rates of experiments at $\text{pH}=1.2$ and under load of 3.2 kg tended to greater for the margins adjacent to the area of last contact than other areas ($p<0.05$). Mean wear rates across the restorations were of the order of $10.4 \mu\text{m}/10^3$ cycles. Mean wear rates for these experiments were significantly higher than mean wear rates of those at higher pH's (7.0, 3.3) and at the same load ($p<0.05$).

Resin-modified-GIC C0 (pH=1.2, load=0.0 kg)

Mean wear rates from this group of experiments were significantly lower than those of under load and same pH ($p<0.05$). After 2 hours storage in lubricant with $\text{pH}=1.2$, mean loss corresponded to a wear rates of the order of $2.41 \mu\text{m}/10^3$.

Overview of Quantitative Results

Table 12.1 briefly shows the mean wear rates of resin modified-GIC with their standard deviations at three different pH's and under four different loads for three defined points.

Table 12.1 Quantitative wear results of resin modified-GIC (RM-GIC) under experimental conditions including pH, load (kg), site, number of specimens (n), mean wear rate ($\mu\text{m}/10^3$) and standard deviation (SD) ($\mu\text{m}/10^3$).

Experiments	pH	Load (kg)	Site	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)
RM-GIC A3	7.0	9.95	First	6	1.84	0.77
			Center	6	1.8	0.6
			Last	6	1.5	0.4
RM-GIC A2	7.0	6.7	First	5	1.5	0.4
			Center	5	1.3	0.4
			Last	5	1.21	0.2
RM-GIC A1	7.0	3.2	First	5	1	0.4
			Center	5	0.9	0.3
			Last	5	0.8	0.2
RM-GIC A0	7.0	0	Center	10	0.0	0.0
RM-GIC B3	3.3	9.95	First	5	2.06	0.6
			Center	5	1.9	0.5
			Last	5	1.4	0.3
RM-GIC B2	3.3	6.7	First	5	1.6	0.4
			Center	5	1.8	0.4
			Last	5	1.4	0.4
RM-GIC B1	3.3	3.2	First	5	1.6	0.4
			Center	5	1.4	0.4
			Last	5	1.1	0.3
RM-GIC B0	3.3	0	Center	8	0.0	0.0
RM-GIC C3	1.2	9.95	First	7	15	6.47
			Center	7	13.6	4.7
			Last	7	10.9	2.7
RM-GIC C2	1.2	6.7	First	5	11.3	3.7
			Center	5	10.3	3.8
			Last	5	10.2	3.8
RM-GIC C1	1.2	3.2	First	5	12.3	1.8
			Center	5	10.8	1.3
			Last	5	8.31	1.8
RM-GIC C0	1.2	0	Center	10	2.41	1.59

ANOVA analysis

An analysis of variance was undertaken to assess the statistical significant of the observed differences in wear rates between experimental groups under various

conditions. Initially, differences between wear rates in the contact-area experimental groups under various conditions for the three analyzed sites (margin adjacent to the area of first contact, area of restoration center, and margin adjacent to the area of last contact) across each facet were assessed. The results are included in Table 12.2.

Table 12.2 Two-way ANOVA analysis of wear rate of resin modified-GIC for contact-area experiments by pH, load, type of material, and contact site including degrees of freedom (df), sum of squares, mean of squares, F-test, and P value.

Source	df	Sum of Squares	Mean Square	F-test	P value
pH (A)	2	32.18.21	1609.105	289.945	1.0E ⁻⁴
Load (B)	2	47.444	23.722	4.275	0.01
AB	4	56.865	9.216	1.661	0.163
Site (C)	2	38.003	19.002	3.424	0.03
AC	4	4.0635	10.159	1.831	0.1276
BC	4	7.494	1.873	0.338	0.8522
ABC	8	10.237	1.28	0.231	0.9846
Error	117	649.313	5.5		

According to ANOVA results, pH, load, and site had significant effect on wear rate of resin modified-GIC.

Qualitative Results

Results obtained from SEM of resin modified-GIC experimental groups are shown to illustrate surface characteristics of restorations objected to wear under different conditions. These results are shown as:

Resin Modified-Glass Ionomer Experiments Series A (pH=7.0)

Resin Modified-GIC A3 (pH=7.0, load=9.95 kg) and

Resin Modified-GIC A2 (pH=7.0, load=6.7 kg)

Under these conditions, there was evidence of the same type of enamel breakdown evident in the experiments involving enamel alone. Margins of restorations appeared consistent with no sign of fracture. The enamel-restoration bond appeared intact even though the adjacent enamel showed extensive breakdown especially at the margin adjacent to the area of first contact.

There was also evidence of breakdown on the surface of restorations causing a rough appearance not unlike that seen in the experiments involving the composite resin restorations.

Resin Modified-GIC A1 (pH=7.0, load=3.2 kg)

At pH=7.0 and under load of 3.2 kg, there was less evident of enamel breakdown. Margins of restorations were intact with the same evidence of more enamel breakdown at the margin adjacent to the area of first contact as seen at higher loads.

The surface of restorations and adjacent enamel were generally less rough than for specimens in experiments under higher loads (9.95, 6.7 kg).

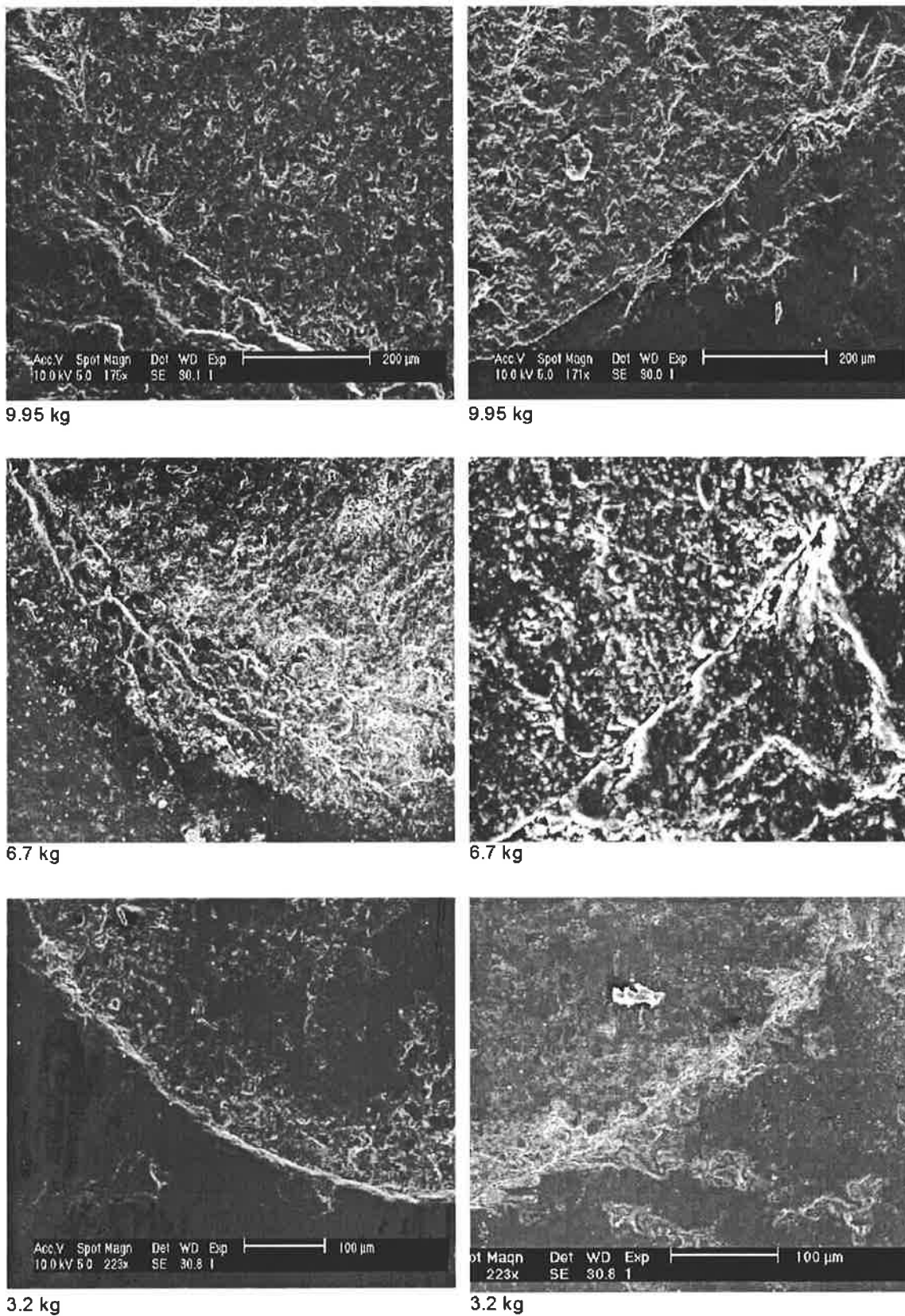


Figure 12.4 SEM results of resin modified-GIC at pH=7.0 and under different loads (kg).

