FATIGUE IN MODERN DENTAL PORCELAIN

Thesis submitted to the University of Sydney
as a requirement for admission to the
degree of Master of Dental Surgery

Bruce Edward Peet, B.D.S.
1971
ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my supervisor, Dr. D.E. Southan, for his guidance in conducting this investigation.

I would also like to thank Miss J. Dunstan for typing the thesis and Miss B. Bischoff for the assistance in the preparation of the photographic prints.
PREFACE

Modern dental porcelain has developed from the traditional triaxial whiteware formula to meet the aesthetic requirements of restorative dentistry. It is not a typical whiteware as there are fundamental differences in its composition to provide the fine aesthetic qualities and manipulative properties so appreciated in dental ceramic restorations.

In meeting the special requirements of modern dentistry, dental porcelain has developed into a highly translucent glass-like material, with properties greatly influenced by this major vitreous phase.

For many years there has been considerable research into the nature and properties of vitreous materials, but the dental profession has made little effort to investigate the properties of dental porcelain in a scientific way and manufacturers have always been unwilling to reveal details of their highly specialized industry.

Recently, dental research workers have used the experience gained in other fields as a basis for more pertinent investigations into the nature and properties of dental porcelain. Unfortunately, much of the recorded information, as in the past, is based on aesthetic requirements and empirical observations with limited awareness of the nature of related industrial ceramic materials. Little attempt has been made to standardize testing procedures or relate test pieces to the structures fabricated in dentistry.

Although porcelain bonded to metal structures have gained
(ii)

popularity with claims of durability and strength, the all porcelain jacket crown or bridge is clinically more desirable. There is a need for further investigation of the properties of dental porcelain, particularly those related to its strength in the oral environment.
# CONTENTS

## PART A.

**REVIEW OF LITERATURE**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CERAMICS</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Composition of Porcelain</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(a) Quartz</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(b) Feldspars</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>(c) Clays</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>DENTAL PORCELAIN</td>
<td>7</td>
</tr>
<tr>
<td>2.1</td>
<td>Composition of Dental Porcelain</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>THE MANIPULATION OF DENTAL PORCELAIN</td>
<td>13</td>
</tr>
<tr>
<td>3.1</td>
<td>The Forming Process</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>Test Specimen Formation</td>
<td>13</td>
</tr>
<tr>
<td>3.3</td>
<td>Condensation</td>
<td>15</td>
</tr>
<tr>
<td>3.4</td>
<td>Firing</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>PHYSICAL PROPERTIES OF DENTAL PORCELAIN</td>
<td>19</td>
</tr>
<tr>
<td>4.1</td>
<td>Shrinkage and Porosity</td>
<td>19</td>
</tr>
<tr>
<td>4.2</td>
<td>Thermal Expansion and Transformation Region</td>
<td>20</td>
</tr>
<tr>
<td>4.3</td>
<td>The Strength of Dental Porcelain</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>(i) Transverse strength or modulus of Rupture</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>(ii) Compressive Strength</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>(iii) Diametral Compressive Strength</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>(iv) Impact Strength</td>
<td>26</td>
</tr>
<tr>
<td>5</td>
<td>GLASS</td>
<td>28</td>
</tr>
<tr>
<td>5.1</td>
<td>The Nature of the Glassy State</td>
<td>28</td>
</tr>
<tr>
<td>5.2</td>
<td>The Structure of Silicate Glasses</td>
<td>31</td>
</tr>
<tr>
<td>5.3</td>
<td>Aluminosilicate Glasses</td>
<td>32</td>
</tr>
</tbody>
</table>
6. THE STRENGTH OF GLASS

6.1 Britleness
6.2 The Flaw Theory
6.3 Nature and Origin of Surface Damage
6.4 Effect of Surface Damage
6.5 Static Fatigue in Glass
6.6 Effect of Moisture
6.7 Effect of Loading Glass
6.8 Strength Reinforcement of Glass
   (a) Thermal Toughening
   (b) Chemical Toughening

SUMMARY

PART B.

ORIGINAL INVESTIGATION

7. STATEMENT OF PROBLEM - PURPOSE AND SCOPE OF INVESTIGATION

8. STRENGTH RELATIONS AND THE BEND TEST

9. THE STRENGTH OF DENTAL PORCELAINS UNDER INCREMENTAL LOADING

MATERIALS AND METHODS

9.1 Modern Dental Porcelains Investigated
9.2 Test Specimen Formation
9.3 The Modulus of Rupture of Different Materials
9.4 The Effect Annealing has on the Modulus of Rupture of Different Materials
9.5 The Effect Surface Compression Created by Low-Temperature Ionic Exchange has on the Modulus of Rupture of Different Materials
(vi)

LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure No.</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Difference between crystalline and vitreous structures.</td>
<td>30</td>
</tr>
<tr>
<td>2.</td>
<td>Atomic arrangement of soda glass.</td>
<td>33</td>
</tr>
<tr>
<td>3.</td>
<td>Three-point loading system.</td>
<td>53</td>
</tr>
<tr>
<td>4.</td>
<td>Thin sections of two dental porcelains.</td>
<td>56</td>
</tr>
<tr>
<td>5.</td>
<td>Moulds for test specimen formation.</td>
<td>60</td>
</tr>
<tr>
<td>6.</td>
<td>Sustained Loading Machine.</td>
<td>73</td>
</tr>
<tr>
<td>7.</td>
<td>Sustained Loading Test.</td>
<td>77</td>
</tr>
<tr>
<td>Table No.</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>I</td>
<td>Modern dental porcelains investigated.</td>
<td>57</td>
</tr>
<tr>
<td>II</td>
<td>Details of porcelains tested.</td>
<td>58</td>
</tr>
<tr>
<td>III</td>
<td>Modulus of rupture of different materials.</td>
<td>68</td>
</tr>
<tr>
<td>IV</td>
<td>Modulus of rupture of annealed dental porcelain.</td>
<td>69</td>
</tr>
<tr>
<td>V</td>
<td>Modulus of rupture of chemically treated dental porcelain.</td>
<td>70</td>
</tr>
<tr>
<td>VI</td>
<td>The relationship between modulus of rupture and the effect of a sustained load on the different materials.</td>
<td>82</td>
</tr>
<tr>
<td>VII</td>
<td>The relationship between modulus of rupture and the effect of a sustained load on annealed dental porcelain.</td>
<td>83</td>
</tr>
<tr>
<td>VIII</td>
<td>The relationship between modulus of rupture and the effect of a sustained load on chemically treated dental porcelain.</td>
<td>84</td>
</tr>
</tbody>
</table>
1. Lee (1961, p. 1) defines ceramics as products made from non-metallic, inorganic materials, generally involving high temperatures in their manufacture. A much broader definition by Kingery (1963, p. 3) defines ceramics as "the art and science of making and using solid articles which have as their essential component, inorganic, non-metallic materials".

Ceramics may be classified as traditional ceramics, such as used by the silicate industries in the original descriptions proposed for the American Ceramic Society in 1899 (Kingery 1963, p. 7), and modern ceramics with unique or outstanding properties which have been developed or discovered more recently.

The largest segment of the traditional Ceramic Industry is concerned with the manufacture of various glass products, manufactured almost entirely as sodium-calcium-silicate glasses (Kingery, 1963, p. 6). Pottery, porcelain and similar fine grained porcelain-like compositions are a more diverse group, included in the classification of whitewares.

The Chinese were the first to make porcelain, more than 1200 years ago. Most Chinese porcelain was made from kaolin and petuntse (pai-tun-tzu), a feldspar. Such a formula is termed hard-paste (or true) porcelain (Savage, 1963). During the 18th Century, the art of making china and other ceramics was spreading and the first porcelain factories in Europe were established at Meissen, Germany in 1715 and
2.

Sèvres, France in 1756.

1.1 Composition of Porcelain

Natural ceramics consist largely of quartz, silicates, aluminosilicates and mineral compounds of oxygen. It is the chemical composition and crystalline structure of these constituents which provides the physical properties. The traditional triaxial white wares, such as: artware, tableware, hotel china, electrical and dental porcelain, are essentially mixtures of equal parts quartz (a crystalline refractory), feldspar (a flux providing the glassy phase) and clay (plastic and finely grained).

(a) Quartz

Quartz is silica in its free state and is one of the three crystalline forms of silica. Quartz is stable at all temperatures up to $870^\circ\text{C}$, Tridymite is stable in the temperature range $870^\circ\text{C}$–$1470^\circ\text{C}$ and Cristobalite is stable from $1470^\circ\text{C}$ to its melting point $1728^\circ\text{C}$. Above this temperature the melt is stable and if cooled rapidly below $1728^\circ\text{C}$, it retains its amorphous condition and forms silica glass. Silica Glass has the largest internal energy content of all forms of silica (Salmang, 1961, p. 161).

Each of the three crystalline forms of silica exist in more than one modification, which are temperature dependent. Reversible transformations occur almost instantaneously when the inversion temperature is attained, without reconstruction of the lattice and with minor changes in the crystal glass. These are referred to as alpha (high inversion) and beta (low inversion) (Lee, 1961, p. 13).
3.

The inversion of quartz takes place at 573°C and this is of practical significance in dental porcelain. Grain size of quartz has a great influence on thermal expansion and contraction of ceramic ware; quartz with a fine grain size has a greater effect than coarse grain size quartz (Russell and Weisz, 1944). Southan (1968, p. 230) describes cracks resembling microfissures in the glassy matrix associated with quartz particles.

(b) Feldspars

The feldspars are widely used as raw materials in the whiteware, enamel, glass and abrasive industries.

Feldspar and Nepheline Syenite are commonly used fluxes which provide the glassy phase in ceramic bodies. As a melt, the liquid medium facilitates the diffusion process and aids the consolidation and formation of a non-porous body (Budinkov and Gevorkyan, 1953).

The principal components of natural feldspars are soda feldspar (Na₂O·Al₂O₃·6SiO₂ or NaAlSi₃O₈), potash feldspar (K₂O·Al₂O₃·6SiO₂), and lime feldspar (CaO·Al₂O₃·2SiO₂ or CaAl₂Si₂O₈). Nepheline Syenite, extensively used in white wares and other ceramic products, is comprised of about 50 per cent soda feldspar (albite), 25 per cent potash (Microcline), and 25 per cent of the feldspathoid, nepheline (Na₂O·Al₂O₃·2SiO₂ or Na₂Al₂Si₂O₈) (Lee, 1961, p. 16).

Commercial feldspars are found in pegmatite minerals along with quartz and are commonly intermediate in composition since the pure minerals do not occur in nature in sufficient commercial quantities (Lee 1961, p. 16). The principal accessory minerals are quartz, mica.
and other silicates, while iron oxide and other impurities in small amounts are common (Geller and Creamer, 1931).

Other than structural factors, the use of feldspars in ceramics is governed by their alkali, and accessory mineral content. The presence of alkalies controls the softening point of a feldspar which becomes lower as the soda content increases and the potassium content decreases. (Kingery, 1965, p. 26). Quartz is particularly undesirable as it is difficult to distinguish visually from the crystalline feldspar and it decreases the fluxing power. In amounts in excess of 10 per cent it raises the melting point but yields a more fluid melt. (Kingery, 1963, p. 424).

Dental porcelain contains a very high percentage of feldspar or nepheline syenite. Nepheline syenite begins to sinter at 945°C and is vitreous at 1135°C (Lee, 1961, p. 19). It deforms at 1190°C and has a longer firing range and is a more active flux than feldspars. The soda feldspars are preferred by glass manufacturers because of their lower melting point.

(c) Clays

Clay is a general term for naturally occurring mineral aggregates consisting essentially of the hydrous silicate of alumina (Lee, 1963, p. 8). They vary over quite wide limits in chemical, mineralogical, and physical characteristics. A common characteristic is their layer-lattice structure (Kingery, 1963, p. 18). They are all composed of electrically neutral or negative aluminosilicate layers which, when associated with water, provide for their plasticity (Salmang, 1961,
5.

pp. 26 and 58).

The mechanism of clay formation is, imperfectly understood, the geologists hold the view that clay minerals are of secondary geologic origin; that is, they were formed as alteration products of alumino-silicate rocks in an environment in which water is present (Kingery, 1963, p. 18). Chemists believe that clay is formed from solutions and this may explain the formation of finely grained, colloidal, sedimentary clays.

Clay serves various functions as a binder and as a suspension aid (Lee 1961, p. 8), its plasticity is basic to many of the ceramic forming processes commonly used. Dried clay wares lose their plasticity only to gain fair mechanical strength, enabling them to be fired into dense and strong articles without loss of shape (Kingery 1963, p. 18).

The most common clay minerals may be classified on the basis of crystallographic structure into the kaolinite group, montmorillonite group, and the illite (hydrous mica) group (Kingery, 1963, p. 19).

The nature of the clay is determined for the most part by the chemical composition of the parent rock and the various weathering conditions. The pH of the environment is especially significant, kaolinite is characteristically formed in neutral or acid environments and montmorillonite forms most readily in a neutral or slightly alkaline environment (Kingery 1963, p. 19).

