BASIC PROPERTIES OF DENTAL MATERIALS

TYPES OF PURE FORCES

Compressive: a force that results in a decrease in length along the direction of the force

Tensile: a force that results in an increase in length along the direction of the force

Shear: a force that causes a sliding displacement of one side of a structure relative to another side

Units of force include kilograms, newtons, and pounds.

STRESS

is the force with which a structure resists an external load placed on it. It is the internal reaction to an externally applied load and is equal in magnitude but opposite in direction to the external load; although technically the internal force, this is difficult to measure and so the accepted way of measuring stress is to measure the external load applied to the cross sectional area; measured in force per area units such as kg/cm^2, MPa (MN/m^2), or psi; is represented by the Greek letter, sigma.

$$\text{Stress} = \text{Force}/\text{Area}$$

Just as there are three types of pure force or load, there are three types of pure stress: compressive, tensile, and shear.

Methods of studying stress distributions:

Photoelastic modeling: provides a graphic demonstration of stress distributions using a bi-refringent material through which light refraction is analyzed. Major drawbacks include difficulty encountered in preparing complex models and finding model materials with a modulus of elasticity which exactly matches the modulus of elasticity of the structure being studied.

Finite element analysis: involves dividing a structure into small segments each with specific physical properties. Computer programs then model the stresses produced by various load applications. One difficulty encountered in using this technique to model dental structures is that they are anisotropic; that is, their properties vary with direction.

STRAIN

is the change in length per unit length that a material undergoes when a force is applied to it; it is dimensionless because it has length per length units of measurement; is often expressed as a percentage; is represented by the Greek letter, epsilon.

Strain = Change in Length/Original Length

Strain can either be *elastic* or *plastic*. Elastic strain is strain that totally disappears once the external load that caused it is removed. Elastic strain is based upon the fact that a net force of zero exists between two atoms when they are at equilibrium. If a compressive or tensile force is exerted on the atoms, an opposite force will attempt to move them back to their equilibrium position. When the applied force is released, the atoms return to their original position; therefore, the material is not permanently deformed. Plastic strain is strain that permanently remains once the external load that caused it is removed. It occurs when the force applied to the atoms moves them so far from their equilibrium position that they do not return to it once the force is removed.

STRESS-STRAIN DIAGRAM

is a graphic way of displaying stress and strain. Generally, the diagram is produced by gradually loading a material using an Instron or similar testing machine. The resultant strain values are measured and used to calculate stress values. These are then plotted against strain to produce the stress-strain diagram for the material. Traditionally, stress is plotted on the vertical axis and strain on the horizontal axis. Many of the basic physical properties of dental materials can be represented on a stress-strain diagram. For example:

--the straight part of the line represents the region of elastic deformation
--the curved part of the line represents the region of elastic and plastic deformation
--the slope of the straight part of the line represents modulus of elasticity
--the length of the curved part of the line represents ductility
--the area under the straight part of the line represents resilience
--the area under the entire line represents toughness

MODULUS OF ELASTICITY (ELASTIC MODULUS, YOUNG'S MODULUS)

is a measure of the relative stiffness or rigidity of a material. The unit values are those of force per area because

Modulus of Elasticity = Stress/Strain

Note, however, that this only applies to the elastic portion of the stress-strain diagram. On the stress-strain diagram, the modulus is indicated by the slope of the linear part of the line. Therefore, a material with a steep line will have a higher modulus and be more rigid than a material with a flatter line. Modulus is a reflection of the strength of the interatomic or intermolecular bonds. It is unrelated to strength and to proportional limit and is unaffected by age hardening heat treatment and by cold working.

PROPORTIONAL LIMIT

is the amount of stress required to produce permanent deformation of a material; can alternatively be defined as the limit of proportionality of stress to strain; is represented on the stress-strain diagram as the point where the plotting converts from a straight line to a curve. Below the proportional limit, stress is proportional to strain. Stresses below the proportional limit cause elastic (non-permanent) deformation and those above it cause elastic and plastic (permanent) deformation. A high proportional limit is desirable for a restorative material.

ELASTIC LIMIT

is the maximum amount of stress that a structure can withstand and still return to its pre-stressed dimensions; it is, for all practical purposes, the same as the proportional limit.

YIELD POINT

is the point of first marked deviation from proportionality of stress to strain on the stress-strain diagram; it indicates that the structure is undergoing a pronounced degree of deformation with little additionally applied stress.