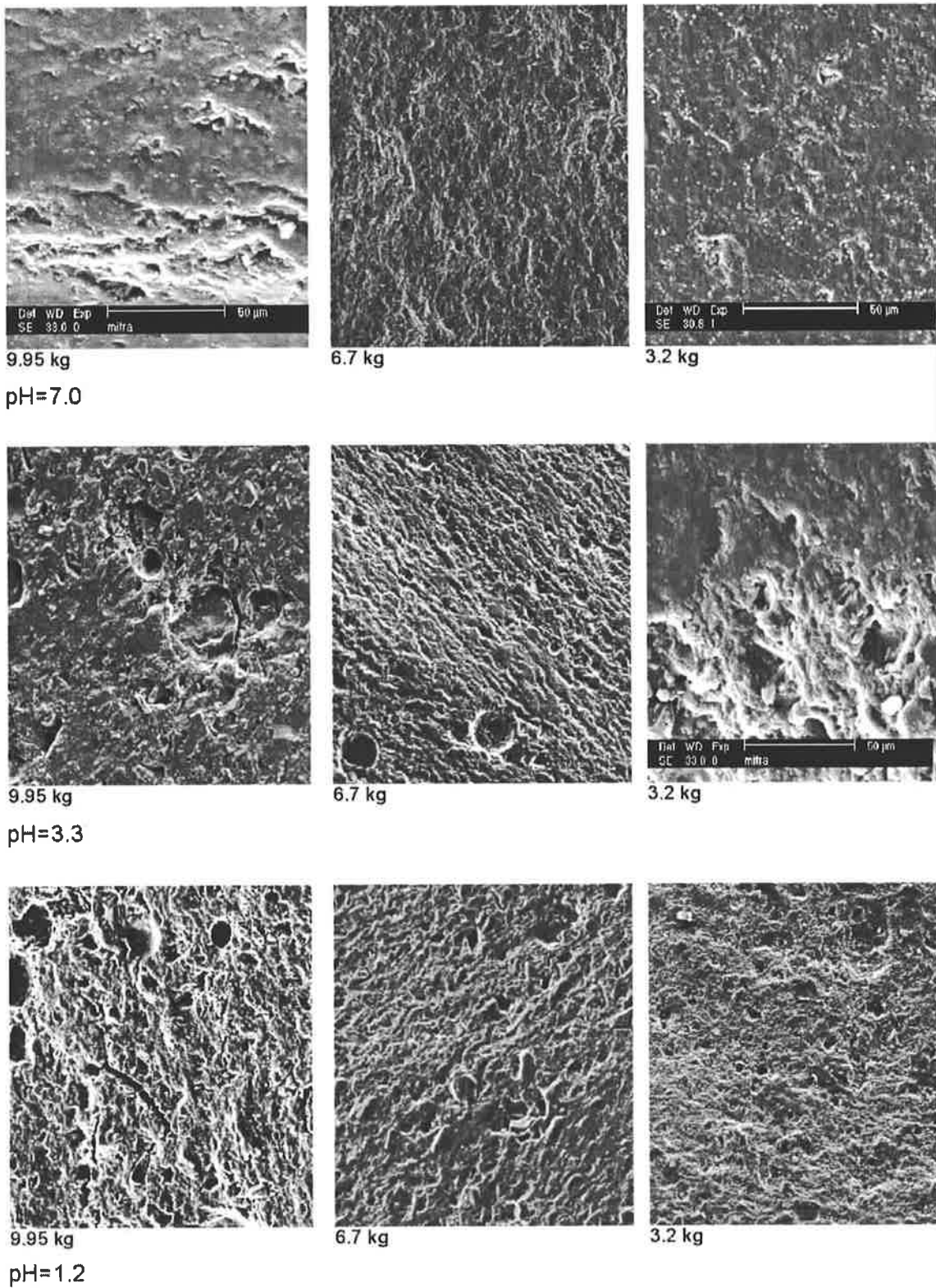


Figure 12.5 SEM results of resin modified-GIC at different pH's and under different loads (kg) with high magnification.

Resin Modified-GIC Experiments Series B (pH=3.3)

Resin Modified-GIC B3 (pH=3.3, load=9.95 kg) and

Resin Modified-GIC B2 (pH=3.3, load=6.7 kg)

Under these conditions there was evidence of corrosion similar to the changes seen in the corresponding series of enamel experiments.

As there was relatively high rate of enamel destruction, margins of restorations were exposed and unsupported by enamel with a step of the order of 20-50 μm from the enamel to the restoration surface. Although there was no sign of marginal fracture, restoration-enamel bonds showed superficial gaps of approximately 1-2 μm .

Surfaces of restorations were generally smooth with voids of 5-10 μm diameter.

Resin Modified-GIC B1 (pH=3.3, load=3.2 kg)

At pH=3.3 and under load of 3.2 kg, the enamel surface was generally smooth and restorations showed some smooth areas and other areas of surface breakdown.

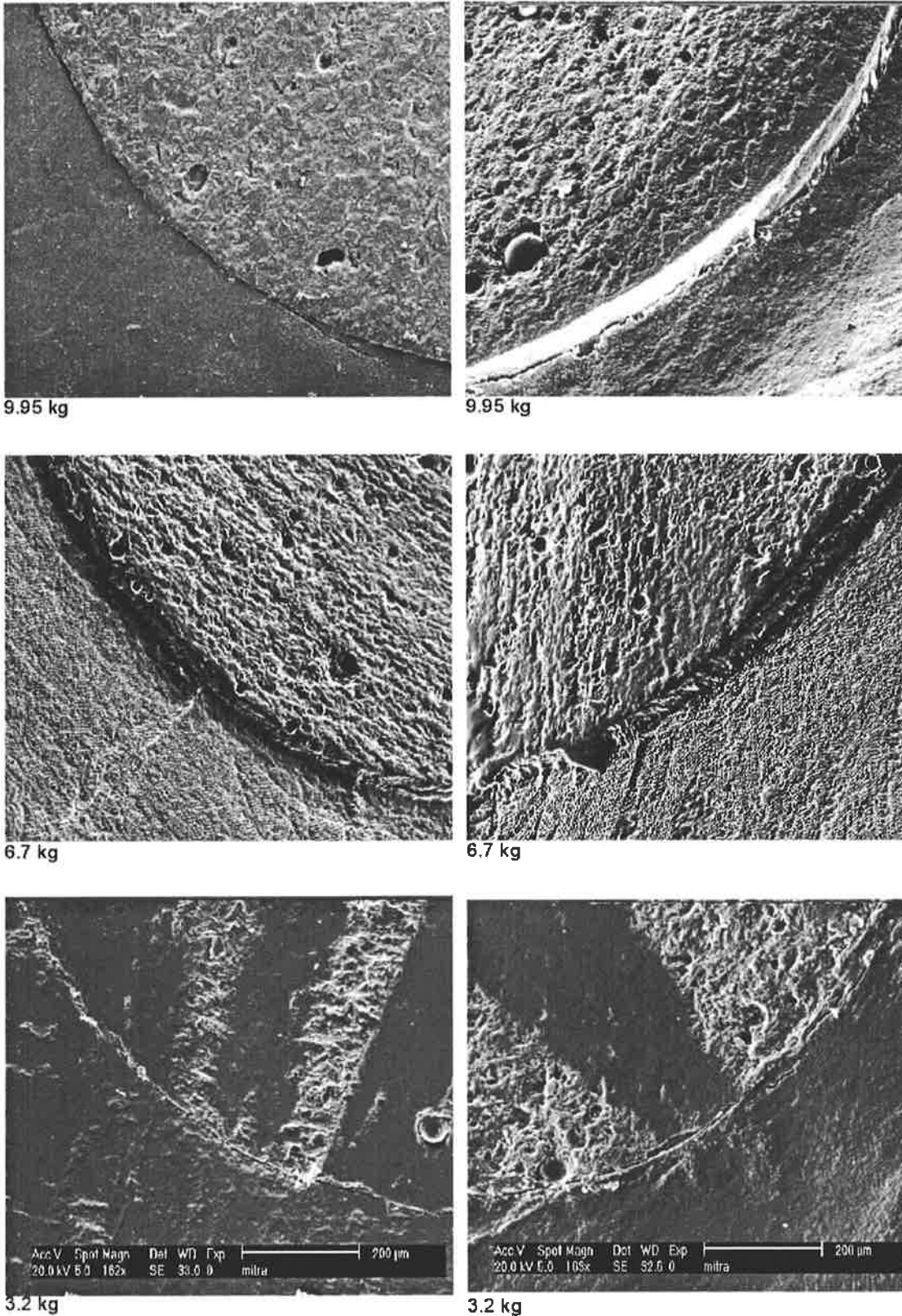


Figure 12.6 SEM results of resin modified-GIC at pH=3.3 and under different loads (kg).

Resin Modified-Glass Ionomer Experiments Series C (pH=1.2)Resin Modified-GIC C3 (pH=1.2, load=9.95 kg)

Under these conditions, there was similar evidence of corrosion to those experiments involving enamel alone particularly in the area of first contact.

Because of relatively high rate of chemical destruction of enamel, margins of restorations were exposed and unsupported by enamel with a step of 100 μm from enamel to the restoration surface. There was no evidence of major fracture of the exposed margins.

Surfaces of restorations generally showed evidence of chemical destruction with the voids of diameter up to 50 μm .