Clays are identified by their sources and are classified by their general functional uses (Lee, 1961, p. 9). The kaolins, which
include china clay, are white and burn white because of their relatively high purity. They produce the most translucent grades of chinaware.

Other clays are commonly characterised by the presence of organic matter, high plasticity, high dry strength, long vitrification range, and natural colours when fired. They are used in all types of whiteware except in the finest chinaware. (Lee, 1961, p. 9).
2. DENTAL PORCELAIN

In 1774, Duchateau, a French Chemist, conceived the idea of making porcelain teeth as an alternative to the ivory and bone replacements for natural teeth. However, it was the French dentist, Dr. Du Bois de Chémant who eventually succeeded in producing porcelain teeth and securing a patent for the sole rights to manufacture mineral teeth (Capon, 1927).

Undoubtedly, Duchateau and de Chémant obtained their ideas, and knowledge of manufacturing porcelain ware from Sévres. Dr. de Chémant later introduced pigments into porcelain teeth for shading, and considered methods of manufacturing dentures entirely from porcelain.

In 1808, an Italian dentist Guiseppangelo Fonzi invented platinum pins for anchorage of porcelain teeth. That same year Dubois Foucou, who had been studying the colour problem in porcelain published his results. Porcelain teeth were opaque and similar to other whitewares until 1838, when Elias Wildman formulated a more translucent porcelain, in colours approaching those of natural teeth (Clark, 1939).

In 1887 Charles H. Land burnished ribbon platinum into a prepared cavity to form a matrix and fused porcelain into it (Capon 1927). Land, not only conceived the principle of using platinum foil as a matrix material, but also designed the various restorations made possible by its use (Clark 1939). Land patented his dental porcelain jacket crown in the U.S.A. in 1889 (Lehman 1967).
The "Land crown", described by Dr. Capon in 1920, consisted of a frame, or sheath, of platinum covering the prepared tooth with a porcelain veneer fused to the labial surface, leaving the lingual surface exposed. The whole structure was cemented into place. In 1902 Land modified his method to provide the all porcelain crown by precisely the same method used today (Clark 1939). The next significant advancement came in 1947 when the Dentists' Supply Co. of New York invented vacuum firing of porcelain teeth, greatly increasing translucency and density. (Lee, p. 79, 1961).

Although modern dental porcelain is a biologically and aesthetically desirable material, its low strength limits its use in dental restorations. Dispersion strengthening of dental porcelain by the addition of alumina crystals was suggested by McLean and Hughes in 1965. The opacity of porcelain is greatly increased by the use of this method.

In 1970 Southan described a method of strengthening modern dental porcelain by ion exchange, observing a greatly increased modulus of rupture.

2.1 Composition of Dental Porcelain

The aesthetics of modern dentistry demand the use of materials which imitate natural tooth enamel. For this purpose, the highly vitreous dental porcelains equal, or in most cases, excel other restorative materials of today. The wear resistance and chemical inertness are known by clinical experience alone to be excellent.

Although the properties of porcelain require very exacting
techniques to meet modern standards, leading clinicians have gradually developed ceramics into an important branch of restorative dentistry. Owing to its relatively poor tensile strength, porcelain sometimes fails as a dental restorative material and its successful use often depends on reinforcement by a metal structure as in the case of the porcelain fused-to-metal restoration.

The methods of fabricating dental restorations which resemble living tooth structure are unique among ceramic practices, while the requirements for forming, firing and final properties, have undoubtedly been responsible for the evolution of today's porcelain.

Conventional dental porcelains have been constituted from feldspar, quartz and kaolin. Since the mid 1940's the trend has been towards the lower fusing compositions (Bartels, 1963).

The principal raw materials used in the composition of dental porcelain are potash feldspar \( \text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \) or nepheline syenite with a small addition of white clay known as kaolin \( \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O} \) and silica \( \text{SiO}_2 \) as quartz (Lee, 1961, p. 71). As only small and simple shapes are involved, the clay content is considerably reduced. The reduced clay content provides increased translucency by restricting the formation of mullite crystals, which have a refractive index differing greatly from the glassy matrix. The quartz content and its crystal sizes must also be regulated to control translucency and thermal expansion (Lee, 1961, p. 71).

Hodson (1957, 1959(b)) investigated 12 porcelain powders including high-, medium- and low-firing varieties of the body, opaque,
translucent, and enamel types. She established that the principal phases were feldspar, quartz and glass. The high-fusing powder was composed principally of feldspar and the medium- and low-fusing powders were glasses which contained feldspar minerals. The absence of clay or kaolin in the powders was verified through X-ray diffraction analysis and quartz was present only in small quantities.

Southan (1968, p. 198) examined fourteen dental porcelain powders and found all contained amorphous frit and birefringent particles. The birefringent particles represented either quartz or alumina. Quartz was either displayed in frit particles or free, the alumina appeared to be supplied simply mixed with the fritted powder. No crystalline feldspar or feldspathoid was evident, nor was there evidence of mullite needle formation.

It is obvious that dental porcelains can be supplied in fritted or unfritted forms or mixtures of both (Lee 1961, p. 73). A frit is a glass that has been melted, quenched, and ground into desired fineness. The fritted dental porcelain offers the following advantages:

1. Melting temperatures are standardized and controlled by the formulation of the frit glass.

2. Firing schedules are shortened because the majority of thermal reactions occur in the preparation of the frit, and dental firing consists primarily of re-fusing the glass particles.

3. The absence of hydrous minerals such as clay, reduces
drying shrinkage and shortens drying time.

The disadvantages of a fritted dental porcelain are, the
difficulties of forming dental structures and the lack of dry strength
(Hodson, 1959, b).

The recommended firing temperatures of various dental porcelain
powders is dependent upon the percentages of ingredients used and
their previous treatment. High-fusing materials are mostly unfritted
(Lee 1961, p. 73).

The auxiliary materials in dental porcelain include aluminium
oxide, tin oxide and zirconium oxide to develop opacity. Borax,
boric acid, sodium carbonate, flourspar, lithium carbonate and
zinc carbonate and zinc oxide are used as fluxes. The metallic oxides
of titania (TiO₂), iron (Fe₂O₃), copper (CuO), nickel (NiO), cobalt
(CoO), uranium (U₃O₈), and manufactured pigments of different colours,
are used for colouring the dental porcelains (Lee 1961, p. 72). Colour-
ing particles were observed by Hodson (1959, b) in body and opaque
porcelains. Pigments used for shading porcelain teeth are concentrated
colour frits, made of the enamel composition, and very finely ground
(Lee 1961, p. 74).

A typical formula for fritted enamel and body porcelain powders
as supplied by Lee (1961, p. 74) is:
<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Enamel %</th>
<th>Body %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feldspar</td>
<td>95.0</td>
<td>90.0</td>
</tr>
<tr>
<td>Calcined Kaolin</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Silica</td>
<td>2.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Colour frits would be added where necessary.

Southan (1968, p. 234) found sodium and potassium to be significant constituents of the porcelain powders and regards the vitreous frit as representing a sodium-potassium aluminosilicate glass.

McLean (1967) experimented with the reinforcement of pigmented glasses with aluminium oxide ($\text{Al}_2\text{O}_3$) for use in the fabrication of jacket crowns. When used as a reinforcing agent, alumina bonds chemically with the porcelain or glass.

The manufacture of dental porcelain has been and continues to be a highly specialized industry. Methods of manufacture and specific knowledge of the field have been closely guarded by the manufacturers.
THE MANIPULATION OF DENTAL PORCELAIN

3.1 The Forming Process

The material is supplied as a dry powder of suitable composition which is mixed with a mobile liquid, usually distilled water, to form a mix of variable viscosity. Although other vehicles such as alcohol and glycol (Sayer, 1938) have been tried, water with its low viscosity and high surface tension, is the most suitable medium. The consistency of the thin paste is maintained during the forming process.

A porcelain crown is formed by moulding the paste over a platinum foil matrix. The required shade is obtained by applying porcelain powders of various colours in layers, considerable artistic ability is required to blend the colours while shaping the porcelain. The unfired crown is carved oversize to allow for shrinkage during firing.

Denture teeth are formed in flexible Korogel moulds by a vibration process, or pressure moulded and biscuited at 350°F in two piece brass moulds. The densely packed tooth forms are then separated from the moulds and fired on trays bedded with silica (Lee, 1961, p. 75).

3.2 Test Specimen Formation

It is important for a test specimen of a material to be representative and reproducible, as any test measures only the properties of the test piece. Unfortunately some workers in the ceramic field have failed to give adequate details of their test
material.

In 1932, Gill carried out his investigations on specimens measuring 13 mm. x 10 mm. x 4 mm, without describing their formation. Felcher (1934) described his split irridio-platinum ferrule for specimen production, but did not give its dimensions. In 1938, Skinner and Fitzgerald used rectangular specimens, 19.88 mm. x 9.00 mm. x 3.96 mm, formed in removable glass slabs set in hydrocal blocks. A standardized, wet vibration of condensation produced bodies which were fired on platinum foil in a dental furnace. Sayer (1938), used a cylindrical split mould 10 mm. high and 6 mm. in diameter, and a glass lined mould with removable walls 31 mm. x 5 mm. x 5 mm. The test pieces were fired on 0.001" platinum foil. A flat rectangular specimen from a metal mould was used by Klaffenbach (1939). Sacchi and Paffenbarger (1957) used a metal cylindrical mould 7 mm. x 4 mm. for the measurement of volumetric shrinkage and compressive strength.

In 1959, Hodson produced disks from a mould 6.5 mm. in diameter and 3 mm. deep and bars 1½" x 3/16", from a rubbery mould. Specimens were fired on platinum foil and fine silex. McLean and Hughes (1965) were the first to seriously attempt to eliminate variables in specimen manufacturing. Rods were formed by compacting weighed quantities into a ½" diameter steel die at a pressure of 14.5 tons per square inch. Bars were produced by wet vibration into a square-section split steel mould, 30 mm. x 5 mm. x 5 mm. The dimensions of the mould used to produce disks were not provided. All the specimens were fired on a tray of ¼" thick asbestos sheeting impregnated with
20 micron calcined alumina. Southan (1969) produced test specimens based on his observations of a typical porcelain jacket crown. The coronal specimen was reproduced from a cobalt-chromium mould with a calculated volume of 0.364 ml. Three mould shapes were constructed with the same volume, two rectangular and one cylindrical. One rectangular specimen had an unfired dimension 6 mm. x 6 mm. x 10 mm. and resembled the bulky sections of the crown. The other rectangular specimen was thin and wafer like with unfired dimensions 3 mm. x 10 mm. x 12 mm. The cylindrical specimen before firing was 7 mm. high and 8.08 mm. in diameter, this specimen was used for a diametral-compression test.

3.3 Condensation

Working the porcelain mix so that the particles are close together is known as condensation. The object of condensation is to obtain a dense homogeneous mass by elimination of the maximum amount of water without weakening the condensed mass of porcelain. Baker (1960) describes the movement of particles over one another under gravitational force by induced instrumental agitation. Water rising to the surface during condensation is blotted away.

The methods used to condense dental porcelain are:

(i) Hand vibration without a mould or into a mould,
(ii) spatulation or ironing,
(iii) whipping,
(iv) mechanical vibration into a mould.

Wet vibration into a mould gives uniform structure with only a few
voids, while condensation by whipping and spatulation methods showed many voids and lack of uniformity (Gill 1932, Clark 1935 and Baker 1960).

Good condensation may be achieved by proper water control and a combination of the various techniques of condensation. When vibrating dental porcelain into a mould, the shape of the mould appears to regulate particle orientation and directional shrinkage during firing (Southan 1968, p. 255).

After condensation the green article has little or no strength, the fritted porcelain powders rely on selected particle sizes or organic binders to assist in the forming process.

3.4 Firing

Modern dental porcelains are generally of the low-fusing variety, requiring short firing cycles. Fritting simplifies the sintering process and vitrification occurs through the natural softening of the glass (Goodyear and Russel 1966). The changes make it possible to fire porcelain jacket crowns and inlays in muffles wound with base metal alloys as opposed to the expensive platinum wound muffles required to fire unfritted compositions (Skinner and Phillips, 1960, p. 529). Firing of dental porcelain is usually carried out in air (Atmospheric) or vacuum (low pressure).

Skinner and Phillips (1967, p. 530) refer to three stages in the firing of dental porcelain; low, medium and high bisque (or biscuit). Southan (1968, p. 66) regards the sintering of fritted dental porcelain powders as a relatively simple process and describes
two stages, which are readily detectable and applicable to air and low pressure firing techniques; viz.,

(i) the absorbent stage and

(ii) the impervious or vitrified stage.

The sintering rate is dependent on the bulk of the ware, the powder particle sizes and composition, the degree of condensation, the temperature and time.