YIELD STRENGTH

is the amount of stress required to produce a predetermined amount of permanent strain (usually 0.1% or 0.2% which is called the percent offset). Although many feel it is equivalent to proportional limit, it is a useful property because it is easier to measure than the proportional limit. This is because you are already a certain way out on the stress-strain curve and are not attempting to measure the exact point where proportionality of stress to strain ends. It is measured using the stress-strain diagram by locating the point 0.1% or 0.2% out on the strain axis and drawing a line up to the curve which is parallel to the line found in the elastic region.

ULTIMATE STRENGTH

is the maximum amount of stress that a material can withstand without undergoing fracture or rupture. It can be applied to compressive, tensile, or shear stresses (i.e., compressive strength is the maximum amount of stress that a material can withstand without undergoing fracture or rupture in compression).

FRACTURE STRENGTH

is the amount of stress required to produce fracture or rupture.

DUCTILITY

is the ability of a material to undergo permanent tensile deformation without fracture or rupture, or the degree to which you can permanently deform a structure using a tensile force without it undergoing fracture or rupture. Ductility can be measured in three ways: percentage elongation, reduction in area of the fractured ends, or the cold bend test. Percentage elongation is measured by scribing a gauge length (usually 50 mm or 51 mm) on a dumbbell-shaped specimen and loading it uniaxially to failure in tension. Percentage elongation is the change in length divided by original length multiplied by 100. Reduction in area of the fractured ends is measured in essentially the same way except that reduction in area is measured. The cold bend test measures the number of bends that a rod or wire can withstand prior to fracture. A specimen is clamped vertically in a vise and bent to the horizontal. Subsequent bends are through angles of 180 . The test is sensitive not only to ductility but also to specimen diameter.

An increase in temperature decreases ductility because a material's strength generally decreases with an increase in temperature. Ductility is unrelated to proportional limit. One way that ductility is used in dentistry is as a measure of burnishability. The burnishability index is defined as the percentage elongation divided by the yield strength. Therefore, the greater the ductility and the lower the yield strength, the greater the burnishability.

MALLEABILITY

is the ability of a material to undergo permanent compressive deformation without fracture or rupture or the degree to which you can permanently deform a structure using a compressive force without it undergoing fracture or rupture.

An increase in temperature generally results in a increase in malleability because malleability is dependent upon dislocation movement, and dislocations generally move more easily at a higher temperature.

BRITTLENESS

is the material behavior where a material undergoes fracture or rupture with little or no prior permanent deformation. Materials that are brittle usually have a very ordered atomic structure which does not permit the easy movement of dislocations. A good example is the class of materials known as ceramics. Their ordered atomic structure does not permit easy dislocation movement, and hence, they are brittle.

Brittle materials are sensitive to internal flaws/cracks/voids and do not respond well to tensile or bending forces because these forces tend to propagate the flaws/cracks/voids. Brittle materials do well under compressive forces, however, because they tend to close cracks.

RESILIENCE

is the resistance of a material to permanent deformation under sudden impact; may also be defined as the amount of energy absorbed by a material when it is stressed to a point just shy of its proportional limit. The property is often described as "springback potential." It is quantitatively measured as the *modulus of resilience* which is the proportional limit squared divided by 2 times the modulus of elasticity. This quantity is reported in units of energy per volume. Resilience is represented graphically by the area under the linear part of the stress-strain diagram.

A high modulus of resilience is desirable in a restorative dental material. For orthodontic wires, it means that they are capable of storing energy which may then be delivered over an extended period of time. Orthodontic wires (specifically beta-titanium and stainless steel wires) illustrate the role that proportional limit and modulus of elasticity play in determining resilience. Beta-titanium wires are more resilient than stainless steel wires though they have essentially the same proportional limit because the beta-titanium wires have a lower modulus of elasticity.

TOUGHNESS

is the resistance of a material to fracture under sudden impact or the amount of energy absorbed by a material when it is stressed to a point just shy of its fracture point. It is the area under the entire stress-strain diagram. Strong materials are generally tough although ductility has a more pronounced effect in determining toughness. Toughness is usually measured using a pendulum impact test like the Charpy (where the specimen is held horizontally) or the Izod (where the specimen is held vertically) and is commonly used in industry for quality control purposes. Toughness is primarily a concern where materials are brittle because ductile materials already have a measure of toughness. A great deal of effort has been expended in dental materials research in an attempt to find ways of increasing toughness.

TEAR STRENGTH

is resistance to tearing. Tear strength is an important property for impression materials; the polysulfides have a high tear strength which is advantageous because it allows them to be removed from undercuts without tearing. The polyethers, on the other hand, have a low tear strength. Tear strength for most impression materials is maximized by removing them with a snap parallel to the long axis of the teeth.