Resin Modified-GIC C2 (pH=1.2, load=6.7 kg)

Enamel appearance in specimens subjected to wear under these conditions was similar to that seen at the higher load with evidence of chemical destruction predominating especially at the margin adjacent to the area of first contact. Again there was evidence of exposed margins similar to that seen at the higher loads. There was also evidence of chemical destruction and breakdown on the surface of restorations similar to, but less extensive than that seen at higher loads.

Resin Modified-GIC C1 (pH=1.2, load=3.2 kg)

At pH=1.2 and under load of 3.2 kg, a high level of chemical destruction of enamel resulted in exposed restoration margins with a step of order of 50-80 μm from the enamel to the restorations surfaces. There was also evidence of breakdown in the enamel-restoration bond of the type seen at load of 6.7 kg.

Surface of restorations also showed evidence of chemical destruction with porosities of up to 20 μm diameter.

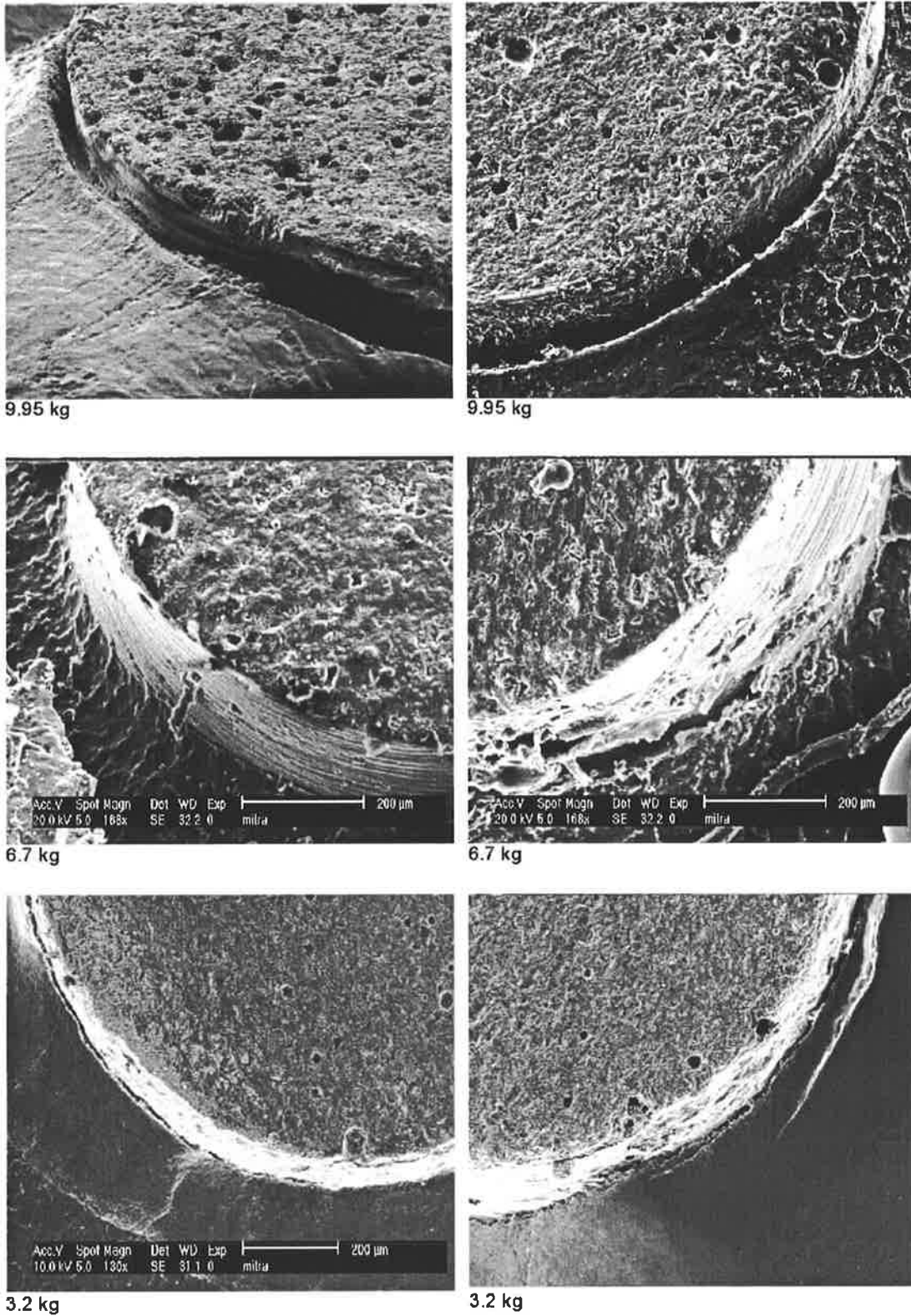


Figure 12.7 SEM results of resin modified-GIC at pH=1.2 and under different loads (kg).

Non-Contact-Area Experiments

Resin Modified-Glass Ionomer Experiments Series A0, B0, C0 (pH=7.0, pH=3.3, pH=1.2)

Resin Modified-GIC A0 (pH=7.0, load=0.0 kg)

Exposure of resin modified-GIC restorations to lubricant at pH=7.0 did not result in any observable surface changes.

Resin Modified-GIC B0 (pH=3.3, load=0.0 kg)

At this pH, there was a relatively higher rate of enamel destruction resulting exposure of margins of restorations with no enamel support with a step of the order of 10 μm from enamel to the restoration surfaces. Surfaces of restorations relatively appeared smooth with some evidence of surface breakdown.

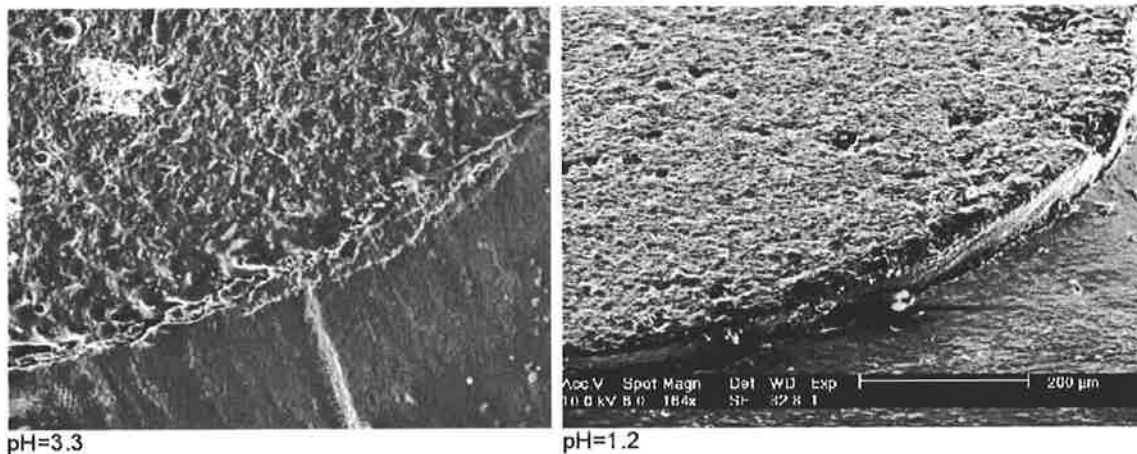


Figure 12.8 SEM results of resin modified-GIC for non-contact-area experiments.

Resin Modified-GIC C0 (pH=1.2, load=0.0 kg)

Because of relatively high rate of chemical destruction of enamel, margins of restorations were exposed and unsupported by enamel with a step of the order of 100 μm from the enamel to the restoration surfaces. There was evidence of cracks on the surfaces of restorations.

Conclusion

The quantitative and qualitative data obtained in this part of study provide the following evidence presenting in Figure 12.9 and Table 12.3.

At pH=7.0 and under higher load (9.95, 6.7 kg), mean wear rates of resin modified-GIC were significantly higher than those under load of 3.2 kg ($p < 0.05$). However, at lower pH's (3.3, 1.2) mean wear rates did not differ significantly by loads ($p > 0.05$).

At pH=1.2, mean wear rates of resin modified-GIC were significantly higher than those under higher pH's (7.0, 3.3) ($p < 0.05$).

Mean wear rates of resin modified-GIC at lower pH's (3.3, 1.2) and under no load were significantly lower than those of under no load ($p < 0.05$).