Dental restorations are formed by adding successive layers of porcelain which are fired at temperatures below glazing temperature. The lower temperatures are used until the desired form is achieved. Traditionally, glazing has occupied its place in the stages of firing, the rate of development of such a surface condition depends also on the surface smoothness of the ware (Southan, 1968, p. 66). The terms gloss and smoothness have been used to describe the degree of glass or fire finishing (Russell and Rowlands 1953 (a)).

Vitrification may be regarded as a process of partial fusion (Lehman, 1967). Goodyear and Russel (1966) define body vitrification as being directly related to the amount of glass present and inversely to its tendency to devitrify during firing.

Overfiring of the article results in rounding, or loss of form and decreases colour stability. The development of gases from feldspar decomposition (Lehman, 1967, Hodson, 1959 (a), Sayre, 1944 and Clark-1935), is minimal with fritted powders owing to the careful selection and homogenisation of the raw feldspars.

Because of the small dimensions of dental articles, rapid
removal from the furnace is possible. However, it is advisable to slowly cool a fired crown under a small pyrex dish. McLean and Hughes (1965) found aluminous dental porcelains, to be particularly resistant to thermal shock on rapid cooling from furnace temperatures.
4. PHYSICAL PROPERTIES OF DENTAL PORCELAIN

4.1 Shrinkage and Porosity

A shrinkage of up to 40% may be expected during the firing of dental porcelain (Lehman, 1967). Condensation is closely related to the firing shrinkage and under identical conditions, poorly condensed articles shrink most (Southan, 1968, p. 238).

Green ware may contain between 25 and 50 volume per cent porosity (Kingery, 1963, p. 395). A fractional void space of about 25 per cent can be reached when a selected particle size distribution provides optimal packing (Hodson, 1959 (a)).

Clark (1935) reported that dental porcelains with a high fraction of small particle sizes, showed a tendency to shrink more during firing. In 1938, Skinner and Fitzgerald found low-fusing porcelains to shrink more than high-fusing. Hodson (1959 (a)) found the low-fusing porcelains she tested to have the highest shrinkage of all firings.

Vacuum firing can produce almost complete densification and very high translucency. All things being equal, the firing shrinkage must be greater. Southan (1968, p. 241) by varying the type of condensation, found the percentage volumetric firing shrinkage to range between 34.7 per cent and 37.3 per cent for air fired and 36 per cent and 40.5 per cent for vacuum fired porcelain.

Internal voids have been attributed to (Vines et al, 1958):

(i) the inclusion of air in the slip;
(ii) muffle atmosphere replacing binder or
20.

water in the interstices of the green ware;

(iii) evolution of gas from a variety of sources,

and

(iv) overfiring.

They concluded that mixed, selected particle sizes result in both maximum density and minimum firing shrinkage.

McLean and Hughes (1965) using aluminous porcelain (40% alumina), found the porosity of green compacts to average 43.8 per cent. Air fired specimens averaged 11.9 per cent porosity while vacuum firing reduced the porosity to 5.4 per cent. The authors claim pyroplastic flow is reduced by the addition of alumina.

4.2 Thermal Expansion and Transformation Region

Low thermal expansion is one of the most valued properties of porcelain and is a major factor in the ability of porcelain to resist thermal shock during fabrication or grinding (Salmang, 1961, p. 339).

The coefficient is strongly affected by the ratio of $K_2O:Na_2O$ and uncombined quartz present. Increases in the alkali content reduce the effect of quartz, tending to give a regular expansion (Rado and Edgar, 1960). Vitreous bodies containing high soda feldspars have the highest thermal expansion (Geller and Creamer, 1931). Sacchi and Paffenbarger (1957) found the coefficient of thermal expansion of typical porcelains (30 to 400°C), to be from $6.4 \times 10^{-6}/°C$ for high-fusing and $7.8 \times 10^{-6}/°C$ for a low-fusing porcelain. This was confirmed in 1965 by McLean and Hughes.

The effect of strain in individual quartz grains on the
mechanical strength of bodies is not known. Smothers (1961) established the following:

(1) Wet grinding creates appreciably less strain in quartz grains enclosed in the glassy matrix than does dry grinding,

(2) Refiring under such conditions does not seem to relieve all strain which may be created in quartz grains by dry grinding.

Southan (1968, p. 269) studied the linear thermal expansion of two modern dental porcelains in order to estimate the transformation temperatures of their vitreous phases. In all tests the cooling curves differed from heating curves in character.

Due to the polymorphic transformation of quartz at, and above 573°C, the closer the vitreous phase transformation region lies to that temperature, the less chance there would be of microstresses and microcracks developing. Alumina has a thermal coefficient of expansion and contraction closer to that of a selected vitreous matrix than quartz.

4.3 The Strength of Dental Porcelain

Ceramic materials with good mechanical strength are usually crystalline in structure and opaque to light. Conversely, dental porcelains that are translucent enough to resemble human tooth enamel are predominantly glass in structure and consequently exhibit the physical properties of glass, characterised by lower resistance to the impact forces.
As with glass, there does seem good reason to believe that rupture occurs in modern dental porcelain only under tension, generally at a surface. But, there appears to be no justification for assuming that the value of this tensile strength will be independent of stresses operating in other directions (Southan, 1968, p. 277).

The result of a strength measurement will depend on any change in the conditions affecting the material as a whole, such as humidity or rate of loading (Black, 1936, Smothers, 1958 and Shevlin and Lindenthal, 1959).

(i) Transverse strength or modulus of rupture

Skinner and Fitzgerald (1938) investigated the transverse strength of high-, medium- and low-fusing dental porcelain with test specimens measuring 19.88 mm. x 9.00 mm. x 3.96 mm. The results ranged from 3,700 to 8,300 p.s.i. with an average of 7,200 p.s.i.

In 1939, Sartori tested high-fusing porcelain specimens formed in a glass-lined mould, 20.63 mm. x 10.53 mm. x 7.17 mm. He found transverse strength to increase to 9,200 p.s.i. after two firings and decrease these after to 6,900 p.s.i. on the eighth firing. Sartori attributed these results to inherent strains set up during cooling and found that veneer glazing with a lower fusing ceramic coating increased the strength to 10,400 p.s.i. While Sartori attributed the increased strength to the relief of stresses by annealing, Russell and Rowlands (1953 (b)) say the strengthening effect results from the development of a compressed glaze layer.
Moldal (1939) using test specimens with dimensions 20.340 mm. x 10.310 mm. x 5.882 mm. constructed from two high-fusing and one low-fusing opaque porcelain recorded values ranging from 8,300 to 10,400 p.s.i.

Sayer (1938) used high-fusing specimens measuring 31 mm. x 5 mm. x 5 mm. before firing. His results ranged from 4,200 to 8,400 p.s.i. and he found the greater the firing shrinkage the less the transverse strength tended to be.

Hodson (1959 (a)) carried out transverse testing on porcelain bars measuring 1\(\frac{1}{2}\)" x 3/16" before firing. She rejected individual values that exceeded the average by plus or minus 15 per cent. The strength of two porcelains was reduced by removing the surface glaze. Strength values ranged between 8,290 and 9,164 p.s.i. and appeared to be independent of porosity although the porcelain with the greatest porosity tended to be the weakest.

In 1965 McLean and Hughes quoted the modulus of rupture of a typical porcelain to be between 3,700 to 12,000 p.s.i. and recrystallized alumina to be 55,000 p.s.i. Aluminous porcelain bars (40 per cent alumina) measuring 30 mm. x 5 mm. x 5 mm. before firing, gave an increased modulus of rupture when porosity was decreased. The modulus of rupture of aluminous porcelain was quoted as being in excess of 18,500 p.s.i.

McLean and Hughes found the strength of dental porcelain to fall dramatically when the surface of the test specimens was ground. The results show that the aluminous rods (glazed were not significantly
stronger than the porcelain rods (glazed) but significantly stronger in the ground condition. Tests carried out on nine ground bar specimens of air-fired, low-fusing porcelain, produced a mean of 10,291 p.s.i. with a standard deviation of 591 p.s.i. Ten ground, aluminous porcelain, low-fusing, air-fired samples appeared as 14,979 ± 876 p.s.i.

The measured values of tensile strength for a brittle material often differ considerably from those obtained from the direct tension test (Milligan, 1953; Berenbaum and Brodie, 1959).

Southan (1968, p. 291) employed the bend test with a system of three-point loading consisting of a brass pad with rounded steel supporting rods 0.25 inches apart at their centres and a Brinell ball (5 mm. diam.) as the loading 'head' centred at mid-span. This compression attachment was assembled into a Hounsfield Tensometer.

Two types of rectangular test specimens were formed in moulds measuring, 6 mm. x 6 mm. x 10 mm. (mould A) and 3 mm. x 10 mm. x 12 mm. (mould B). The specimens were fired for four minutes and their surfaces abraded on 220-A silicon carbide paper. Groups of specimens were chemically strengthened by low-temperature ionic exchange using molten potassium nitrate, potassium ions replace the smaller sodium network - modifying ions in the vitreous matrix (Southan, 1968, p. 297). The values for modulus of rupture calculated for some of the different materials were similar and strength appeared to be little affected by porosity.
Southan concluded that differences gained when testing different materials made from mould (A), were minimized when mould (B) was employed, because of the magnification of other factors. The involvement of serious surface flaws, due to the increased area under tensile stress is one; an increase in the possibility of a mean free path of glassy phase, due to the thinness of the specimens, could be another. The effect of the chemical preferential pre-stressing on thin specimens (mould B) was marked, the average increase in the modulus of rupture was about 122%.

(ii) Compressive Strength

Compression tests on dental porcelain were carried out by Sacchi and Paffenbarger (1957) on specimens measuring 7 mm. high and 4 mm. in diameter. For each test an average of five readings produced identical results of 48,000 p.s.i. for low- and high-fusing porcelain.

(iii) Diametral Compressive Strength

Southan (1968, p. 318) investigated the diametral compressive strength of dental porcelain using a test specimen 7 mm. high and 8.08 mm. in diameter before firing in air or vacuum for four minutes. One series of specimens were abraded at the ends, vacuum-fire-finished for three minutes and chilled to room temperature. Another series were preferentially pre-stressed chemically as sintered and the third group of specimens were tested in the as-fired condition.
The rate of loading approached 2,000 lb/in$^2$/mm, and a triple-cleft type of fracture was common amongst the stronger samples. The results, like those of the bend test, showed no significant differences in strength of the air- and vacuum-fired porcelains tested. Although the aluminous could not be shown to be significantly stronger than a non-aluminous porcelain, the chemically treated groups were.

Southan concluded that for practical purposes this test is not of great value in measuring the increase in practical strength gained from aluminous porcelains as demonstrated in transverse testing.

(iv) Impact Strength

Although the modulus of rupture test has been accepted by most workers to approximate the forces experienced by porcelain crowns in the mouth (Pitt, Roche, 1949), Hodson (1959 (a)) believes that impact forces are the most significant forces acting on dental restorations.

Fox et al (1960) and Kulp et al (1961) realising that there is no reliable method of measuring the impact strength of ceramic materials, developed a highly empirical impact test. Symmetrically shaped conical porcelain specimens were subjected to weights of known hardness dropped down a vertical chute. They found that vacuum-fired porcelain yielded 50 to 117 per cent higher impact strength readings than air-fired porcelains. Like Pettrow (1961)
they attributed these findings to the higher density of vacuum-fired porcelain.

It is claimed by McLean and Hughes (1965) that aluminous dental porcelains have a considerable resistance to impact and thermal shock.

Southan (1968, p. 323) in order to study the behaviour of modern dental porcelains under dynamic loading, designed a specialized drop-ball impact machine. The identical three-point loading system used in his bend tests was incorporated into the machine. Rectangular test specimens from moulds (A) and (B) (See p. 15) were used and a steel ball weighing 44.6 gm. was selected to deliver the impact. For mould (A) samples, impacts began at 15 cm. and for mould (B), at 4 cm. with height increments of 0.5 cm. between each release.

The equation described by Roark (1965, p. 371) was applied.

$$K = \frac{1 + \frac{17}{35} \frac{M_1}{M} + \frac{M_2}{M}}{(1 + \frac{5}{8} \frac{M_1}{M} + \frac{M_2}{M})^2}$$

Southan concluded that his method of impact testing modern dental porcelain was of some value. The dispersion-strengthened porcelains showed a marked ability to absorb energy, but in thin sections the chemically strengthened porcelain was the toughest.
GLASS

Dental porcelains may be classified as glass-crystal composites. The predominant phase is the glass matrix which provides the basis for high translucency and relative homogeneity so necessary in dental restorations (Southan, 1970a).

5.1 The Nature of the Glassy State

McMillan (1964, p. 7) defines glass as an inorganic product of fusion which has cooled to a rigid condition without crystallizing.

To describe a substance as being in the glassy state, it must be an undercooled liquid and have taken on its properties of a solid simply by being cooled down from a fused condition (Warren, 1942). The permeability of glass to small particles, such as sodium ions, indicates its "open" liquid-like structure (Johnson et al, 1951).