FRACTURE TOUGHNESS

is a measure of the resistance of a material to failure from crack propagation in tension. It is most often measured by using a single-edge notch, three-point loading test. Since fracture toughness is an inherent property of a material, it tells more about the material than transverse strength which is more dependent upon specimen preparation. Because fracture toughness relates to crack propagation as opposed to crack initiation, surface condition is of little importance.

TRANSVERSE STRENGTH (FLEXURE STRENGTH, MODULUS OF RUPTURE)

is a measure of how a material behaves when under multiple stresses. It is measured by subjecting a beam of the material to three- or four-point loading which results in the development of compressive stresses on the top of the beam, tensile stresses on the bottom, and shear stresses on the sides. Compressive stresses convert to tensile ones through the neutral axis along the center of the beam. This type of test is reserved for materials like denture base resins that experience these types of multiple stresses during function. The test is very sensitive to specimen preparation, specifically to the condition of the surface on the tensile side.

FATIGUE

Fatigue refers to the fact that under cyclic loading a material will undergo failure at a lower applied stress than it normally would if it were not under cyclic loading. The name "fatigue" is derived from the fact that the materials seem to tire under this type of repetitive loading. Two common ways are used to discuss fatigue; *endurance limit* and *service lifetime*. Endurance limit is the maximum applied stress that a material can withstand and still have an unlimited number of cycles to failure. Service lifetime describes a way of predicting the number of cycles to failure a material can be expected to undergo prior to failure when it is loaded with a specific force. Fatigue leads to failure of materials because it promotes crack propagation. Surface conditions (roughness and sharp angles) promote fatigue failure. Fatigue has a role to play in the failure of amalgam and denture base resins.

RHEOLOGY

the study of the flow of matter.

Viscosity

is resistance to flow. Therefore, a liquid with a high viscosity is thick and has a high resistance to flow and a liquid with a low viscosity is thin and has a low resistance to flow. Viscosity is caused by the internal frictional forces in the liquid and is measured as shear stress divided by shear strain rate. Units of measurement are centipoise.

Viscoelastic

describes materials that exhibit characteristics of both a viscous liquid and an elastic solid. These types of materials have properties that vary with rate of loading. Viscoelastic materials, like alginates, show little permanent deformation when loaded quickly but exhibit a great deal of permanent deformation if loaded slowly.

Types of Fluid Behavior

1. *Newtonian (ideal) Liquids*

are liquids with a constant viscosity regardless of shear rate. Examples include water and newly mixed zinc phosphate cement.

2. *Plastic Liquids*

are rigid until a certain yield stress is applied to them. The application of this yield stress to cause flow in a plastic material is called the Bingham characteristic. A non-dental example is catsup.

3. *Pseudoplastic (shear-thinning) Liquids*

show a decrease in viscosity with an increase in shear rate. Examples include the polycarboxylate cements and non-water mixed glass ionomer cements.

4. *Dilatant (shear-thickening) Liquids*

show an increase in viscosity with an increase in shear rate. Traditional (conventional) resin composites are a good example.

5. *Thixotropic Liquids*

are liquids whose viscosity depends upon their previous shear history. In other words, if you shear them, their viscosity will decrease; if you then allow them to remain undisturbed, their viscosity will increase to presetressed levels. Examples include prophy pastes and topical fluoride gels. The opposite of thixotropic is rheopexic.

Working Time is defined as the amount of time from the start of mixing until the material becomes so thick that it can no longer be manipulated.

Setting Time is the amount of time from the start of mixing until the material achieves a specific degree of rigidity appropriate to its application.

The desired situation is one in which there is adequate working time with a snap set.

Clinical Applications of Rheology

The aqueous and nonaqueous elastomeric impression materials, being viscoelastic, should be removed from the mouth with a snap to minimize permanent deformation.

Ideally, we want cements and light-body (syringe) impression materials to be pseudoplastic so that with increasing shear strain rate, they exhibit a decrease in viscosity.

The reason many highly viscous cements (e.g., polycarboxylates, non-water mixed glass-ionomer cements) form thin film thickness layers is because they are pseudoplastic.

LINEAR COEFFICIENT OF THERMAL EXPANSION

The linear coefficient of thermal expansion is defined as the change in length per unit length that a material undergoes when it is subjected to a 1°C change in temperature. This number, which varies from material to material, is often expressed in exponential form. The basis for coefficient of thermal expansion relates to the fact that at equilibrium, atoms are at their lowest energy level. When energy is applied to them, they begin to vibrate and move apart. This results in a gross expansion of the material.