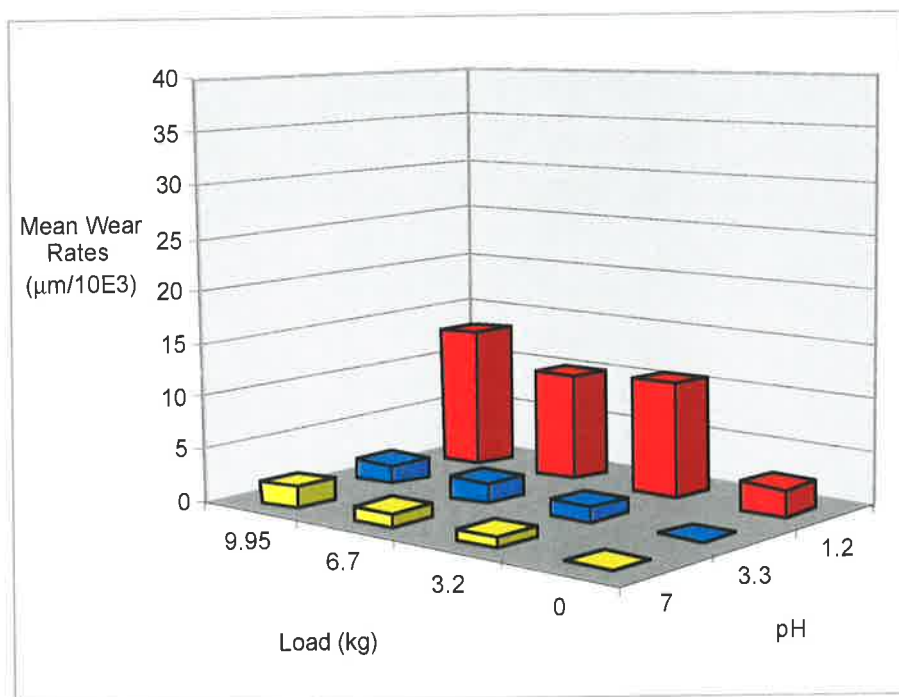


Figure 12.9 Mean wear rates of resin modified-GIC at different pH's and under different loads (kg).

Table 12.3 summary of quantitative and qualitative results of resin modified-GIC experiments at different pH's and under different loads (kg).

Load (kg)	pH		
	7.0	3.3	1.2
9.95	Low wear rate (1.8 $\mu\text{m}/10^3$), intact enamel-restoration bond, rough surface with evidence of breakdown	Low wear rate (1.9 $\mu\text{m}/10^3$), exposed margins with no evidence of fracture, superficial gaps of 1-2 μm in enamel-restoration bond, relatively rough surface with voids	Very high wear rate (13.6 $\mu\text{m}/10^3$), exposed margins with no enamel support with a step up of the order of 100 μm from the enamel to the restoration surface.
6.7	Low wear rate (1.3 $\mu\text{m}/10^3$) intact enamel-restorations bond, rough surface with evidence of breakdown	Low wear rate (1.8 $\mu\text{m}/10^3$), exposed margins with no evidence of fracture, superficial gaps of 1-2 μm in enamel-restoration bond, relatively rough surface with voids	Very high wear rate (10.3 $\mu\text{m}/10^3$), exposed margins, chemical destruction and breakdown on the surface of restorations similar to but less extensive than that seen at higher loads
3.2	Lowest wear rate (0.9 $\mu\text{m}/10^3$), intact margins, relatively less rough surfaces	Low wear rate (1.4 $\mu\text{m}/10^3$), some smooth surface areas and other areas of surface breakdown	Very high wear rate (10.8 $\mu\text{m}/10^3$), evidence of enamel-restoration bond and chemical destruction with porosities of less than 20 μm in diameter
0.0	No material loss, no observable surface changes	No material loss, exposed margins of restorations with unsupported enamel with a step of the order of 5-10 μm	Moderate wear rate (2.41 $\mu\text{m}/10^3$), exposed margins of restorations with unsupported enamel with a step up of order of 100 μm

SECTION 4

DISCUSSION & CONCLUSION

Chapter 13

Discussion

Introduction

Recently demand for tooth-coloured restorative materials such as composite resins and glass ionomer cements has increased due to their lack of mercury and their aesthetic advantages. In spite of improvements in their physical properties, these materials can have problems with high wear.

To date many *in vitro* and *in vivo* studies of wear of dental materials have been reported. Interpretation of the results of these studies is difficult because *in vitro* experiments can not duplicate the dynamic oral environment and well controlled, *in vivo* studies are not always possible as they are expensive, time-consuming and can involve ethical problems.

Many wear machines have been used to simulate different types of wear. Some of them have been designed to determine abrasive wear of tooth and dental materials (Luggasy and Greener, 1972; Peterson et al., 1966; Tilliston, et al., 1971) while more complicated machines have been used to simulate other types of wear (Condon and Ferracane, 1996, 1997; De Gee and Pallav, 1994; Ratledges et al., 1994).

In addition to the differences in experimental approach, many methods have been applied to assess and quantify wear. Some of them are simple and inexpensive (such as USPHS system and Olio system), others are more expensive but more accurate. These include methods involving profilometry, reflex microscopy, and the MTS system (Cvar and Ryge, 1971; Dastane et al., 1996; Olio et al., 1987; Scott, 1981; Winkler et al., 1996).

In this study a systematic approach to the analysis of wear has been adopted. This involves:

- The *in vitro* analysis of the wear of standard restorations under controlled conditions.
- The qualitative and quantitative investigation of wear over a range of pH's and loads which might be encountered clinically to develop a wear map of the micro-morphology of wearing teeth and restorations and a systematic modeling of wear rates.

The results of the experiments conducted at pH=7.0 (**Series A**) showed significant differences between wear rates at the highest loads compared with wear rates at the lowest load and a consistent trend for wear rates to increase with load for all of the materials and for enamel (Figure 13.1, 13.2, and Table 13.1). These results are consistent with previous investigations that have shown a linear relationship between wear rate and load (Burwell and Strang, 1952; Halling, 1975). A previous study of enamel (Kaidonis et al., 1998) also showed higher wear rates at higher loads.

According to SEM results under higher loads (9.95, 6.7 kg) wear appeared to be a combination of adhesive and three-body wear resulting in cratering and surface breakdown. Under load of 3.2 kg, enamel surfaces were generally smoother with areas of surface pitting and chipping characteristic of three-body wear rather than adhesive wear.

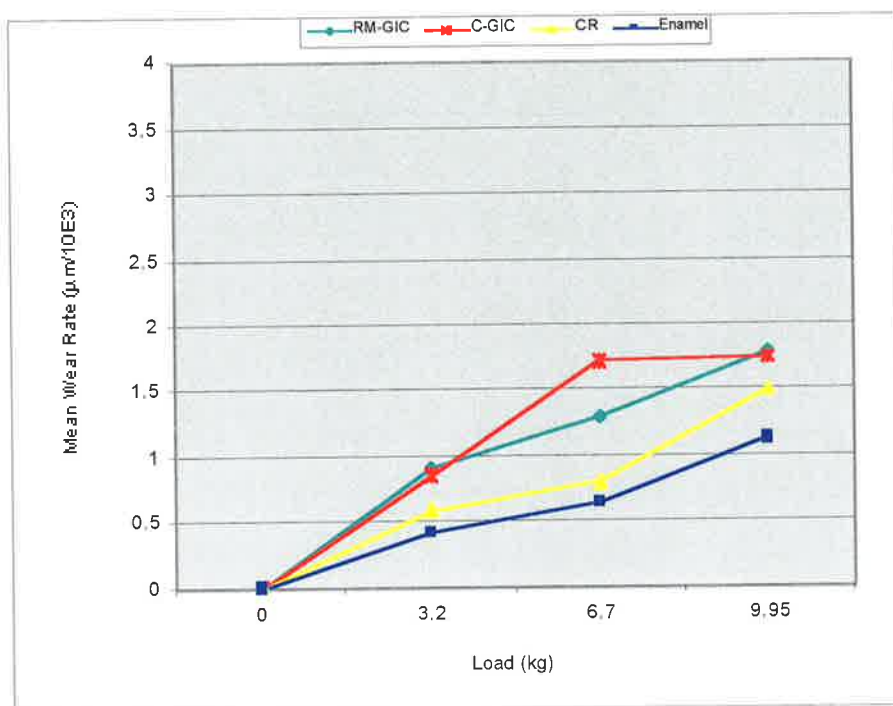


Figure 13.1 Mean wear rates (µm/10³ cycles) of experimental materials at pH=7.0 and under different loads (kg) (standard deviations are included in Table 13.1).

Table 13.1 Quantitative results of experimental materials at pH=7.0 and under different loads (kg) including load (kg), number of specimens (n), mean wear rate, and standard deviation (SD).

pH	Load (kg)	Materials	n	Mean (µm/10 ³)	SD (µm/10 ³)
7.0	9.95	enamel	6	1.13	0.32
		composite resin	5	1.5	0.3
		conventional-GIC	6	1.76	0.59
		resin modified-GIC	6	1.8	0.6
	6.7	enamel	8	0.65	0.29
		composite resin	5	0.8	0.3
		conventional-GIC	5	1.76	0.11
		resin modified-GIC	5	1.2	0.2
	3.2	enamel	5	0.42	0.14
		composite resin	6	0.6	0.1
		conventional-GIC	7	0.86	0.35
		resin modified-GIC	5	0.9	0.3

Surface breakdown may be due to cyclical loading causing fatigue wear (Friedrich, 1984; Söderholm, 1998). During cyclical loading, microscopic defects form within the surface region due to localized stress. This cyclic loading can nucleate cracks below the surface as subsurface deformation continues. Further loading and deformation causes cracks to

extend and to propagate laterally, and to link to each other and finally, when these cracks shear to the surface in certain weak sites, long and thin wear sheets “delaminate”. The amount of wear depends on location of subsurface crack growth, which is controlled by the normal and the tangential loads at the surface (Suh, 1973, 1977).