Glass forming materials are ones in which there is sufficient bonding in the melt to produce a highly viscous liquid. The high viscosity produced by transient bonding prevents the atomic rearrangement, necessary for crystallization, when the liquid is brought down to temperatures at which the free energy of the crystalline phase would be lower than that of the randomly bonded structure (Warren, 1942).

Thus the glassy state is continuous with the liquid state and is distinguished from the normal liquid state by the high magnitude of the viscosity. Liquids, unlike gases, are not structureless and
x-ray diffraction measurements show a certain degree of regularity. The atomic or molecular units of structure in a liquid are the same as in the crystalline solid but not arranged in a regular manner. The liquid has short-range order but not long-range order whereas the crystalline solid possesses both short-range and long-range order, leading to complete regularity throughout the solid (McMillan, 1964, p. 8).

Warren (1934) found the x-ray diffraction pattern of glass virtually indistinguishable from that given by a liquid, both being amorphous forms of matter. However, there is a structural difference, each atom in glass has permanent neighbours at a fairly definite distance, while in a liquid the neighbours about any atom are continually changing.

A strong but highly flexible scheme of bonding is necessary for glass-forming ability. In vitreous silica, each silicon is bonded tetrahedrally to four oxygens and each oxygen is bonded to two silicons. The bonding is so flexible that it is possible to build up a random, non-repeating network, whose energy is not much higher than that of the crystalline forms of silica (Warren, 1942). Figure 1 illustrates schematically in two dimensions the regularly repeating structure of a crystal as distinguished from the irregular structure of a glass.

Zachariasen (1932) pointed out that the ability of an oxide
Fig. 1: Schematic two-dimensional figures to illustrate the difference between the regularly repeating structure of a crystal (a) and the random network of a glass (b).
Fig. 1.
to form a tetrahedral configuration, could not be an absolute
criterion of glass-forming ability since the radius ratio for BeO,
for example, will permit oxygen ions to form tetrahedral groupings
around the beryllium ion, yet this oxide cannot be obtained in the
glassy state. Zachariasen used as a basis the established laws
of crystal chemistry to predict the random network structure of
glass.

The present picture of the atomic arrangements in glass has
developed from the laws of crystal chemistry, the x-ray diffraction
study of glass, the various measured physical properties of glass
and the kinds of materials and ranges of composition in which glass
forming properties exist (Warren, 1942).

5.2 The Structure of Silicate Glasses

Vitreous silica (fused quartz) is one of the simplest and
commonest glasses. The basic structural unit is a silicon-oxygen
tetrahedron with a silicon atom at its centre and oxygen atoms
at the four vertices. This tetrahedral unit is believed to be
almost regular, with each of the six oxygen-silicon-oxygen angles
being close to $109^\circ$ and the silicon-oxygen distances varying
by no more than a few per cent from their mean value of 1.62 angstroms
(Dean and Bell, 1970).

There are two kinds of oxygens, those bonded to two silicons
and those bonded to only one silicon. The sodium ions are situated
at random in the holes in the silicon-oxygen network, each sodium
ion having approximately six oxygens as immediate neighbours. Figure 2 is a two-dimensional schematic representation of a soda-silica glass.

A glass may be regarded as a collection of ions, some positively and others negatively charged (Ainsworth, 1954). In $\text{Si}_4\text{O}_4$ tetrahedra, the valencies of the central ions $\text{Si}^{4+}$, are completely saturated by their bonds to oxygen, but each oxygen has one valency free. This radical may be regarded as a $(\text{SiO})^{4-}$ anion (Weyl, 1946; Johnson and Bristow, 1951). Thus the joining of $\text{Si}_4\text{O}_4$ tetrahedrons is accomplished through free oxygen valencies.

Zachariasen (1932) regarded commercial glasses as resulting from the accommodation of non-glass-forming cations (network modifiers) in holes in the $\text{Si}_4\text{O}_4$ network, the dimensions of the holes are determined by the size of the cations occupying them.

The distinction between network-forming and network modifying cations is based on the different strengths of their electric fields (Weyl, 1946). Apparently, monovalent network-modifying ions fit into the structure as best they can. Large size and small charge is demanded of network-modifying cations as small and highly charged cations will tend to produce devitrification. (Zachariasen, 1932).

5.3 Aluminosilicate glasses

These are a group of glasses which contain approximately 20 to 25 per cent alumina (Skinner and Wilson, 1934) and characterised by their high softening temperatures.
Fig. 2: A two-dimensional model of the atomic arrangement in a soda glass. The oxygen-silicon ratio is greater than two, due to the oxygen introduced by the Na₂O. It is impossible for every oxygen ion to be bonded to two silicons. Hence, there are two kinds of oxygens; those bonded to two silicons and those bonded to only one silicon.

This model can also be considered to represent, in a simplified fashion, the structure of the multi-component glasses (Warren, 1942).
Fig. 2.
The aluminium ion in crystals can be four or six co-ordinated with oxygen to give rise to tetrahedral AlO₄ or Octahedral AlO₆ groups. The AlO₄ can replace the SiO₄ in silicate lattices (Warren, 1942). In small amounts, Al³⁺ can replace Si⁴⁺ in vitreous structures (Stafford and Silverman, 1947), forming AlO₄ tetrahedra with dimensions approximating those of SiO₄ tetrahedra. The AlO₄ tetrahedra is the characteristic structural unit in aluminosilicate glasses.

Southan (1968, p. 231) following an analysis of sodium and potassium in dental porcelain, concluded that sodium is present in more than negligible amounts, while potassium also constitutes a significant proportion of the powders makeup. He regards the vitreous frit as representing a sodium-potassium aluminosilicate glass.
6.

THE STRENGTH OF GLASS

The application of glass is generally limited by its reputation for unreliable mechanical strength, whereas glasses of good quality are fundamentally high strength materials (Shaver, 1964). Glass is distinguished from most other materials by its excessive brittleness and characteristic conchoidal fracture.

6.1 Britleness

The concept of brittleness is of itself a complex one, not easily defined in rigorous terms. The fundamental physical factors involved are, the presence of a relatively high elasticity, a fair to high tensile strength and a complete absence of plasticity or ability to store energy or dissipate it by plastic flow (Preston, 1942).

Flow in response to shearing stresses is no longer possible when viscosity becomes infinite, by exceeding something like $10^{15}$ poises. At temperatures where the viscosity of glass is negligible, macroscopic deformation is insignificant under most forms of loading. Glass will break in response to tensile stress before it flows (Ainsworth, 1954) and at right angles to the maximum tension (Preston, 1931).

Fortunately brittleness is not synonymous with weakness and the theoretical estimates of the strength of glass result in values from $1 \times 10^6$ p.s.i. to $5 \times 10^6$ p.s.i. (Ritter, 1968). In practice, strengths of bulk glass in excess of $7 \times 10^3$ p.s.i. are seldom
realised, if they are it is because of additional process treatment (Sugarman, 1967). It becomes necessary then to explain not the strength of glass, but rather the weakness.

6.2 The Flaw Theory

Griffith (1920) proposed that microcracks or small flaws exist at the surface of glass. He explained the discrepancy between the theoretical estimated strength of glass and the observed tensile values by equilibrating the rate of decrease of strain energy associated with growth of the flaw under stress to the rate of increase of surface energy. The fracture stress was found to be inversely proportional to the depth of the surface flaw. Orowan (1944) reached the same conclusion and proposed that fracture is due to the stress concentrating action at the tip of a surface flaw. Griffith cracks in glass are estimated to be of the order of $10^{-3}$ cm. long (Gurney, 1946).

Fracture occurs when the applied stress produces a stress at the flaw tip equal to the intrinsic strength of the glass. The observed strength of a specimen of glass is thus the applied tensile stress that will initiate crack propagation at the most severe flaw present in the stressed region. Once started, the extension of the crack is ensured by the applied stress and the increasing stress - concentration factor of the growing crack (Ritter, 1968). In the course of propagation, the crack does not necessarily remain
a single surface, but may fork and become a highly ramifying system of fractures (Preston, 1942).

Since the flaws cannot grow under a compressive stress, the flaw concept also accounts for the fact that glass is extremely strong in compression (Ritter, 1968). There is no evidence to suggest that glass can be broken in compression or in shear, except insofar as these produce accidental or incidental, tensions (Preston, 1942).

The Griffith theory, at least in its essentials, is adopted by most workers in this field.

6.3 Nature and Origin of Surface Damage

Flaws in the surface of glass of a size below 100 Å in width cannot be revealed by conventional optical aids. Although flaws of 10 Å width could produce substantial stress raisers with the attendant loss in strength, electron microscopy has not positively identified such flaws (Sugarman, 1967).

Andrade and Tsien (1937) demonstrated expansion changes and defects in the surface brought about by the sodium-vapour treatment. Ernsberger (1960) used a technique of ion exchange by lithium salts, and concluded that the defects revealed by previous sodium treatments were caused by expansion differences and their real origin was in Griffith flaws.

Levengood (1959) has shown, by a sodium fluoride reaction on a glass surface, that small defects react differently from larger cracks, and that the strength of the article could be correlated
with the number and orientation of the flaws.

The gross surface defects on glass as a result of mechanical contact, certainly explain the drastically reduced strength of glass. However, inherent flaws must be present in virgin glass to reduce its strength to about $3 \times 10^5$ p.s.i. These flaws may be due to surface inclusions and Brearley and Holloway (1963) concluded from detailed examination of the broken surfaces of tensile testpieces, that fracture was due to surface inclusions such as dust particles settled on the surface during the drawing process.

Contamination by atmospheric attack which might yield microcrystalline particles could also conceivably provide the origin of some surface flaws (Sugarman, 1967).

Levengood and Butler (1953) have described the origin of Griffith cracks as due to rapid chilling of the outer layers creating tension enough to cause fractures.

Gurney (1947) is of the opinion that a likely cause of Griffith cracks could be due to tensile stresses set up by non-uniform volumetric changes in the glass as its atoms rearrange themselves so as to approach equilibrium configuration.

6.4 Effect of Surface Damage

It is well known that sheet glass will, under load, withstand higher pressure than plate glass. The principal difference is the state of the surface, plate glass is ground and polished and sheet glass is drawn from the melt and fire finished. Glass weakened
by grinding can be restrengthened as much as four-fold, by fire-
finishing or fire-polishing (Sugarman, 1967).

Jones (1949) found that the experimental variation in
strength results, is always smaller when glass is weakened by the
deliberate introduction of surface flaws. Surface cracks can be
produced mechanically and by chemical attack (Gowan, 1948-49) and
glass may also be strengthened by etching with hydrofluoric acid
under controlled conditions, the effect being to round crevices
(Preston, 1942). However, in uncontrolled conditions, the formation
of insoluble etching products allows preferential etching to
eventually weaken the glass (Bowden and Field, 1964).

Griffith (1920) found thin glass fibres to be very much
stronger than massive glass (dimensions exceeding 0.1 cm. in any
direction), and concluded that the tensile breaking strength of
glass, tested in the form of fibres, was closely dependent upon
diameter and structural orientation. Gurney (1964) believes there
is little evidence of the effect of size on strength of freshly drawn
glass fibres with undamaged surfaces.

Annealing undamaged fibres drastically reduces their high
strength and the electron microscope reveals that the smooth
surfaces of the fibres become quite rough after annealing (Argon et
al, 1960).

Baker and Preston (1946) found specimens thoroughly baked out
and tested in vacuum to be considerably stronger than those tested
in air.

The weakness of glass is not entirely due to surface flaws and the interior of glass is apparently not a great deal stronger than its surface. Jones (1949) has suggested on geometrical grounds that surface flaws can be approximately twice as dangerous as internal flaws of the same shape and orientation.

6.5 Static Fatigue in Glass

An area of great technological importance and scientific interest is the time dependent strength effect, commonly referred to as "static fatigue". In 1899 Grenet observed that the strength of glass depended on the rate of loading or on the length of time a load was applied. Fatigue, or the decrease of breaking stress with increased duration of load, is pronounced for glass under tensile loading (Ritter, 1968).

Glass loaded at a rapid rate or forced to support a given load for a short time is relatively strong. In contrast, glass is relatively weak if the loading rate is slow or if the glass is forced to support a given load for a long time. When Holland and Turner (1940) reduced the load to about one-third of the mean modulus of rupture as determined rapidly, none of the specimens of a batch of 100 fractured in a time of 1,000 hours.

Baker and Preston (1946) found that increasing loading times from milliseconds to hours decreased the strength by some 40%. The effect was more pronounced with wet glass, and zero effect was found for glass baked out and tested in vacuo. These findings were confirmed
by Gurney Pearson (1949), who found also there was no fatigue in dry air or air from which the carbon dioxide had been removed.

It is now generally believed that static fatigue is caused by a stress corrosion reaction between glass and water. Even the small amount of water vapour normally found in the atmosphere is sufficient to cause the breaking stresses for long time load durations to be on the order of 50% of those for short time duration (Ritter, 1968).