A relationship exists between coefficient of thermal expansion and melting point in that materials with low melting points exhibit large coefficients of thermal expansion. This is because their interatomic bond strengths are low and their atoms easily move apart when energy is applied. The opposite is true for materials with high melting points. Because their interatomic bond strengths are high, they exhibit small coefficients of thermal expansion. When coefficients of thermal expansion of a restorative material and tooth structure are different, they expand and contract to differing degrees as temperatures change; this promotes leakage at the interface between them.

THERMAL CONDUCTIVITY

The coefficient of thermal conductivity is defined as the amount of heat in calories/second passing through a 1-cm thick specimen having a cross-sectional area of 1 cm^2 when the heat differential between the ends is 1°C. The higher the value, the greater the material's ability to conduct thermal energy. These values may vary according to the specimen material and have been measured for tooth structure, cements, and dental amalgam.

THERMAL DIFFUSIVITY

measures the rate of transfer of thermal energy when the heat source is fluctuating. This may be a more important property in dentistry than thermal conductivity because temperatures change rapidly in the oral cavity. It can, for example, be related to the ability of a base material to protect a tooth from thermal damage. The effectiveness of a base material in this regard is inversely proportional to the square root of the thermal diffusivity.

HARDNESS AND HARDNESS TESTING

Hardness can be defined as resistance to permanent indentation. Various tests are used to measure the hardness of dental materials.

Classification of Hardness Tests

1. By method of applying indenter: Static (slowly applied) or Dynamic (rapidly applied)
2. By amount of load applied through indenter: Macrohardness (when more than 1 kilogram of load is applied) or Microhardness (when less than 1 kilogram of load is applied)
3. By size of indenter: Microindentation (small-indenter tip) or Macroindentation (large-indenter tip)

Some of the most familiar hardness tests are the *Brinell, Vickers, Knoop,* and *Rockwell*.

In general, hardness test numbers are obtained by dividing the load applied to the specimen by the area or depth of the indentation that is produced.

Brinell

This test employs a 1.6-mm hardened steel ball through which a 27.7-pound load is applied to the material being tested. The BHN values are technically expressed in terms of kg/mm^2, however most commonly a number is given without associated units. The higher the value, the harder the material. This test is best suited for testing ductile materials.

Limitations of the test:

--cold worked metals show "ridging" around the indentation

--annealed metals show "sinking" of the indentation

Both of these make it difficult to accurately measure the diameter of the indentation.

Certain requirements exist for proper testing:

1. the specimen must be flat
2. the specimen must be 10 times thicker than the expected depth of the indentation
3. the testing should not be done close to the edge of the specimen
4. indentations should not be made too close to each other

Vickers

The Vickers hardness test employs a 136 pyramid-shaped diamond indenting tool with a square base that applies a constant load to the material being tested. The lengths of both diagonals of the indentation are measured to allow calculation of the indentation area. A significant advantage of this test is that it can be used for testing very small specimens because the indenter tip is small. Also, because the load applied to the specimen can be varied, the test can be used on materials that are soft as well as on those that are hard. The Vickers test is best suited for the testing of brittle materials but can also be used for ductile ones.

Knoop

One of the most commonly used tests for measuring the hardness of dental materials, the Knoop hardness test is a microindentation test using a pyramid-shaped diamond indenter with a rhomboidal base. Although it can be used for measuring hardness of both ductile and brittle materials, it is ideal for the measurement of elastic materials because most of the recovery of these materials is across the short diagonal. This is important because only the long diagonal is measured for calculation purposes. The Knoop test has the same advantages as the Vickers test. Major disadvantages are that the specimen surface must be highly polished and the time required to complete the test is longer than for other hardness tests.

Rockwell

The indenters used in this test are diamond cones or steel balls. Main advantages are that it is a quick test taking only 10 to 15 seconds, and readings are taken directly from a dial so the operator performing the test does not have to enter into a subjective measurement process (which can introduce error).

Method: A minor load (light load) is applied to the indenter and the dial gauge is set to zero. A major load (heavier load) is then applied and after reduction back to the minor load, the reading is made. The test essentially measures the distance from the bottom of the minor load indentation to the bottom of the major load indentation.

Both *Rockwell* and *Superficial Rockwell* tests exist; the difference between the two involves the magnitudes of the major and minor loads. The Superficial Rockwell test uses lighter loads and measures hardness on the surface of the material being tested.

General Hardness Information

Two other hardness tests exist: the *Shore A Durometer* and the *Barcol*. These are used to measure rubbery materials.

Conversion of hardness numbers from one test (eg, Vickers) to hardness numbers of another test (eg, Knoop) can be made but these types of conversions are at best only an approximation.