Although composite resin seemed to show higher wear rates than enamel, these differences were not significant ($p > 0.05$). The difference in mean wear rate of enamel and composite resin under load of 9.95 kg was close to the results of a clinical wear study for a period of 24 months (Willmes et al., 1993). As with enamel, there was no significant difference between mean wear rate of composite resin at lower loads (6.7, 3.2 kg) while mean wear rates under high load (9.95 kg) were significantly higher than that for loads of 6.7 and 3.2 kg ($p < 0.05$). This finding contrasts with the results reported by Condon and Ferracane (1996) who found that composite resin was less susceptible to localized wear produced by enhanced loads. The composite resin used in these experiments had a high concentration of filler particles (~80%) of various sizes. Many researchers have demonstrated that better physical properties for composite resin can be achieved by high concentration of filler particles and the use of a non-uniform size distribution of filler (Braden et al., 1998; Condon and Ferracane, 1997; Ferracane, 1995; Li et al., 1985). The monomer resin of this composite resin is bis-GMA with the addition of TEGDMA which has been documented to increase wear resistance of composite resin (Kawai et al., 1998).

Marginal fracture under high load (9.95 kg) was similar to that reported by Ferracane and Condon (1999). They suggested that for composites resistance to marginal fracture is of greater importance than marginal adhesion in determining resistance to marginal degradation. They also found a linear correlation between marginal breakdown and fracture toughness. Marginal fracture has been known as one of reasons for composite resin replacement since the enamel-restoration junction is a mechanical bond and these materials suffer from polymerization shrinkage (Mjör, 1997; Mjör and Toffenti, 1992). It has been suggested that repeated cyclic loading may cause a fatigue failure of material,

leading to marginal breakdown (Mazer and Leinfelder, 1992). It appeared that cracks are propagated during the loading cycle from existing flaws. These cracks ultimately become large enough that critical flaw size is exceeded and the crack propagates (Söderholm, 1998, Mair et al., 1996)

For composite resin restoration surfaces were relatively smooth, particularly under low load (3.2 kg) with evenly distributed irregularities.

GIC's showed significantly higher wear rates under loads of 9.95 and 6.7 kg than under load of 3.2 kg ($p < 0.05$). At pH=7.0 and under different loads (9.95, 6.7, 3.2 kg) mean wear rates of these materials were also significantly higher than mean wear rates of enamel ($p < 0.05$). Although under high load (9.95 kg), mean wear rates of these materials tended to be higher than composite resin, these differences were not significant ($p > 0.05$). Under a load of 6.7 kg, these materials also showed significantly higher wear rate than that for composite resin ($p < 0.05$). It appeared that all of these materials were more susceptible to localized wear under high load (9.95 kg) while under lower load, composite resin wore much less than GIC's. Many previous studies have also shown higher wear resistant for composite resin compared with GIC's (Forss et al., 1991; Momoi et al., 1997; Peutzfeldt et al., 1997).

In spite of the higher wear rate of GIC's, they showed less evidence of marginal fracture particularly under high load (9.95 kg) compared with composite resin. This reconfirmed previous findings of a strong bond between GIC's and hard dental tissue (Davidson and Mjör, 1999; Fritz et al., 1996; Matis et al., 1996). Despite their generally intact margins, GIC's showed generally rougher surfaces with more signs of surface breakdown and porosity than composite resins.

At pH=7.0, no significant difference was found between mean wear rates of conventional-GIC and resin modified-GIC except for those under load of 6.7 kg. Resin modified-GIC are claimed to have improved mechanical properties because of inclusion

of resin in the conventional-GIC, however there are varying reports in the literature. In some studies, resin modified-GIC were found to be inferior to those of conventional-GIC while in other studies they showed similar results (Iwami et al., 1994; Kao et al., 1994; Momoi et al., 1997).

The higher wear rates of resin modified-GIC compared with conventional-GIC may be due to differences in matrix formation. The matrix of conventional-GIC consists of an ionically cross-linked polyalkenoate network resulting from an acid-base reaction while the set of resin modified-GIC has similar cross-linked polyalkenoate network but these are entangled with HEMA polymer chain. The coherence of filler particles embedded in the interpenetrating matrices of polyalkenoate and polymer in resin modified-GIC is inferior to that of the particles in the conventional matrix. This is probably related to the partial replacement of the rigid polyalkenoate network by the flexible polymer chains (Davidson and Mjör, 1999; De Gee et al., 1996).

There was no significant difference between the margins of conventional-GIC and resin modified-GIC restoration. However, there are different reports in the literature. Some have shown higher bond strength to enamel for resin modified-GIC while others reported conflicting results (Davidson and Mjör, 1999; Trina et al., 1994;). The mechanism of adhesion of conventional-GIC is thought to be based on a dynamic ion-exchange process, while resin modified-GIC probably adhere through a combination of the ion-exchange and micro-mechanical bonding (Akinmade and Nicholson, 1993; Lin et al., 1992; Maneenut and Tyas, 1995).

Conventional-GIC exhibited rougher surfaces under higher loads (9.95, 6.7 kg). The increased deformation of surfaces by the load of antagonist enamel could lead to subsurface microcrack formation in the ionic cross-linked polyalkenoate matrix, with a subsequent loss of coherence.

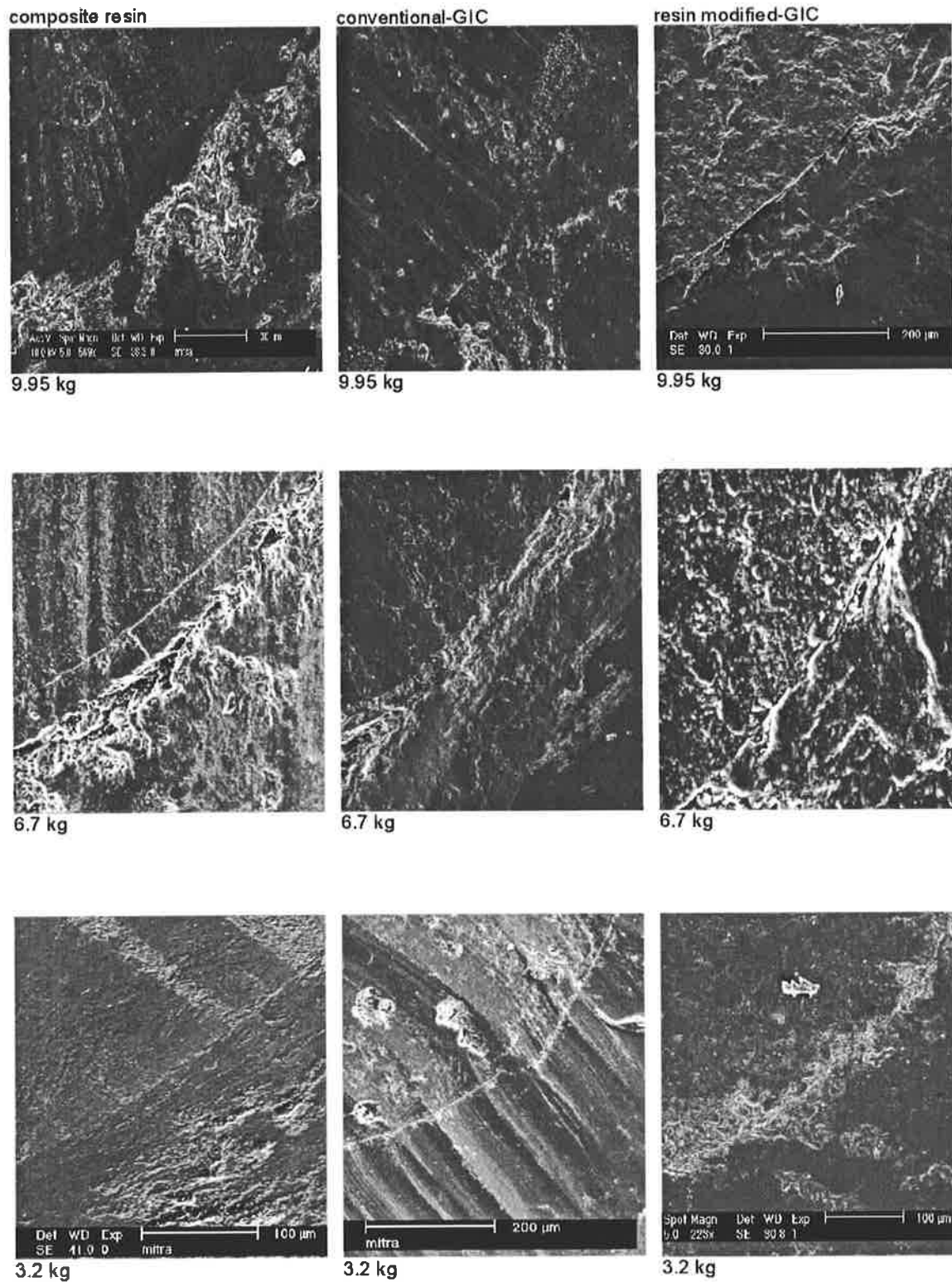


Figure 13.2 SEM results of experimental materials at pH=7.0 and under different loads (kg).