Mould and Southwick (1959) produced a universal fatigue curve of the examination of abraded glass samples tested under water. The fatigue rate under tension varied exponentially with the original flaw size, and a limiting strength was claimed. The rate of reaction depends on the roots of small cracks in the surface of the glass and consequently the reaction proceeds at its greatest rate from these roots (Wiederhorn, 1967).

Two stages of crack growth can be visualised, a slow crack motion or propagation resulting from chemical attack at the crack tip and a catastrophic or critical crack motion initiated when the crack is long enough to satisfy the Griffith criterion. The time to failure in a static fatigue experiment is the time required for the crack to grow from subcritical to critical Griffith size (Wiederhorn 1967). Gurney (1945 and 1947) has suggested that the slow spreading of a crack might be a "stress-assisted" approach to thermodynamic equilibrium in the glass at the apex.
6.6 Effect of Moisture

Thus the dominant belief is that static fatigue results from a stress-dependent chemical reaction between water vapour and the surface of the glass. The rate of reaction depends on the state of stress at the surface, the rate increasing with increasing stress (Wiederhorn, 1967).

Stockdale et al (1951) suggested that the reduction in glass strength when specimens were broken under water was due to capillary action with a resultant high pressure within a flaw. They further postulated that reaction products opened a flaw and increased the apex of stress.

Stockdale et al (1951) and Mould (1960) observed that mechanically damaged glass rods that had been stored unstressed in water became stronger. This occurs presumably because of rounding (ageing) of abrasions by solution and precipitation, or in such a way as to reduce stress concentration on loading.

Mould (1960) found the ageing effect depended strongly on the medium in which the specimens were stored. Distilled water proved to be highly effective as an ageing medium, however, in air ageing depended strongly on the relative humidity.

It is possible that strengthening and weakening effects can exist together and the predominance of one over the other may well depend upon the surface condition and the environmental state.
6.7 Effect of Loading Glass

In the past, many of the workers investigating both static and dynamic fatigue effects, have in the main concluded that slow rates of loading yield lower strengths.

The behaviour of glass under dynamic or impact loading appears to depend on the velocity of the impact. Preston (1931) and Haward (1944) found in the case of slow impact, using object much heavier than the specimen, the energy required to break the glass is greater than that required under static conditions. Haward has shown that the initial stresses in a material near the point of impact are not zero, but are proportional to \( \sqrt{EP} \), where \( V \) is the impact velocity, \( E \) the Young's modulus, and \( \rho \) the density. As the velocity of impact is increased the energy required to fracture generally diminishes markedly. In the case of a high velocity impact, stresses are concentrated around the point of impact, and the resulting break follows the lines of compression at right angles to the lines of maximum tension.

Baker and Preston (1946) found that increasing loading times from milliseconds to hours decreased the strength by some 40%. The effect was more pronounced with wet glass. Pranatis (1969) observed that specimens subjected to stepwise loading had considerably higher fracture strength than those brought to their breaking stress immediately and that some process analogous to the "coaxing" noted in metal fatigue was occurring.

Since no structural change can occur in glass prior to fracture,
glass does not fatigue under cyclic loading appreciably faster than it does under static loading. This fatigue behaviour is quite opposite to that of metals where metals are very dependable under static loads, but cyclic loading can cause fatigue failure at relatively low loads (Ritter, 1968).

6.8 Strength Reinforcement of Glass

As discussed previously, the extremely large differential between the theoretical strength of glass and the observed practical strength, is primarily due to the presence of surface defects in which stress corrosion can initiate failure at low tensile stresses.

(a) Thermal toughening

As early as 1892, Schott produced a "cased" glass, wherein the outer skin of glass has a lower coefficient of thermal expansion than the main glass and thus in a state of compression. Similarly, the tensile stress of porcelain can be increased considerably by using a glaze that has a lower coefficient of thermal expansion and consequently is under compressive stress at the surface. This compressive stress must be overcome by an applied tensile load before fracture can start at the glaze surface (Kingery, 1963, p. 606).

Pre-stressed glass products with a high surface compression have an increased practical usable strength. Many present day articles such as windscreens and tumblers, are toughened by being heated to near softening point and rapidly quenched on the outside, usually by air. The process requires uniform compressive stress over the entire
surface which is balanced by a high interior tension. The outer compressed layer must be of sufficient thickness to withstand abrasion.

(b) Chemical toughening

In the literature many chemical methods have been described which can increase the strength of glass. However, of all the techniques tried, the indications are that ionic substitution by larger or smaller ions is the most attractive and practical process.

Effective ion-diffusion processes were first described in the literature by Kistler (1961), who discussed ionic diffusion at temperatures primarily below the glass softening point. If the glass is heat-treated in a potassium nitrate salt bath at temperatures up to about 450°C, then, because of the diffusion into the glass of the larger potassium ion and the diffusion out of the smaller sodium ion, a compressive surface stress results (Sugarman, 1967). Kistler (1961) observed surface compressive stresses of over 100,000 p.s.i.

In patents issued to the Corning Glass works and the Pittsburgh Plate Glass Co., claims are made that potassium ion-diffusion processes have, in conjunction with additional treatments, increased strengths and improved durability and abrasion resistance (Sugarman, 1967). Nordberg et al (1964) found unabraded strength, and its reduction due to abrasion, to depend on both the type of strengthening treatment and the glass composition.

Much of the work done with the ion-diffusion process, indicates that at any temperature of treatment there exists an optimum time
of treatment. The strength increases with temperature of treatment to a point below the transformation range, however, above the optimum, and certainly as the transformation region is reached, a decrease in strength is observed due to stress relaxation.

Exposure to heat of chemically strengthened glass reduces the induced stress, probably by a composition-gradient, induced migration of ions, changing irreversibly the surface composition. (Kerper and Scuderi, 1966).
47.

SUMMARY

The history and composition of the conventional white-ware and dental porcelain has been presented. It is clear that the triaxial white-ware formula, clay/feldspar/quartz, is not sensitive to minor alterations in composition, forming methods and firing temperature.

The development of the modern dental porcelains from traditional porcelains has been considerably influenced by the desire for greater translucency. The variation in the formula is such that the fired ware must contain a very high percentage of vitreous phase.

Much of the information available on the properties of dental porcelain is antiquated and irrelevant to modern materials. There has been little attempt to standardize test methods or critically present data on mechanical properties.

Since glass is the dominant phase in modern dental porcelain, some of the important characteristics of the glassy state and mechanical properties of vitreous materials have been examined.
PART B.
ORIGINAL INVESTIGATION

7. STATEMENT OF PROBLEM – PURPOSE AND SCOPE OF INVESTIGATION

It is clear that there are factors associated with the fracture mechanism of dental porcelain which are not entirely understood. A survey conducted by Lehman (1967) appears to show that a time factor is involved in the failure of porcelain jacket crowns. Until now, all investigations have centred upon the short-time incremental strength of these materials.

It has been shown that glass does fatigue in the presence of water and that dental porcelain is a pigmented, glass - crystal composite (Southan, 1970). Water is the active ingredient in any stress assisted corrosion process of a glass and jacket crowns must function in the presence of moisture; externally from saliva and internally from the cementing agent.

It is not unreasonable then to expect some fatigue in dental porcelain structures and the purpose of this investigation is to identify the part that fatigue might play in the practical strength of dental porcelain.

In view of the fact that the problem of fatigue in dental porcelain has not previously been investigated, an attempt has been made to use standardized test methods established by Southan (1968) as a basis for this study.
Because there is no effective crack healing in glass, it matters little if the applied load is static or intermittent. Therefore, a static test was devised which I considered could render some information that might be of clinical interest.

The scope of this work is to study the behaviour of untreated, annealed and chemically treated wafer type specimens when subjected to a selected sustained load for a period of one week. This load was one which specimens could withstand for short periods and was established from modulus of rupture controls.
8. STRENGTH RELATIONS AND THE BEND TEST

Strength can be measured in terms of a stress, a strain, or an energy and comparisons between materials are made after testing similar quantities with similar dimensions by the same means.

In static loading the specimen is usually required to resist a definite force; the static stress being the observed stress required to rupture a material. The load may be applied immediately or so gradually over a period of a few minutes, that at any instant all parts are in equilibrium. For sustained loading the maximum required force is applied to the test piece instantaneously.

In dynamic loading the loaded specimen is usually required to absorb a definite amount of energy at impact. The stress conditions are complex and the rate of change of momentum of the parts has to be taken into account.

Contrary to Pitt Roche's (1949) idea, it appears that a true impact force would be difficult to attain in the mouth owing to the cushioning effect of the periodontal membrane. The only time impact could be significant would be as result of severe trauma where fracture of the crown rather than tooth or bone would be preferable.

Like glass, dental porcelain appears to rupture only under tension, generally at a surface. However, there is no evidence to suggest that the value of this tensile strength will be independent of stresses operating in other directions, or any change in conditions affecting the material as a whole, such as humidity or rate of loading.

The measurement of tensile strength for brittle materials is a difficult task as they have little or no capacity for flow plastically and compensate for small misalignment in a uniaxial tension test.

Some of these difficulties can be overcome by using the simple bend test to determine the breaking strength of brittle materials. A bar specimen is bent under the action of a three- or four point loading system and the maximum tensile stress at failure estimated from the applied bending moment using the simple beam theory. The material is in a state of pure tension at the convex surface of the beam, where the maximum tension exists directly opposite the point of load application (Ritland, 1955) and may be calculated from the equation:  

\[ C_t = \frac{M}{Z} \]

where \( C_t \) is the maximum tensile stress in the bottom fibres; \( M \) the bending moment and \( Z \) the modulus of section of the test piece (Duckworth, 1951, Tweeddale, 1964, p. 221).

From the bend test, the modulus of rupture or transverse strength or flexure strength may be calculated to enable comparisons to be made between various vitreous materials. Several assumptions are made in deriving the conventional equation:  

\[ C_t = \frac{3w}{2bd} \cdot \frac{1}{d} \]
where \( w \) is the applied load; \( l \) is the length between the transverse supports; \( b \) is the breadth of the specimen and \( d \) is the depth of the specimen (Duckworth 1951, Black, 1936).

The modulus of rupture is not a true stress but is used to predict and compare the strength of similar beams of the same material (Roark, 1965, p. 35).

Short beams and very wide beams are not considered to be ideal for estimating tensile strength in a bend test. Roark (1965, p. 131) shows that for span/depth ratios between 1.5 and 1, there is not an inordinate difference between maximum tensile stress and the calculated maximum fibre tensile stress.

In view of the comparatively small span/depth ratios in the selected test pieces, the same three point loading system as employed by Southan (1968, p. 291) was used for all tests.

The bend test was performed on a Hounsfield Tensometer*. A compression attachment illustrated in Fig. 3 was assembled into the machine and consisted of a compression die and a Brinell ball (5 mm. diam.) loading head.

The compression die consisted of a brass pad \((1" \times 7/16" \times 7/16")\) in which hardened-steel supporting rods \((0.0913 \text{ in. diam.})\) were set parallel to one another. The distance between the centres of these

* Hounsfield Tensometer, Type W., Tensometer Ltd.,
81 Morland Road, Croydon, Surrey, U.K.
Fig. 3 - Three-point loading system - photoelastic analysis.

A two-dimensional representation of the distribution and intensity of stress in a glass test piece, when a force was applied to the loading head.

(Courtesy D.E. Southan).
rods was 0.25 inches. This assembly was fixed to the compression attachment of the testing machine.

The rate of tensile loading at the convex surfaces approached 6,000 lb/in^2/minute as calculated from the conventional modulus of rupture equation.
THE STRENGTH OF DENTAL PORCELAINS UNDER INCREMENTAL LOADING

MATERIALS AND METHOD

9.1 Modern Dental Porcelains Investigated

Southan (1970, B) classified modern dental porcelains into two broad groups by matrix characteristics; those with a disrupted vitreous matrix and those with an intact vitreous matrix.

The matrix-disrupted group are quartz-bearing porcelains whose matrix is rigid at the inversion temperature of quartz (about 573°C). As these porcelains cool from sintering temperature, the quartz particles undergo a sudden volumetric shrinkage at 573°C resulting in the disruption of the matrix surrounding the quartz grains by semi-lunar microcracks, as shown in Fig. 4(a).

Those porcelains with a matrix free of disruptions fall into the matrix-intact group shown in Fig. 4(b). They include quartz-bearing porcelains with matrices plastic at 573°C, non quartz-bearing and aluminous porcelains.

Of the porcelains investigated, only \( V_{v1} \) (See TABLE I) was from the matrix-disrupted group.
Fig. 4 - Thin sections of two modern dental porcelains, transmitted light.

(a) A quartz-bearing dental porcelain, the matrix disruptions are near quartz grains.
(b) An aluminous dental porcelain, the matrix is intact.

(Courtesy D.E. Southan)
# TABLE I.