Reasons for measuring hardness

--we measure hardness not so much for the property itself but as an indicator of other properties; it is, however, sometimes valuable to know just how hard a material is. For example, knowing that the base metal alloys are 30% harder than the Type IV gold alloys indicates that special finishing equipment will be needed to finish them.

Hardness can also be used as an indicator of:

*resistance to wear - although hardness is not an absolute indicator of wear resistance, in the case of resin composites it has been shown that hardness of the matrix plays a major role in resistance to wear

*strength - some materials like gypsum show a relationship between hardness and strength

*degree of polymerization - hardness indicates degree of monomer conversion in denture base resins and resin composites; higher hardness values indicate a greater degree of polymerization

*depth of cure of resins - depth of cure of light-activated resins can also be evaluated using hardness tests. This is done by light activating a composite specimen of known depth, measuring the surface hardness, then turning it over and measuring the hardness on the bottom surface; to be considered completely polymerized, the bottom surface must be at least 80% as hard as the top surface

Thickness of the tested specimen is important in performing hardness tests because if the specimen is too thin, you will actually be measuring the surface beneath the specimen and not the specimen itself.

Changes in the indenter tip (dulling, in particular) can alter the accuracy of the hardness test.

Knoop Hardness Numbers (KHN) of selected materials:

enamel	300
dentin	65
amalgam	100
hybrid resin composite	35
microfill resin composite	25

Hardness is a requirement of ADA Specification No. 5 (Dental Gold Casting Alloys); No. 17 (Denture Relining Resins); No. 27 (Direct Filling Resins) as a means of determining setting times; and No. 64 (dental explorers).

WEAR

Wear is the loss of material from one or both of two contacting surfaces because of the mechanical activity between them. It is a complicated process and is affected by properties such as ductility, hardness, and ultimate strength.

Four Types of Wear:
1. Abrasive
2. Adhesive
3. Fatigue
4. Corrosive

Abrasive (or Frictional)

happens when a smooth, soft surface is worn away by a rough, hard surface.

It is important to note that abrasive wear can either be two-body or three-body; two-body may convert to three-body if portions of the sliding surfaces break away and act as an abrasive.

Hardness is not an absolute indicator of wear and wear resistance. Hard surfaces do not necessarily exhibit greater wear resistance than do soft surfaces.

Two requirements for abrasive wear are that there must be a definite difference in hardness between the two surfaces and the harder one has to be the rougher.

Adhesive

occurs when asperities (microscopic projections) from the two contacting surfaces adhere or cohere to each other and fragment as the surfaces move.

This is the most common type of wear and the most difficult one to prevent because even the most highly polished surfaces exhibit asperities.

Fatigue

occurs when fatigue from cyclic loading causes cracks to develop under the contacting surfaces; the sliding action then causes the surfaces to be lost.

Corrosive

occurs when two contacting surfaces corrode and the sliding action causes the corrosion by-products to be worn away.

WEAR TESTING

In vitro testing: the basic problem with laboratory wear testing of dental materials is that laboratory tests frequently have little predictive value as to what will happen intraorally. The reason is that usually the test process has to be accelerated in an attempt to produce data in a reasonable period of time. This skews or distorts the results and reduces their predictive ability.

Some in vitro tests for wear do exist:

1. weight loss and volume loss
2. two-body and three-body wear
3. indentation hardness
4. surface profilometry

In vivo testing: in vivo wear evaluation may be either direct techniques in which existing clinical wear is compared using established categories to assess degree of wear, or indirect techniques which utilize replicas that are microscopically examined or are compared to standardized dies.

Characteristics of an Ideal Abrasive:

1. irregular shape
2. harder than the surface it is intended to abrade
3. high impact (or body) strength
4. high attrition resistance

Porcelain is a good example of the fact that intraoral wear must always be considered to be a coupled phenomenon; not just the involved material should be examined for wear, but also the opposing dentition or restorative material.

DIMENSIONAL CHANGE

affects a wide range of dental materials. For some materials, like investments, dimensional change is both necessary and beneficial. For other materials, such as resin composites, dimensional change is an unwanted property.

Three Sources of Dimensional Change:

1. thermal
2. chemical
3. mechanical

Thermal Dimensional Change

occurs when thermal energy is added to a system; atoms move away from their equilibrium positions and dimensional change results.

Chemical Dimensional Change

takes place when reactants come together and produce a product having a volume that is different than that of the reactants. A good example are the denture base resins which undergo a volumetric shrinkage of 7% when polymer is added to monomer in a ratio of 3:1 by volume.

Mechanical Dimensional Change

is simply strain, the change in dimension that occurs when a load is applied to a material.