Although an acidic environment has already been shown to be erosive to hard dental tissue and some restorative dental materials, little previous research has involved the effect of chemicals on moving surfaces resulting in corrosive wear (Dahl et al., 1993; Mair, 1992; Mair et al., 1996).

For the experiments conducted under conditions resembling an acidic diet at pH=3.3 (**Series B**) mean wear rates of enamel were significantly higher than those at pH=7.0 ($p<0.05$). In addition the rate of enamel wear was consistently higher than the wear rates for any of the restorative materials across the range of loads (Figure 13.3, 13.4, and Table 13.2).

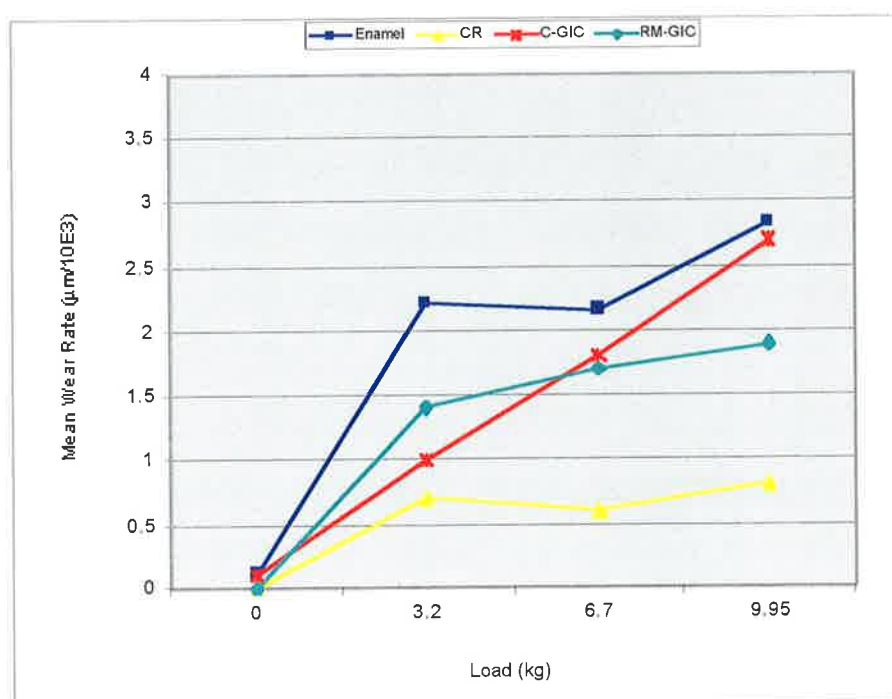


Figure 13.3. Mean wear rate ($\mu\text{m}/10^3$ cycles) of experimental materials at pH=3.3 and under different loads measured for three sites (standard deviations included in Table 13.2).

For enamel, SEM results confirmed an etched and worn surface under high load (9.95 kg) and only etched surface under lower loads (6.7, 3.2 kg). It is known that chemical reactions in the oral cavity between the enamel surface and inorganic ions immediately

adjacent to the tooth surface occur continuously. These ions include $\text{Ca}_5(\text{PO}_4)_3\text{F}$ (fluorapatite), $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ (hydroxyapatite), CaHPO_4 , CaF_2 , and $\text{Ca}_4\text{H}(\text{PO}_4)_3$. (Macpherson et al., 1991).

Table 13.2. Quantitative results of experimental materials at pH=3.3 and under different loads (kg) including load (kg), number of specimens (n), mean wear rate, and standard deviation (SD).

pH	Load (kg)	Material	n	Mean ($\mu\text{m}/10^3$)	SD $\mu\text{m}/10^3$
3.3	9.95	enamel	10	2.84	0.33
		composite resin	6	0.8	0.2
		conventional-GIC	5	2.7	0.6
		resin modified-GIC	5	1.9	0.5
	6.7	enamel	8	2.16	0.71
		composite resin	5	0.6	0.2
		conventional-GIC	5	1.81	0.7
		resin modified-GIC	5	1.7	0.3
	3.2	enamel	8	2.23	0.58
		composite resin	5	0.7	0.3
		conventional-GIC	5	1.0	0.7
		resin modified-GIC	5	1.4	0.4
	0.0	enamel	9	0.12	0.03
		composite resin	10	0.0	0.0
		conventional-GIC	10	0.1	0.01
		resin modified-GIC	10	0.03	0.01

In vitro studies have confirmed that in the presence of an unsaturated solution of hydroxyapatite and fluorapatite adjacent the tooth surface, dissolution of the enamel produces a surface similar to a typical erosive lesion (Larsen, 1973). If the solution is saturated with respect to fluorapatite but unsaturated with respect to hydroxyapatite, then fluorapatite is deposited on the enamel surface, keeping it intact even though the subsurface enamel is demineralised.

It is postulated that during tribochemical wear with a lubricant at pH=3.3, the environment adjacent the facet surface may differ at times to that described above. If the solution adjacent to the enamel surface is saturated or supersaturated with respect to both fluorapatite and hydroxyapatite, precipitation of solid particles such as calcium phosphate and calcium fluoride may occur. These particles probably act as a third body between the affected surfaces in the form of an amorphous slurry. Etching of the enamel

surface produces undermined enamel aspirates that break off under load producing a continuous supply of particles between the opposing surfaces.

At pH=3.3, mean wear rates of composite resin were significantly lower than those at pH=7.0 ($p<0.05$). Composite resin exhibited significantly lower wear rates than enamel under different loads ($p<0.05$). It may be due to higher erosion resistance of polymer matrices and the relative weakness of opposing enamel. According to Chadwick et al. (1990) storage of composite resins at different pH did not affect the abrasion resistance.

Under higher loads (9.95, 6.7 kg), mean wear rates of composite resin were significantly lower than those for conventional-GIC and resin modified-GIC ($p<0.05$). This finding is confirmed by SEM results showing more chemical erosion for GIC's particularly for conventional-GIC. This finding agrees with previously published studies showing higher wear resistant of composite resin in acidic pH compared with GIC's (De Gee and Pallav, 1994; De Gee et al., 1996).

The surfaces of composite resin restorations appeared relatively smooth with exposure of filler particles and also exposed margins with a little evidence of surface breakdown. Under lower loads (6.7, 3.2 kg) there was no sign of marginal breakdown. Studies of *in vivo* wear of composite resin restorations have also reported surface crazing and exposure of filler particles in acidic environment (Kusy and Leinfelder, 1977; Power and Fan, 1980).

Even though there was no significant difference between mean wear rates for resin modified-GIC and conventional-GIC, resin modified-GIC appeared to exhibit a relatively smoother and stable surfaces than conventional-GIC. The presence of resin seems to protect this material against an environment with low pH.

In absence of load, all of materials showed significantly lower wear rates than those subjected to loads ($p < 0.05$). For all of restorative materials, there was also no evidence of surface breakdown or marginal fracture.