MODERN DENTAL PORCELAINS INVESTIGATED

<table>
<thead>
<tr>
<th>MANUFACTURER’S DESCRIPTIONS</th>
<th>AUTHOR’S DESIGNATIONS*</th>
</tr>
</thead>
<tbody>
<tr>
<td>VITA – VACUUM – KERAMIK 1130°C</td>
<td>$V_{V_1}$</td>
</tr>
<tr>
<td>DENTINMASSE NR. 56</td>
<td></td>
</tr>
<tr>
<td>VITADUR 980°C (ALUMINOUS)</td>
<td>$VA_{V_1}$</td>
</tr>
<tr>
<td>DENTINE POWDER No 356</td>
<td></td>
</tr>
<tr>
<td>DE TREY’S ALUMINOUS PORCELAIN</td>
<td></td>
</tr>
<tr>
<td>(VACUUM-FIRED) 900°C–950°C</td>
<td>$DA_{V_0}$</td>
</tr>
<tr>
<td>CORE $C_{25}$</td>
<td>$DA_{V_1}$</td>
</tr>
<tr>
<td>DENTINE $D_{22}$</td>
<td></td>
</tr>
<tr>
<td>ALUMINOX 980°C (ALUMINOUS)</td>
<td></td>
</tr>
<tr>
<td>DENTINE POWDER No 202</td>
<td>$AL_{V_1}$</td>
</tr>
</tbody>
</table>

* After Southan, 1968
### TABLE II

**DETAILED OF PORCELAINS TESTED**

<table>
<thead>
<tr>
<th>TYPE OF PORCELAIN</th>
<th>AUTHOR'S DESIGNATION</th>
<th>TYPE OF MATRIX</th>
<th>TRANSFORMATION REGION</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUARTZ-BEARING BODY</td>
<td>V₁</td>
<td>DISRUPTED</td>
<td>Ca 700°C</td>
</tr>
<tr>
<td>ALUMINOUS BODY</td>
<td>V₁</td>
<td>INTACT</td>
<td>Ca 620°C</td>
</tr>
<tr>
<td>ALUMINOUS BODY</td>
<td>D₁</td>
<td>INTACT</td>
<td>Ca 635°C</td>
</tr>
<tr>
<td>ALUMINOUS BODY</td>
<td>A₁</td>
<td>INTACT</td>
<td>Ca 625°C</td>
</tr>
<tr>
<td>ALUMINOUS CORE</td>
<td>D₀</td>
<td>INTACT</td>
<td>Ca 620°C</td>
</tr>
</tbody>
</table>

*From Southan, personal communication.*
9.2 TEST SPECIMEN FORMATION

In designing a research project such as this, consideration must be given not only to the choice of test material but the form in which it is to be tested. As a test measures only the properties of the test piece, it is essential to use a simple, standardized, reproducible method of making test pieces which at least simulate practical conditions.

Southan (1969) devised a method of producing standardized test pieces based on his observations of a typical porcelain jacket crown. For this study I have chosen his rectangular specimen produced from mould B. This test piece is comparatively thin and wafer-like and might be related to the labial or lingual parts of a porcelain jacket crown.

The moulds used for specimen manufacture were fabricated precisely from tool steel* and had internal dimensions 3 x 10 x 12 mm. Fig. 5(a) shows the sections of the mould, the sides and ends could be located accurately by means of ledges cut into the mould base. Fig. 5(b) shows the assembled mould held firmly in the metal holder by four screws.

To ensure some degree of uniformity in the test material, the contents of a number of bottles of the particular porcelain to be

* Chapman and Goldsmith Pty. Ltd.

Engineers, Bathurst Street, Sydney, 2000, Australia.
Fig. 5 - The rectangular mould used for test specimen formation.

(a) The mould dismantled.

(b) Mould assembled and bolted into its holder.
tested were thoroughly mixed together by agitation in a bulk container. The required quantity of powder was then removed from the container and mixed with distilled water on a watch glass to form a thin paste.

The condensation method which proved most satisfactory with these moulds was the wet vibration technique described by Southan (1968, p. 179). Wet vibration of successive increments of the carefully mixed paste was effected on a mechanical vibrator for a total time of five minutes. Clean, dry tissues were used to absorb excess moisture as it appeared on the surface with well condensed porcelain.

The excess material was carefully carved away with a sharp razor blade and the surface whipped with a large sable-hair brush.

The mould was then removed from its holder and placed on a glass slab, where the sides of the mould were slid away from the specimen. The long sides were repositioned so as to support the condensed porcelain when the short sides were removed, one at a time. The long sides could again be withdrawn from the compact on the mould base which was then laid on its side. The condensed sample was separated from the base by pushing at its end with one of the long side pieces of the mould.

Each specimen was then transported to the firing tray without distortion by means of a broad spatula. All specimens throughout this work were prepared in the foregoing manner.

A fireclay tray which could accommodate eight specimens, covered
with a thin layer of levigated alumina powder*, proved to be a most satisfactory method of supporting specimens during firing. No restriction of the firing shrinkage was apparent and there was only minimal interference with the smoothness of their undersurfaces.

The furnace** was switched on at least one hour before use to ensure the muffle area was thoroughly heat soaked. Fluctuations in mains voltage particularly in peak electrical periods could affect rates of temperature rise in this furnace. Best results were obtained by bringing the muffle to a selected temperature (in the case of \( V_{\text{v1}}, \text{1090}^\circ\text{C} \)) and holding it automatically.

Condensed specimens were carefully dried out over a period of at least fifteen minutes by progressively moving them nearer the doorway of the furnace. The thoroughly dry specimens were finally placed on the firing stage of the furnace ready for sintering.

All specimens were subjected to low-pressure sintering for a period of four minutes (Southan, 1968, p. 192) at the temperature range recommended by the manufacturer. A partial vacuum which could support a 740 mm. column of mercury was induced as the test specimens were transported into the muffle.

---

* 1557 AB Levigated Alumina Powder, Buehler Ltd.
Metallurgical Apparatus, Evanston, Illinois, U.S.A.

**Dentsply Biomat Furnace Model C-3B,
The Dentists' Supply Company, New York, Pennsylvania, U.S.A.
After four minutes the partial vacuum was released and the firing stage lowered. The sintered specimens were removed from the firing stage and placed on a mat of asbestos below the muffle to cool gradually to room temperature.

Four minutes firing at the selected temperature produced specimens that retained their colour and shape, yet exhibited some surface gloss.

9.3 The Modulus of Rupture of Different Materials

Test specimens of $V_{V1}$, $DA_{V0}$, $DA_{V1}$, $VA_{V1}$ and $AL_{V1}$ were prepared from mould (B) and fired. To obtain uniform surfaces, the faces and sides of each specimen were prepared by abrading with #220A silicon carbide paper under running water. The direction of grinding was longitudinal.

Before testing the breadth and depth of each specimen was measured with a micrometer and recorded. Diagonals were then drawn in pencil on a face of each specimen and the centre point marked for location of the loading head.

A series of ten specimens were prepared from each material and tested in a thoroughly moist state on the Hounsfield Tensometer*.

9.4 The Effect Annealing has on the Modulus of Rupture of Different Materials

Ten specimens of each of the porcelains $V_{V1}$, $DA_{V0}$, $DA_{V1}$, $VA_{V1}$

* Hounsfield Tensometer, Type W., Tensometer Ltd.,
81 Morland Road, Croydon, Surrey, U.K.
and $\text{AL}_v$ were prepared in the manner described in section 9.2 and surfaces abraded.

Groups of ten specimens of each material were annealed in air at their respective transformation temperature as shown in TABLE II, for fifteen minutes.

The temperature required for annealing was set on the furnace and held automatically but vacuum was switched off. Specimens were loaded on the firing stage and transported into the muffle.

After fifteen minutes the specimens were removed from the furnace and cooled slowly to room temperature. The centre point of each specimen was marked, its measurements recorded before being tested in the presence of 100 per cent humidity.

9.5 The Effect Surface Compression Created by Low-Temperature Ionic Exchange has on the Modulus of Rupture of Different Materials

A stress can be produced at the surface of dental porcelain by low-temperature ionic exchange. Molten potassium nitrate is an abundant source of potassium ions which could replace the smaller network-modifying ions in the vitreous matrix of dental porcelain (Southan, 1968, p. 297). The specimens were placed in a pyrex dish containing solid potassium nitrate and then in a furnace* with an automatic temperature control for the immersion process.

A group of ten specimens of each of the porcelains $V_{vl}$, $VA_{vl}$, $DA_{vl}$, $AL_{vl}$ and $DA_{vo}$ were prepared and abraded as before. The $V_{vl}$ specimens were preferentially prestressed by immersion in the potassium nitrate at $500^\circ C$ for 18 hours.* $VA_{vl}$, $DA_{vl}$, $AL_{vl}$ and $DA_{vo}$ specimens were treated for 18 hours at $450^\circ C$.

The treated specimens were removed from the molten potassium nitrate and thoroughly washed in hot water to remove excess salt prior to being tested, on the tensometer.

* From P.H. Adair, Personal communication.
9.3 The Modulus of Rupture of Different Materials

Table III displays the similarity between the transverse strengths of the body porcelains $V_{V_{1}}$, $VA_{V_{1}}$, $DA_{V_{1}}$ and $AL_{V_{1}}$, the higher strength of the $V_{V_{1}}$ could only be described as a tendency.

Specimens of the core material $DA_{V_{0}}$ did show a higher modulus of rupture than $V_{V_{1}}$ at greater than 90 per cent but less than 95 per cent levels of confidence.

9.4 The Effect Annealing has on the Modulus of Rupture

The results in Table IV show an increase in the modulus of rupture of the body porcelains after annealing.

The annealed $AL_{V_{1}}$ was considerably stronger than the unannealed $AL_{V_{1}}$ at greater than 99 per cent levels of confidence. Similarly, the annealed $DA_{V_{1}}$ was stronger than unannealed $DA_{V_{1}}$ at greater than 99 per cent but less than 99.9 per cent levels of confidence.

The annealed core material $DA_{V_{0}}$ showed a tendency to be slightly weaker after annealing, but this was not significant.

9.5 The Effect of Low-Temperature Ionic Exchange on the Modulus of Rupture

Chemical preferential pre-stressing of the specimens had a dramatic effect on the measured strengths of all the porcelains tested (Table V).

When compared to the transverse strengths for the different materials shown in Table III, the average increase in strength was about 146 per cent after chemical treatment.
The dispersion-strengthened DA\textsubscript{V1} and Al\textsubscript{V1} were considerably stronger when chemically treated, being approximately 198 per cent and 158 per cent stronger respectively under the conditions of testing. V\textsubscript{V1} and VA\textsubscript{V1} showed an average increase of 143 per cent in measured strength, while the transverse strength of the core material DA\textsubscript{V0} was approximately 99 per cent greater following chemical treatment.
<table>
<thead>
<tr>
<th>PORCELAIN</th>
<th>NUMBER OF SPECIMENS</th>
<th>MODULUS OF RUPTURE</th>
<th>STANDARD DEVIATION</th>
<th>*f.s.d. (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{VL} )</td>
<td>10</td>
<td>7,339 ( \text{p.s.i.} ) 514 ( \text{Kg/cm}^2 )</td>
<td>1,754 ( \text{p.s.i.} ) 123 ( \text{Kg/cm}^2 )</td>
<td>1,254 ( \text{p.s.i.} ) 88 ( \text{Kg/cm}^2 )</td>
</tr>
<tr>
<td>( VA_{VL} )</td>
<td>10</td>
<td>6,129 ( \text{p.s.i.} ) 429 ( \text{Kg/cm}^2 )</td>
<td>1,903 ( \text{p.s.i.} ) 133 ( \text{Kg/cm}^2 )</td>
<td>1,360 ( \text{p.s.i.} ) 95 ( \text{Kg/cm}^2 )</td>
</tr>
<tr>
<td>( DA_{VL} )</td>
<td>10</td>
<td>6,525 ( \text{p.s.i.} ) 457 ( \text{Kg/cm}^2 )</td>
<td>1,816 ( \text{p.s.i.} ) 127 ( \text{Kg/cm}^2 )</td>
<td>1,298 ( \text{p.s.i.} ) 91 ( \text{Kg/cm}^2 )</td>
</tr>
<tr>
<td>( AL_{VL} )</td>
<td>10</td>
<td>6,689 ( \text{p.s.i.} ) 468 ( \text{Kg/cm}^2 )</td>
<td>1,231 ( \text{p.s.i.} ) 86 ( \text{Kg/cm}^2 )</td>
<td>880 ( \text{p.s.i.} ) 62 ( \text{Kg/cm}^2 )</td>
</tr>
<tr>
<td>( DA_{VO} )</td>
<td>10</td>
<td>8,787 ( \text{p.s.i.} ) 615 ( \text{Kg/cm}^2 )</td>
<td>1,558 ( \text{p.s.i.} ) 109 ( \text{Kg/cm}^2 )</td>
<td>1,114 ( \text{p.s.i.} ) 77 ( \text{Kg/cm}^2 )</td>
</tr>
</tbody>
</table>

