

Permeability

It is one of the physical properties which is an average (or macroscopic) medium property that measure the ability of the porous medium to transmit fluid through it.

In 1856, Darcy first developed the equation to describe fluid flow through a porous media.

$$Q = - (KA/\mu) * (dP/dx)$$

Q = Volumetric Flow (cm³/s)

K = permeability (Darcy's), (cm² x cP)/(sec.x atm))

A = cross-sectional area (cm²)

μ = viscosity (centipoises (cP))

P = pressure (atm); x = length (cm)

Mechanical Testing

The classical view of ceramic materials includes the following:

1. They are brittle.
2. Dislocations are not important because they do not move.
3. They are polycrystalline and fracture along grain boundaries.

Once again the classical view of ceramics and many of our preconceived ideas of how they behave are not always correct. The modern view of ceramics is therefore very different:

1. We may be using the ceramic as a thin film where stresses may be very high.
2. Deformation at high temperatures may be important.
3. In some special “new” ceramics, displacive transformations become important.

Figure A shows (σ–ε) curves for three different materials **at room temperature**.

Material I: This has a high Young’s modulus, high failure stress, low ductility, low toughness, and fractures without significant plastic deformation. This behavior is characteristic of many ceramics.

Material II: This has moderate strength, moderate ductility, deforms plastically prior to failure, and is the toughest of the three. This behavior is characteristic of many metals.

Material III: This has a low Young’s modulus, is very ductile, and has low ultimate tensile strength and limited toughness. This behavior is characteristic of many elastomers.

The strength of ceramics is affected by many factors, and this complexity is illustrated in Figure B The composition and microstructure are particularly significant and mechanical properties depend strongly on these characteristics.

Figure C shows two specific examples that illustrate the role of microstructure on the strength of ceramics.

16.3 ELASTIC CONSTANTS AND OTHER “CONSTANTS”

In this section we will define some of the parameters that describe the mechanical behavior of materials. Some of these parameters are constants, like Young’s modulus E. Some, like hardness, are not. Hardness depends on how the material was tested. These are four constants that are most common.

1- E—Young’s modulus (also referred to as the elastic modulus) is a material constant defined by Eq. 1 for a linear elastic material under uniaxial tensile or compressive stress.

$$\sigma = E\varepsilon \dots\dots\dots(1)$$

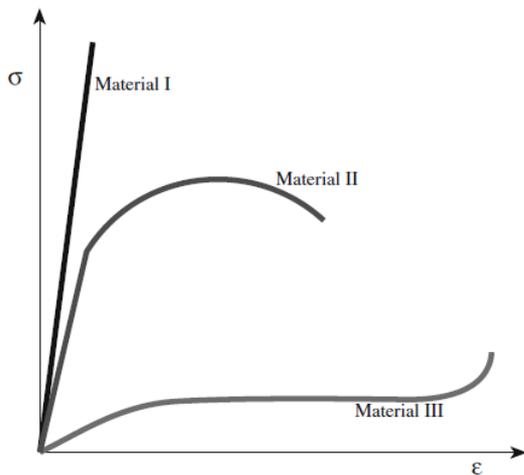


FIGURE A: Idealized stress–strain curves for different materials classes.

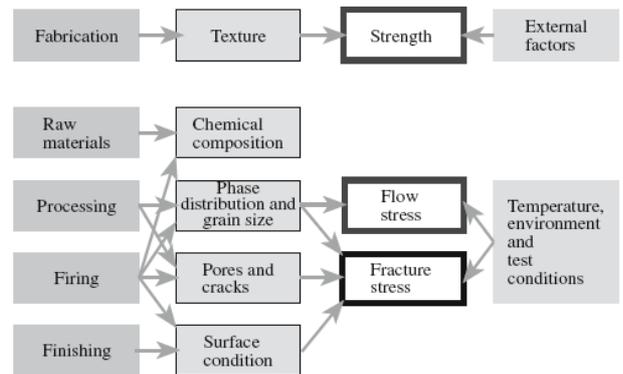


FIGURE B: Factors affecting the mechanical properties of ceramics.

It is therefore the slope of a (σ–ε) curve where only elastic deformation occurs.

2. ν—Poisson’s ratio is the negative ratio of the transverse strain (ε_T) to longitudinal strain (ε_L).

$$\nu = -\varepsilon_T/\varepsilon_L \dots\dots\dots(2)$$

For many ceramics and glasses it is in the range 0.18–0.30.

3. μ—Shear modulus is the ratio of shear stress to shear strain.

$$\mu = \tau/\gamma \dots\dots\dots(3)$$

4. B—Bulk modulus is the ratio of stress to strain for hydrostatic compression.

$$B = -P(\Delta V/V) \dots\dots\dots(4)$$

Although these constants are related directly to bonding forces between atoms, in real ceramics they are affected by microstructure, e.g., porosity and the presence of second phases. Because strain is dimensionless, elastic moduli have the same dimensions as those of stress: force per unit area (N/m²) or in the SI classification Pa and the relationship among them are:

$$E = 2\mu (1 + \nu); \quad E = 3B (1 - 2\nu)$$

EFFECT OF MICROSTRUCTURE ON ELASTIC MODULI

In real ceramics we have to consider the fact that we often have more than one phase present. The overall modulus is then going to be a combination of the properties of each of the phases; it lies somewhere between the high- and low-modulus components. Analytical expressions that represent the upper and lower bounds for Young's modulus include the following.