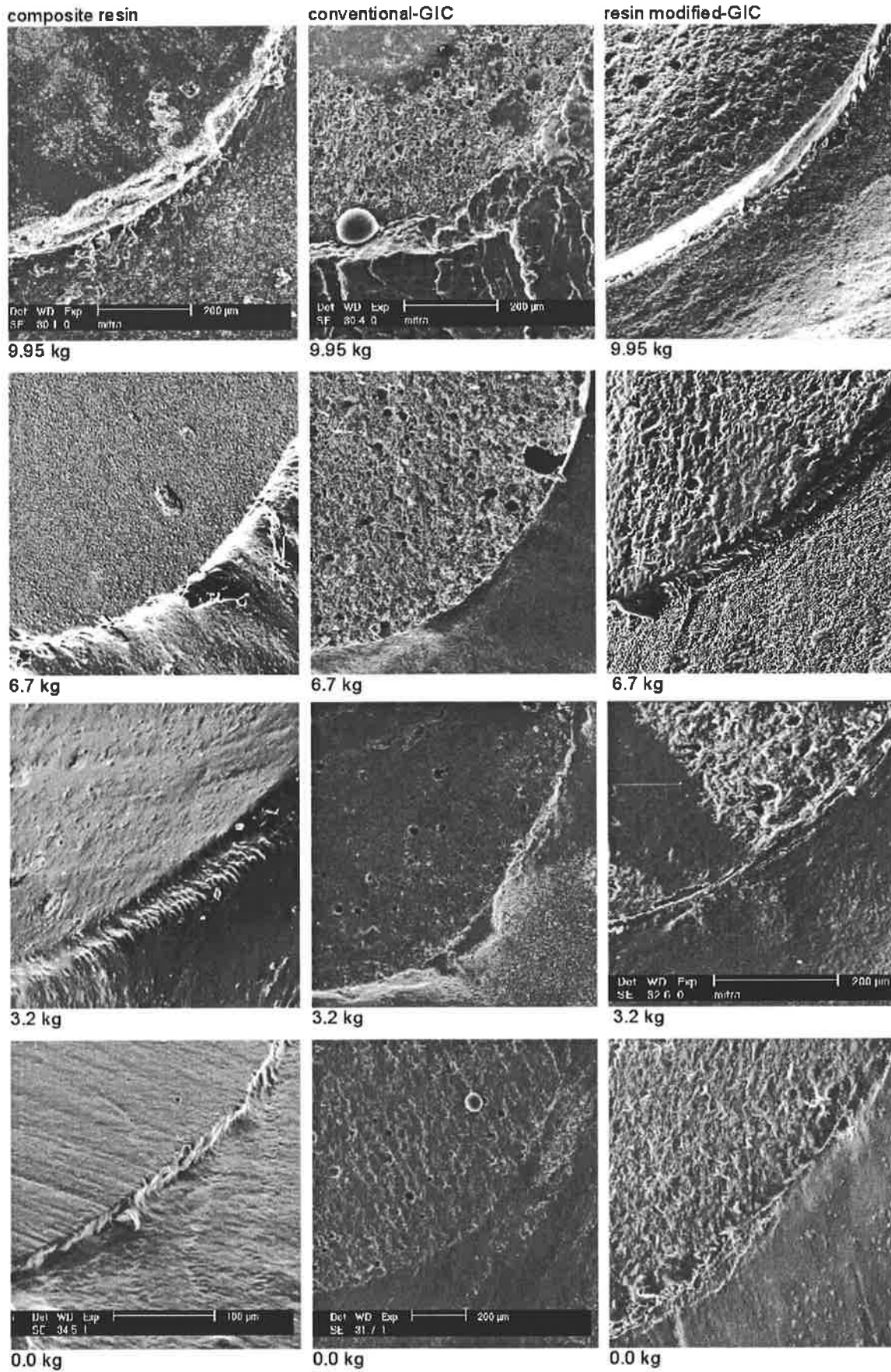


Figure 13.4 SEM results of experimental materials at pH=3.3 and under different loads (kg).

It has been shown that some conditions can reduce the pH of oral cavity greatly causing wear of hard dental tissue (Allen, 1969; Andrew, 1982; Eccles, 1979; Hellstrom, 1977; Hurst et al., 1977; Järvinen et al 1988). The results for the series of experiments conducted at pH=1.2 reflecting the effect of regurgitated acid is shown as part of Figure 13.5, 13.6, and Figure 13.6. At this pH and under different loads (9.95, 6.7, 3.2 kg) enamel and all of the restorative materials showed higher wear rates than were evident at higher pH (7.0, 3.3). Enamel and conventional-GIC appeared to be more sensitive to acidic pH showing extensive chemical destruction.

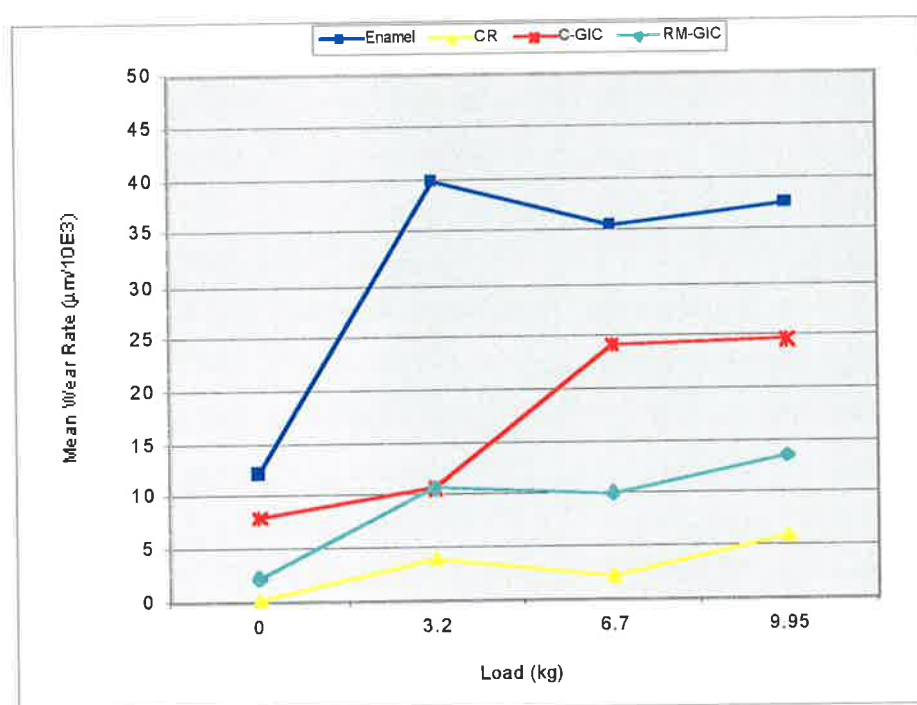


Figure 13.5 Mean wear rates ($\mu\text{m}/10^3$ cycles) of experimental materials at pH=1.2 and under different loads (kg) (standard deviations are included in Table 13.3).

At pH=1.2, enamel showed significantly higher wear rates than was evident at less acidic conditions. This supported previously reported findings (Kaidonis, 1995). SEM results also showed extensive chemical destruction of enamel. Under load of 9.95 kg, acid etching and the superimposed wear revealed the prism structure of the enamel with the exposed rods showing evidence of flattening associated with the concurrent wear. Under loads of 6.7 and 3.2 kg, there was extensive destruction with little remaining

evidence of the original enamel micro-anatomy. Because of this extensive and deep destruction of enamel, saturation levels at the wear interface would not occur. Therefore there is no chance for remineralisation.

Table 13.3 Quantitative results of experimental materials at pH=1.2 and under different loads (kg) including number of specimens (n), mean wear rate ($\mu\text{m}/10^3$), standard deviation (SD).

pH	Load (kg)	Material	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)
1.2	9.95	enamel	9	37.54	7.71
		composite resin	5	6.0	1.7
		conventional-GIC	7	24.6	5.3
		resin modified-GIC	7	13.6	4.7
	6.7	enamel	9	35.56	7.26
		composite resin	6	2.7	0.9
		conventional-GIC	6	24.3	6.4
		resin modified-GIC	5	10.3	3.8
	3.2	enamel	9	39.92	8.42
		composite resin	5	4.0	0.8
		conventional-GIC	5	10.8	1.7
		resin modified-GIC	5	10.8	1.3
	0.0	enamel	10	12.22	3.58
		composite resin	10	0.23	0.11
		conventional-GIC	10	8.12	2.74
		resin modified-GIC	10	2.41	1.59

At this pH, mean wear rates of composite resin were significantly higher than those of at pH of 7.0 and 3.3 ($p < 0.05$). Mean wear rates of composite resin were also significantly lower mean wear rates of enamel, conventional-GIC, and resin modified-GIC at the same pH ($p < 0.05$). It may reflect weakness of the opposite enamel and the relatively higher resistance of resin to acid erosion. There were also signs of a gap in the enamel-restoration junction of conventional-GIC and resin modified-GIC. As there is ionic bonding between GIC and enamel, hydrochloric acid which assumed to be a very powerful acid may have a chemical effect on this bond.