* For calculation of 95% Confidence limits for the true mean.
**TABLE IV**

MODULUS OF RUPTURE OF ANNEALED DENTAL PORCELAIN

<table>
<thead>
<tr>
<th>PORCELAIN</th>
<th>n*</th>
<th>ANNEALING TEMPERATURE (^{\circ}\text{C})</th>
<th>TIME MINUTES</th>
<th>TRANSVERSE STRENGTH p.s.i. Kg/cm(^2)</th>
<th>STANDARD DEVIATION p.s.i. Kg/cm(^2)</th>
<th><strong>f.s.d. (95%)</strong> p.s.i. Kg/cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{v1})</td>
<td>10</td>
<td>700(^{\circ}\text{C})</td>
<td>15</td>
<td>8,251 578</td>
<td>1,446 101</td>
<td>1,034 72</td>
</tr>
<tr>
<td>(V_{a1})</td>
<td>10</td>
<td>635(^{\circ}\text{C})</td>
<td>15</td>
<td>7,112 498</td>
<td>975 68</td>
<td>697 49</td>
</tr>
<tr>
<td>(D_{a1})</td>
<td>10</td>
<td>620(^{\circ}\text{C})</td>
<td>15</td>
<td>9,373 656</td>
<td>1,943 136</td>
<td>1,389 97</td>
</tr>
<tr>
<td>(A_{v1})</td>
<td>10</td>
<td>625(^{\circ}\text{C})</td>
<td>15</td>
<td>10,043 703</td>
<td>1,253 88</td>
<td>896 63</td>
</tr>
<tr>
<td>(D_{a0})</td>
<td>10</td>
<td>620(^{\circ}\text{C})</td>
<td>15</td>
<td>8,379 586</td>
<td>1,750 122</td>
<td>1,251 88</td>
</tr>
</tbody>
</table>

* Numbers of Specimens

** For calculation of 95% Confidence limits for the true mean.
### TABLE V

MODULUS OF RUPTURE OF CHEMICALLY TREATED DENTAL PORCELAIN

<table>
<thead>
<tr>
<th>PORCELAIN</th>
<th>n*</th>
<th>TREATMENT TEMPERATURE (°C)</th>
<th>TIME HOURS</th>
<th>TRANSVERSE STRENGTH p.s.i. Kg/cm²</th>
<th>STANDARD DEVIATION p.s.i. Kg/cm²</th>
<th><strong>f.s.d. (95%)</strong> p.s.i. Kg/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vᵥ₁</td>
<td>10</td>
<td>500°C</td>
<td>18</td>
<td>17,695 1,239</td>
<td>1,276 89</td>
<td>912 64</td>
</tr>
<tr>
<td>VAᵥ₁</td>
<td>10</td>
<td>450°C</td>
<td>18</td>
<td>15,022 1,403</td>
<td>1,136 79</td>
<td>812 57</td>
</tr>
<tr>
<td>DAᵥ₁</td>
<td>10</td>
<td>450°C</td>
<td>18</td>
<td>19,483 1,364</td>
<td>1,908 134</td>
<td>1,364 95</td>
</tr>
<tr>
<td>ALᵥ₁</td>
<td>10</td>
<td>450°C</td>
<td>18</td>
<td>17,188 1,203</td>
<td>1,208 84</td>
<td>863 60</td>
</tr>
<tr>
<td>DAᵥ₀</td>
<td>10</td>
<td>450°C</td>
<td>18</td>
<td>17,565 1,229</td>
<td>1,399 98</td>
<td>1,000 70</td>
</tr>
</tbody>
</table>

* Numbers of Specimens

** For calculation of 95% Confidence limits for the true mean.
CONCLUSIONS

Under the conditions of testing, all the body porcelains showed similar transverse strengths. The core material DA₁₀ had a comparable strength showing only a tendency to be stronger than the body porcelains.

Although there was a tendency for the annealed body porcelains to be stronger than the unannealed, only two porcelains, DA₁ and AL₁ were significantly stronger after annealing.

The preferential prestressing of the porcelain surfaces by ionic exchange greatly increased the transverse strength of all the porcelains tested. The best results were obtained with the matrix-intact body porcelains VA₁, DA₁ and AL₁.
10. THE SUSTAINED LOADING TEST

MATERIALS AND METHODS

In order to study the behaviour of modern dental porcelain under sustained loading, a specialized machine was devised to enable ten specimens to be tested simultaneously for a sustained period.

In an attempt at uniformity, ten three-point loading systems identical to that described in section 8 were employed.

Fig. 6 shows the sustained loading machine that was designed by the author and manufactured by Chapman and Goldsmith Pty. Ltd.*

The framework of the machine was fabricated from 1" x 1/8" angle steel and had a base area of approximately five square feet. The machine was designed so that the ten arms complete with weights and compression attachments occupied as little space as possible, yet the total weight and dimensions of the machine were such that it was completely stable and little or no vibration was evident at any time, even when a specimen fractured.

The length of each arm from the centre of the pivot to the centre of the hole for the weight carrier was 36". Although five holes were provided for selection of mechanical advantage, a ratio of 12:1 was selected for all the experiments conducted, the Brinell

* Chapman and Goldsmith Pty. Ltd., Engineers
  Bathurst Street, Sydney, 2000, Australia.
SUSTAINED LOADING MACHINE

SPECIFICATIONS

Width of base : 23\(\frac{1}{2}\)"
Length of base : 32"
Height of platforms : 10\(\frac{3}{16}\)"
Width of platforms : 3\(\frac{1}{2}\)"
Length of arms : 36\(\frac{1}{2}\)"

EXACT MEASUREMENTS

Length between centre of pivot and centre of
hole for weight carrier : 36"

Length between centre of pivot and;
centre of 1st hole for Brinell ball : 1"
" 2nd " " " " : 1\(\frac{1}{2}\)"
" 3rd " " " " : 2"
" 4th " " " " : 2\(\frac{3}{4}\)"
" 5th " " " " : 3"

Distance between centre of pivot and level
of platform : 1\(\frac{13}{16}\)"

Distance between lower edge of arm
and upper part of angle-iron switch support : 9\(\frac{1}{16}\)"
Distance between lower edge of arm and
upper surface of platform : 1\(\frac{5}{16}\)"
Fig. 6.
ball being located three inches from the arm pivot (Fig. 7(a)).

The weights and weight carrier were manufactured to the author's specifications by A. James Wedderburn*. Five, two and one pound weights could be added to the weight carrier which itself weighed exactly one pound. Lead shot was weighed and added as required to bottles attached to the carrier.

To record the time in which specimens fractured, ten digital electric clocks** were wired to ten microswitches positioned on the machine frame directly under each arm near its weighted end. Both the switch and a stop screw were adjusted so that on specimen fracture the arm would fall only a few millimeters before breaking the clock circuit and recording the day and time of fracture. This enabled the experiments to be conducted for long periods with minimal supervision.

The tests were conducted in the presence of water and the moist conditions were maintained by the wick system shown in Fig. 7(a).

10.1 The Machine Calibration and Sustained load Determination

To select a suitable sustained load, the modulus of rupture results were studied to determine the maximum tensile load which

* A. James Wedderburn Scale Manufacturers,
74 Liverpool Street, Sydney, 2000, Australia.

** Simplex International Time Equipment Pty. Ltd.
61 Great Buckingham Street, Redfern, N.S.W. 2016, Australia.
specimens could survive in short time tests. It was established that the sustained load required was the weight necessary at the end of each arm to provide a tensile force of 6,000 p.s.i. at the lower fibres of each test specimen.

To calibrate the machine each arm was weighed in the horizontal position by suspending it from the centre of the hole made for the weight carrier.

**CALIBRATION OF SUSTAINED LOADING MACHINE**

<table>
<thead>
<tr>
<th>ARM</th>
<th>WEIGHT OF ARMS (gms.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>715</td>
</tr>
<tr>
<td>2</td>
<td>715</td>
</tr>
<tr>
<td>3</td>
<td>719</td>
</tr>
<tr>
<td>4</td>
<td>715</td>
</tr>
<tr>
<td>5</td>
<td>712</td>
</tr>
<tr>
<td>6</td>
<td>728</td>
</tr>
<tr>
<td>7</td>
<td>729</td>
</tr>
<tr>
<td>8</td>
<td>721</td>
</tr>
<tr>
<td>9</td>
<td>729</td>
</tr>
<tr>
<td>10</td>
<td>721</td>
</tr>
</tbody>
</table>

\[ \overline{X} = 720.4 \text{ gms. or } 1.6 \text{ lb.} \]

\[ \frac{720.4}{454} = 1.5867 \text{ lb.} \]

or \(1.6\text{ lb.}\)

Therefore weight of each arm at point of loading = 1.6 lb.

The load to be applied could now be calculated by the following method.
Ten specimens were ground longitudinally to a breadth of 8.0 mm. or 0.315 inches and a height of 2.5 mm. or 0.0984 inches. The length is constant at 0.25 inches.

Now \[ C_t = \frac{3wL}{2bh^2} \]

where \( w \) is the applied load; \( l \) the length between the transverse supports; \( b \) the breadth of the specimen and \( h \) the height of the specimen.

then \[ 6,000 \text{ p.s.i.} = \frac{3 \times w \times 0.25}{2 \times 0.315 \times 0.00968} \]

\[ w = \frac{6,000 \times 0.0061}{0.75} \]

\[ w = \frac{36.6}{0.75} \]

\[ = 48.8 \text{ lb.} \]

Mechanical Advantage \[ = \frac{36}{3} \]

Therefore Load required at end of arms to deliver a load of 48.8 lbs. to the specimens.

\[ = \frac{48.8}{12} = 4.066 \text{ or 4.07 lb.} \]

Weight of each arm at loading point \[ = 1.6 \text{ lb} \]

Weight of each pan \[ = 1.0 \text{ lb} \]

One Weight \[ = 1.0 \text{ lb} \]

Lead Shot in bottle \[ = 0.47 \text{ lb} \]

Total \[ = 4.07 \text{ lb} \]

\( (0.47 \text{ lb} = 213.4 \text{ gms.}) \)

In all the subsequent experiments in this investigation, the
Fig. 7 - Sustained loading test.

(a) A specimen mounted and under test conditions in the presence of water supplied by a wick from a pyrex dish.

(b) A specimen after fracture.
sustained load used produced a tensile force of 6,000 p.s.i. at the lower fibres of the test specimen.

10.2 The Effect of Sustained Loading on the Different Materials

The modern dental porcelains $V_{v_1}$, $VA_{v_1}$, $DA_{v_1}$, $AL_{v_1}$ and $DA_{v_0}$ were tested in groups of ten. Test specimens were produced by the method described in section 9.2 and their faces and sides abraded longitudinally on #220A silicon carbide paper to a predetermined height and breadth for the sustained load to be used.

The height of each brass compression pad had been adjusted so that with a specimen mounted and loaded, the arms of the machine were approximately level. Each of the arms, brass pads and digital clocks were correspondingly numbered.

A very thin layer of adhesive was used to mount the specimens on the steel rods of the brass pad. Diagonals were then drawn on the specimen and the centre point marked. The specimens were thoroughly moistened before the brass compression pads were positioned on the machine platform.

The ten digital clocks were synchronized and the sustained load of 6,000 p.s.i. applied to each specimen as gently but as quickly as possible. Wicks were positioned against the specimens and the experiment starting time recorded.

A total time limit of seven days was allowed for each experiment. Times of failure were recorded during these periods. Survivors of the seven day experiment were immediately removed and
fractured on the Hounsfield Tensometer; their transverse strengths being calculated and recorded.

10.3 The Effect Annealing has on the Sustained Loading of Different Materials

Test specimens of the materials $V_{v1}$, $VA_{v1}$, $DA_{v1}$, $AL_{v1}$ and $DA_{v0}$ were prepared in groups of ten as in section 10.2.

When the necessary grinding was complete, annealing of each group was carried out by the method described for the control groups in section 9.4. The annealed specimens were subjected to a sustained load of 6,000 p.s.i. for a period of seven days.

10.4 The Effect Surface Compression Created by Low-Temperature Ionic Exchange has on the Sustained Loading of Different Materials

A group of ten specimens from each of the materials $V_{v1}$, $VA_{v1}$, $DA_{v1}$, $AL_{v1}$ and $DA_{v0}$ was prepared for sustained loading by the method described in section 10.2.

The chemical treatment of each group was identical to that described for the control groups in section 9.5. The treated specimens were subjected to a sustained load of 6,000 p.s.i. for a period of seven days.
10.2 The Effect of Sustained Loading on the Different Materials

As shown in Table VI, only two \( V_{v_1} \) and four \( D_{A_{v_0}} \) specimens survived the seven day sustained loading test.

Failure times varied considerably but all of \( V_{A_{v_1}}, D_{A_{v_1}} \) and \( A_{L_{v_1}} \) specimens fractured within the first hours of the experiment.

The transverse strengths of the survivors are compared with the strengths of the control specimens in Table VI and there was a tendency for the survivors to be stronger than the control specimens.