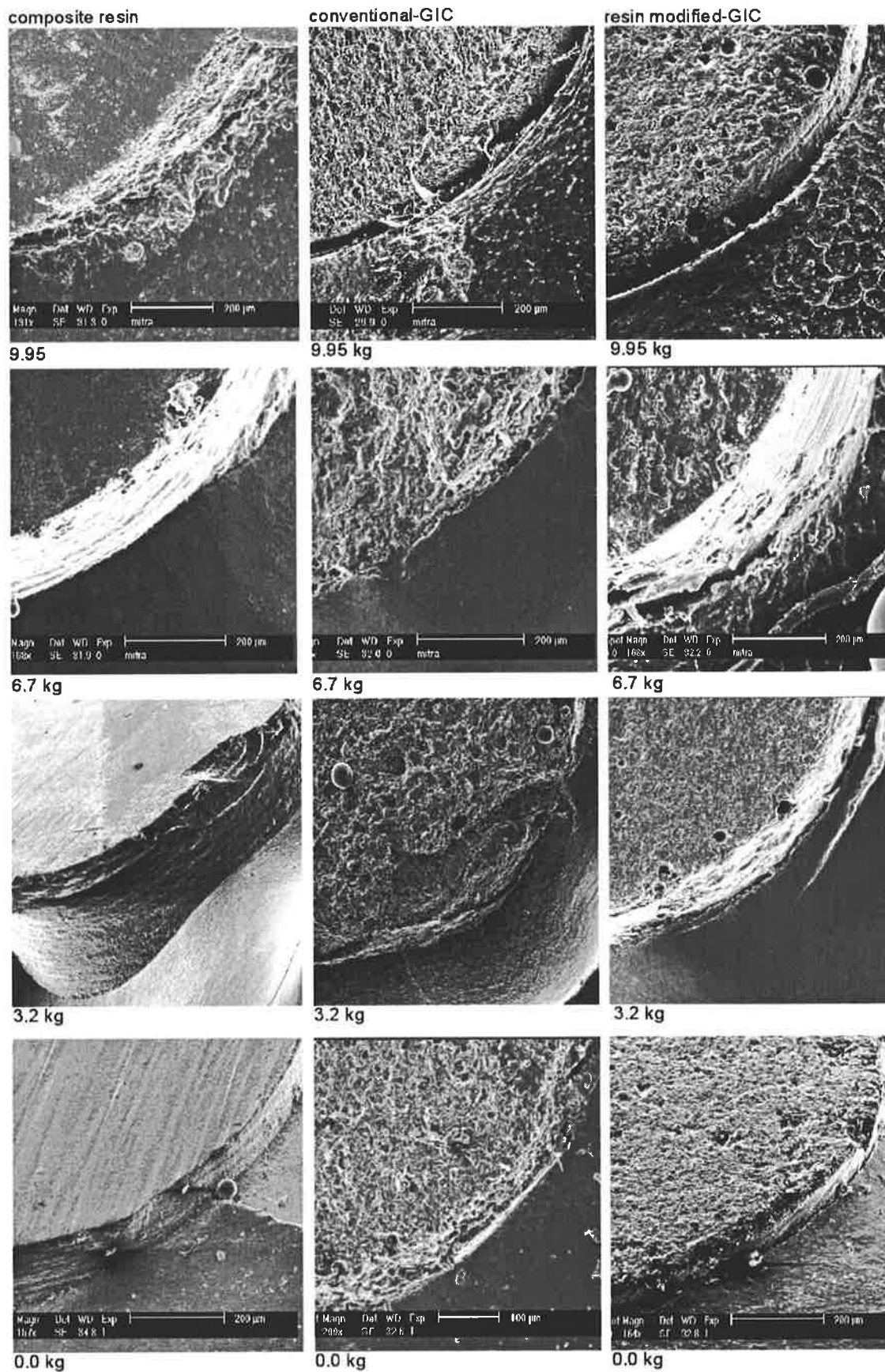


Figure 13.6 SEM results of experimental materials at pH=1.2 and under different loads (kg).

Overview of Quantitative Results

The mean wear rates for each of the materials under each of the experimental conditions are summarized in Table 13.4.

Table 13.4. Quantitative results of experimental materials wear under experimental conditions including pH, Load (kg), number of specimens (n), mean wear rate ($\mu\text{m}/10^3$ cycles), and standard deviation (SD).

pH	Load (kg)	Materials	n	Mean ($\mu\text{m}/10^3$)	SD ($\mu\text{m}/10^3$)
7.0	9.95	enamel	6	1.13	0.32
		composite resin	5	1.5	0.3
		conventional-GIC	6	1.76	0.59
		resin modified-GIC	6	1.8	0.6
	6.7	enamel	8	0.65	0.29
		composite resin	5	0.8	0.3
		conventional-GIC	5	1.76	0.11
		resin modified-GIC	5	1.2	0.2
	3.2	enamel	5	0.42	0.14
		composite resin	6	0.6	0.1
		conventional-GIC	7	0.86	0.35
		resin modified-GIC	5	0.9	0.3
3.3	9.95	enamel	10	2.84	0.33
		composite resin	6	0.8	0.2
		conventional-GIC	5	2.7	0.6
		resin modified-GIC	5	1.9	0.5
	6.7	enamel	8	2.16	0.71
		composite resin	5	0.6	0.2
		conventional-GIC	5	1.81	0.7
		resin modified-GIC	5	1.7	0.3
	3.2	enamel	8	2.23	0.58
		composite resin	5	0.7	0.3
		conventional-GIC	5	1.0	0.7
		resin modified-GIC	5	1.4	0.4
	0.0	enamel	9	0.12	0.03
		composite resin	10	0.0	0.0
		conventional-GIC	10	0.1	0.01
		resin modified-GIC	10	0.03	0.01
1.2	9.95	enamel	9	37.54	7.71
		composite resin	5	6.0	1.7
		conventional-GIC	7	24.6	5.3
		resin modified-GIC	7	13.6	4.7
	6.7	enamel	9	35.56	7.26
		composite resin	6	2.7	0.9
		conventional-GIC	6	24.3	6.4
		resin modified-GIC	5	10.3	3.8
	3.2	enamel	9	39.92	8.42
		composite resin	5	4.0	0.8
		conventional-GIC	5	10.8	1.7
		resin modified-GIC	5	10.8	1.3
	0.0	enamel	10	12.22	3.58
		composite resin	10	0.23	0.11
		conventional-GIC	10	8.12	2.74
		resin modified-GIC	10	2.41	1.59

ANOVA Results

The significant differences between enamel and each of the materials and the complex and differing effect of variation in pH and load on the wear rates of each of the materials, makes analysis of the statistical significance of the observed differences in wear rate complex. However, an analysis of variance including data from contact-area experiments demonstrated the significant effect of pH, load, and type of material on wear rates. Not unexpectedly, there were significant interactions between pH and load, pH and type of material, load and type of material, and load, pH and type of material (Table 13.5) indicating that each of the materials responded differently to each of the experimental conditions

Table 13.5 ANOVA results for contact-area experiments.

source	df	sum of squares	mean square	F-test	p-value
pH (A)	2	963714.461	481857.231	215.757	1.0E ⁻⁴
load (B)	2	288239.711	144119.856	64.531	1.0E ⁻⁴
AB	4	16734.895	4183.724	1.873	0.1137
material (C)	3	1955026.701	651675.567	291.794	1.0E ⁻⁴
AC	6	2180330.95	363388.492	162.711	1.0E ⁻⁴
BC	6	121687.352	20281.225	9.081	1.0E ⁻⁴
ABC	12	52435.483	4369.624	1.957	0.262
site (D)	2	9161.567	4580.784	2.051	0.1296
AD	4	2065.835	516.459	0.231	0.9208
BD	4	6022.304	1505.576	0.674	0.6101
ABD	8	6335.747	791.968	0.355	0.9437
CD	6	37611.585	6268.597	2.807	0.107
ACD	12	6787.693	565.641	0.253	0.9951
BCD	12	20337.982	1694.832	0.0.759	0.6932
ABCD	24	32133.037	1338.877	0.599	0.9348
error	531	1185902.309	2233.338		

To summarize this complex relationship a multiple regression model was fitted to the data. The results of this analysis are presented in Table 13.6. The multiple regression model gives an equation of the form:

$$\text{Wear rate} = a + b (\text{pH}) + c (\text{load})$$

Where “a” is a constant term, “b” describes the independent effect of variation in pH and “c” describes the independent effect of load.

The moderate to high correlation coefficients ($r=0.67-0.77$) indicate that the model describes a significant proportion of the observed variation in wear rate.

Table 13.6 Results of multiple regression analysis for each of experimental materials.

Material	r	pH	Load	Constant
Enamel	0.74	-5.7	1.3	-25
Composite resin	0.67	-0.39	0.28	1.4
Resin modified CIC	0.75	-1.48	0.70	5.6
Conventional GIC	0.74	-2.87	1.17	11.4

The multiple regression coefficients suggest that:

- Enamel is influenced most by variation in pH ($b=-5.7$) compared with composite resin which is least effected by acid ($b=-0.39$).
- Conventional-GIC is more susceptible to the effect of variation in pH than composite resin ($b=-2.87$).
- The acid susceptibility of resin modified-GIC is intermediate between that of composite resin and conventional-GIC.
- Enamel and conventional-GIC are effected similarly by load ($c=1.3$ and 1.17 respectively).
- Composite resin is relatively resistant to wear at higher loads ($c=0.28$).
- The effect of load on resin modified-GIC is intermediate between that composite resin and conventional-GIC.

The fact that the properties of resin modified-CIC are consistently intermediate between those of composite resin and conventional-GIC reflects its intermediate composition.

Chapter 14

Conclusion

Demand for direct-tooth-colored restorative materials has encouraged many research groups to investigate and to compare the wear characteristics of these materials. Among them, composite resins and GIC's are the most common materials to be compared. This *in vitro* study was designed to determine the wear characteristics of enamel and some GIC's and composite resin in contact-area and non-contact-area conditions.

In this study a systematic approach to the analysis of wear has been adopted. This involves:

- The *in vitro* analysis of the wear of standard restorations under controlled conditions.
- The qualitative and quantitative investigation of wear over a range of pH's and loads which might be encountered clinically to develop a wear map of the micro-morphology of wearing teeth and restorations and a systematic modeling of wear rates.

The results of preliminary experiments showed that:

- The wear rate of enamel was independent of the speed at which opposing teeth were worn.

- The wear rate of enamel was independent of the direction in which teeth were worn.
- There was no significant difference in wear rates of lower and upper contacting teeth.
- Initial fact area had no significant effect on wear rate.

The results of this study showed that:

- Significant effects of pH, load, and type of material on wear rate while site in margins compared with center of restorations showed no significant effect on wear rate.
- Enamel wear was influenced most by variation in pH compared with composite resin which was least effected by acid
- Conventional-GIC appeared to be more susceptible to the effect of variation in pH than composite resin by showing higher wear rate and extensive destruction in low pH's.
- The acid susceptibility of resin modified-GIC was found to be intermediate between that of composite resin and conventional-GIC.
- Enamel and conventional-GIC were effected similarly by load.
- Composite resin appeared to be more resistant than GIC's to wear at higher loads.
- The effect of load on resin modified-GIC was intermediate between that composite resin and conventional-GIC.

The fact that the properties of resin modified-GIC were consistently intermediate between those of composite resin and conventional-GIC reflects in intermediate composition.

The results of this study have provided interesting information about the wear characteristics of composite resin and GIC's under a range of conditions. The data provides a basis for the future evaluation of a wider range of materials.

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