The \( D_{A_{v_0}} \) survivors were found to be stronger than the \( V_{v_1} \) survivors at greater than 90 per cent but less than 95 per cent levels of confidence.

10.3 The Effect Annealing has on the Sustained Loading of Different Materials

The results in Table VII show a significant improvement in the performance of the annealed body porcelains \( V_{v_1}, D_{A_{v_1}}, A_{L_{v_1}} \) and to a lesser extent, the \( V_{A_{v_1}} \). The annealed core material \( D_{A_{v_0}} \) gave identical results to the unannealed \( D_{A_{v_0}} \) specimens in the previous experiment.

Again there was a wide variation in the recorded fracture times and the failures occurred in the first hours of the experiment.

The transverse strengths of the annealed survivors are compared with the annealed control specimens in Table VII. The strengths recorded for the annealed \( V_{A_{v_1}} \) survivors were significantly higher
than those of the annealed control specimens at greater than 99 per cent and less than 99.9 per cent levels of confidence. Lower strengths were recorded for the annealed AL\textsubscript{V1} and DA\textsubscript{V0} survivors, however, this could only be described as a tendency.

10.4 The Effect of Low-Temperature Ionic Exchange on the Sustained Loading of Different Materials

The results of the experiments are shown in Table VIII and the survival rate was significantly higher when compared with the untreated groups.

The chemically treated aluminous body porcelains were totally resistant to the sustained load of 6,000 p.s.i. for the seven day period. The only failures recorded in this series were two V\textsubscript{V1} and one DA\textsubscript{V0} specimen. The fractures occurred within the first half hour of each experiment.

The transverse strengths of the survivors are compared with the control specimens in Table VIII. The chemically treated V\textsubscript{V1}, VA\textsubscript{V1}, DA\textsubscript{V1} and DA\textsubscript{V0} survivors showed a tendency to be weaker than the chemically treated control specimens. Although higher strengths were recorded for the AL\textsubscript{V1} survivors, this was not a significant trend.
TABLE VI

THE RELATIONSHIP BETWEEN MODULUS OF RUPTURE AND THE
EFFECT OF A SUSTAINED LOAD OF 6,000 P.S.I. FOR SEVEN DAYS
ON THE DIFFERENT MATERIALS

<table>
<thead>
<tr>
<th>PORCELAIN</th>
<th>HOUNSFIELD TENSOMETER CONTROL TRANSVERSE STRENGTH P.S.I.</th>
<th>SUSTAINED LOADING TEST</th>
<th>SUSTAINED LOADING SURVIVORS TRANSVERSE STRENGTH P.S.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n*</td>
<td>Mean</td>
<td>s.d.</td>
</tr>
<tr>
<td>Vv1</td>
<td>10</td>
<td>7,339</td>
<td>1,754</td>
</tr>
<tr>
<td>VAv1</td>
<td>10</td>
<td>6,129</td>
<td>1,903</td>
</tr>
<tr>
<td>DAv1</td>
<td>10</td>
<td>6,525</td>
<td>1,816</td>
</tr>
<tr>
<td>Alv1</td>
<td>10</td>
<td>6,689</td>
<td>1,231</td>
</tr>
<tr>
<td>DAv0</td>
<td>10</td>
<td>8,787</td>
<td>1,558</td>
</tr>
</tbody>
</table>

* Number of Specimens tested.
TABLE VII

THE RELATIONSHIP BETWEEN MODULUS OF RUPTURE AND THE EFFECT OF A SUSTAINED LOAD OF 6,000 P.S.I. FOR SEVEN DAYS ON ANNEALED DENTAL PORCELAIN

<table>
<thead>
<tr>
<th>PORCELAIN</th>
<th>HOUNSFIELD TENSOMETER CONTROL ANNEXED TRANSVERSE STRENGTH P.S.I.</th>
<th>SUSTAINED LOADING TEST</th>
<th>SUSTAINED LOADING SURVIVORS TRANSVERSE STRENGTH P.S.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n*</td>
<td>Mean</td>
<td>s.d.</td>
</tr>
<tr>
<td>Vv1</td>
<td>10</td>
<td>8,251</td>
<td>1,446</td>
</tr>
<tr>
<td>VaV1</td>
<td>10</td>
<td>7,112</td>
<td>975</td>
</tr>
<tr>
<td>DaV1</td>
<td>10</td>
<td>9,373</td>
<td>1,943</td>
</tr>
<tr>
<td>Ałv1</td>
<td>10</td>
<td>10,043</td>
<td>1,253</td>
</tr>
<tr>
<td>DaVo</td>
<td>10</td>
<td>8,379</td>
<td>1,750</td>
</tr>
</tbody>
</table>

* Number of Specimens tested.
TABLE VIII
THE RELATIONSHIP BETWEEN MODULUS OF RUPTURE AND THE EFFECT
OF A SUSTAINED LOAD OF 6,000 P.S.I. FOR SEVEN DAYS ON
CHEMICALLY TREATED DENTAL PORCELAIN

<table>
<thead>
<tr>
<th>PORCELAIN</th>
<th>HOUNSFIELD TENSOMETER CONTROL KNO₃ TREATED TRANSVERSE STRENGTH P.S.I.</th>
<th>SUSTAINED LOADING TEST</th>
<th>SUSTAINED LOADING SURVIVORS TRANSVERSE STRENGTH P.S.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n*</td>
<td>Mean</td>
<td>s.d.</td>
</tr>
<tr>
<td>Vᵥ₁</td>
<td>10</td>
<td>17,695</td>
<td>1,276</td>
</tr>
<tr>
<td>VAᵥ₁</td>
<td>10</td>
<td>15,022</td>
<td>1,136</td>
</tr>
<tr>
<td>DAᵥ₁</td>
<td>10</td>
<td>19,483</td>
<td>1,908</td>
</tr>
<tr>
<td>ALᵥ₁</td>
<td>10</td>
<td>17,188</td>
<td>1,208</td>
</tr>
<tr>
<td>DAᵥₒ</td>
<td>10</td>
<td>17,565</td>
<td>1,399</td>
</tr>
</tbody>
</table>

* Number of Specimens tested.
CONCLUSIONS

The property of static fatigue has been shown to exist in dental porcelain. The times taken for identical specimens to fracture under similar sustained loads varied considerably.

Of the five dental porcelains subjected to the sustained loading test in section 10.2, only $V_{V_1}$ and $DA_{V_0}$ showed survivors after a seven day period. These survivors gave no indication of having been weakened by the sustained loading.

Annealing had a significant effect on the performance under sustained loading of all the body porcelains. The performance of the aluminous core material was not changed by annealing and more work is required to clarify the finding.

Chemical treatment significantly improved the performance under sustained loading of all the porcelains except the quartz-bearing body porcelain $V_{V_1}$. For reasons which are not as yet clear, all the chemically treated survivors except $AL_{V_1}$ did show a tendency to have been weakened by the sustained loading.
DISCUSSION

The values for the modulus of rupture calculated for the different materials were not unalike. It would appear that the quartz grains and the associated matrix-disruptions are a comparable crack-stopping mechanism to the alumina particles in the matrix-intact materials. Increasing the alumina content above approximately 25 per cent did not seem to influence the strength markedly. Clearly, the loss of translucency associated with the addition of alumina has limited its application to body porcelains.

Annealing had a significant strengthening effect on two of the dispersion-strengthened body porcelains. There was no apparent effect on the strength of the core material. The results indicate that some stresses such as those remaining after surface abrasion, can be relieved by annealing. Similarly, the considerable variation in the results suggests the presence of stresses in the core specimens which cannot be relieved by annealing.

When the surfaces of specimens were preferentially prestressed by ionic exchange, the transverse strengths of the materials increased markedly. I am in agreement with Southan (1968, p. 347) who believes this to be due to some lessening of the dangerous effects of surface flaws.

The influence of the vitreous matrix of modern dental porcelain on its mechanical performance is not well appreciated and its unpredictable behaviour in service continues to be the main criticism.
The modulus of rupture results provide an excellent basis for comparison of the various materials under identical conditions of testing. But they give only a limited appreciation of their performance under the states of stress that may be encountered in the oral environment.

In the modulus of rupture tests the effect of the most dangerous flaw in the stressed area was of primary importance and the differing chemical compositions of the vitreous matrices somewhat less so. Clinically, there remains the problem of the porcelain jacket crowns which fracture in service after variable, and in some cases lengthy periods of time.

Pitt Roche (1949) believed impact forces to be of great importance in the performance of ceramic crowns, however, the cushioning effect of the periodontal ligament during normal function tends to eliminate such forces. True impact forces resulting from trauma frequently are not absorbed and in such circumstances the fracture of a porcelain crown is more desirable than tooth structure.

A survey conducted by Lehman (1967) indicated an average time of two and a half years for fracture of porcelain jacket crowns in service. Such a finding may suggest the existence of stress-assisted corrosion or static fatigue as exhibited by glass. Clinically there is no way this can be assessed owing to the wide variations in the fracture times of porcelain crowns.
Southan (1968, p. 351) predicted that under static conditions of stress, fatigue of the vitreous matrix of dental porcelains would be a factor affecting their service.

The sustained loading tests on the different materials demonstrates that a load established from the control tests to be less than critical, when applied and sustained in the presence of water was capable of fracturing most test specimens. The fracture times were extremely variable and, in the main, recorded in the first hours of the experiment. The fact that only two porcelain brands could produce survivors was interesting, particularly as one was a quartz-bearing body porcelain and the other an aluminous core material.

With the exception of the aluminous core material and one of the aluminous body porcelains, there was a significant improvement in performance after annealing. Chemically prestressed aluminous porcelains were extremely resistant to sustained loading whereas the quartz-bearing body porcelain specimens showed no improvement over those that were annealed.

The results indicate that modern dental porcelain shows static fatigue. A possible interpretation of the findings in this research is the relationship between the minor phases and major, vitreous phase in the individual materials.

The quartz-bearing porcelain tested has been shown by Southan (1968) to have microcracks surrounding the quartz grains. These
cracks induced by stresses associated with the sudden and violent contraction of the quartz around 573°C, could assist the performance of this material by stopping a crack propagating at right angles to them. However, under other conditions such as after chemical prestressing, they could be areas of weakness in the tensed internal matrix. Sustained loading would give time for these cracks, dangerously orientated in relation to the tensile forces in the matrix set up by the surface compression, to propagate. Incremental loading may not.

Annealing relieves stresses in porcelain that are set up by external influences such a differential thermal gradient during cooling, chemical prestressing or grinding or scratching.

If there is a thermal expansion mismatch between the alumina and the matrix, then annealing cannot relieve the stresses set up on cooling because they occur only below the transformation region. These internal and surface stresses could override the relief of stresses induced by grinding.

There is enough alumina in the core material to form groups of grains that are touching each other. Such a situation could induce stresses on cooling because the grains resist contraction towards each other. It is also possible that the alumina in the core material DAy0 and the body porcelain DAy1 may not be thoroughly wetted by the matrix at the time/temperature combinations used for sintering. Under these circumstances the bond between the matrix
and the alumina grains may not be strong. When such a system is placed under tension internally by surface compression, crack formation and crack extension internally may result when the specimen is subjected to sustained loading. This process could take considerable time as these materials with a high alumina content have many crack-stopping interfaces in them.

Briefly, the performance of a modern dental porcelain under sustained loading may depend upon its crack-stopping ability, the presence or absence of internal stresses and the ability of the matrix to support a surface compression. At present this is pure speculation and a great deal of work needs to be done.

The survivors of the sustained loading tests were of particular interest when their transverse strengths were compared with the control specimens. The untreated and annealed survivors showed no indication of having been weakened by the prolonged loading, whereas, for reasons which cannot be explained, some of the chemically prestressed survivors did tend to show lower transverse strengths.

Perhaps the specimens which survived the sustained loading for one week, could survive for very much longer periods without being weakened.

The fracture times in all tests were found to vary considerably and apart from a tendency for the failures to occur in the early hours of each experiment, no other trend was observed.

There is a great possibility that the process of a stress-assisted corrosion or static fatigue found in dental porcelain is a
major factor in the mechanical failure of porcelain jacket crowns.

I believe that the results obtained with the annealing experiments were of particular clinical interest. It would appear that any abrasive adjustment to a porcelain jacket crown not followed by annealing or re-glazing, may seriously reduce its life expectancy.
SUMMARY

The dental porcelain brands investigated in this research were representative of the quartz-bearing (matrix-disrupted) and the aluminous (matrix-intact) types.

The modulus of rupture of these porcelains was determined by incremental loading in the untreated, annealed and chemically prestressed states.

A sustained loading experiment was designed and a machine manufactured to facilitate the investigation of the fatigue properties of modern dental porcelain in the untreated, annealed and chemically prestressed state.

The results of the sustained loading experiments clearly indicates that the major phase in dental porcelain shows static fatigue and that under certain conditions such as annealing and chemical prestressing appears to be moderated.

The results of this research have been discussed and a possible interpretation of the sustained loading observations presented.
BIBLIOGRAPHY