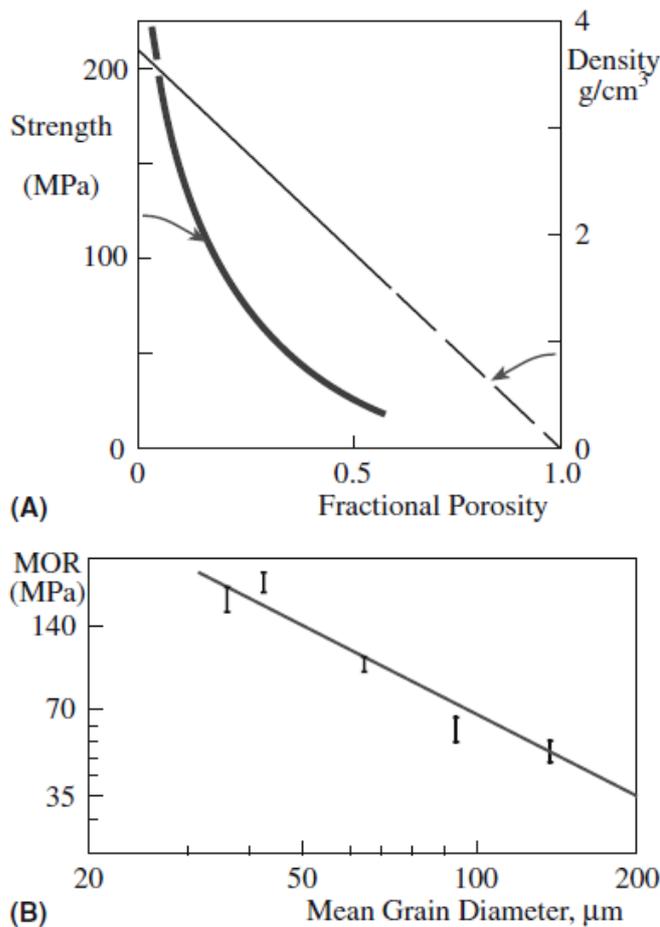


FIGURE C (a) Effect of porosity on the strength of polycrystalline Al₂O₃. (b) Effect of grain size on the strength of BeO.

Voigt Model

Assumption: Strain in each constituent is the same. It represents the upper bound of Young's modulus.

$$E = V_2 E_2 + (1 - V_2) E_1 \quad \dots\dots\dots(5)$$

Reuss Model

Assumption: Stress in each phase is the same. It represents the lower bound of Young's modulus.

$$\frac{1}{E} = \frac{V_2}{E_2} + \frac{(1 - V_2)}{E_1} \quad \dots\dots\dots(6)$$

If the second phase is porosity, as is often the case in polycrystalline ceramics, then intuitively we realize that there will be a decrease in the elastic modulus. A pore has zero stiffness.

TEST TEMPERATURE

Mechanical properties often show strong variations with temperature. The change with temperature may be more abrupt than the gradual decrease in E with increasing temperature. Do ceramics experience a ductile-to-brittle (or the converse) transition and is it important? Ceramics can exhibit both types of behavior over different temperature ranges. Figure D illustrates the temperature dependence of strength for ceramics.

_ Region A: the fracture is brittle and the fracture strain is $\sim 10^{-3}$. There is no significant plastic deformation prior to failure and the strength varies little with temperature.

_ Region B: the fracture is again brittle but slight plastic deformation occurs prior to failure. The failure strain is usually in the region $10^{-3} - 10^{-2}$ and strength falls with increasing temperature.

_ Region C: Appreciable plastic flow occurs, with strains of the order of 10^{-1} prior to failure. This behavior is rarely observed in ceramics, even in ductile polycrystalline ceramics.

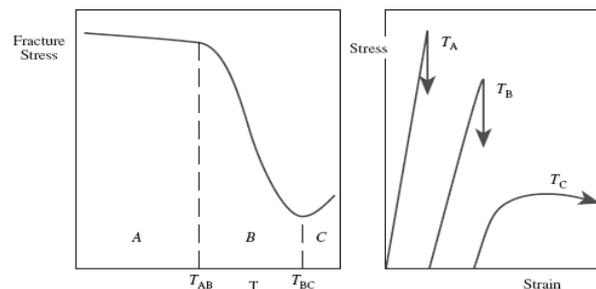


FIGURE D: Illustration of the effect of temperature on fracture stress for a ceramic. The key temperatures are T_{AB} and T_{BC} .

TEST ENVIRONMENT

YOUNG’S MODULUS

We can change the equilibrium spacing (r_0) of the atoms in a solid by applying a force. We can push the atoms closer together (compression), $r < r_0$, or pull them further apart (tension), $r > r_0$. Young’s modulus (E) is a measure of the resistance to small changes in the separation of adjacent atoms. It is the same for both tension and compression.

Young’s modulus is related to the interatomic bonding forces and, as you might expect, its magnitude depends on the slope of the force–distance curve at r_0 . Close to r_0 the force–distance curve approximates a tangent; when the applied forces are small the displacement of the atoms is small and proportional to the force.

We can define the stiffness of the bond, S_0 , as the slope of this line:

$$S_0 = \left(\frac{dF}{dr} \right)_{r=r_0} = \left(\frac{d^2E}{dr^2} \right)_{r=r_0}$$

TABLE 1 Typical Bond Strengths

<i>Type of bond</i>	<i>Bond energy (kJ/mol)</i>
Ionic	50–1000
Covalent	200–1000
Metallic	50–1000
van der Waals	0.1–10
Hydrogen	10–40

The stiffness is analogous to the spring constant or elastic force constant of a spring and is the physical origin of Hooke’s law. Close to r_0 we can assume that the force between two atoms that have been stretched apart a small distance r is:

$$F = S_0(r - r_0)$$

If we consider pulling two planes of atoms apart then the total force per unit area can be obtained by dividing F by r_0^2

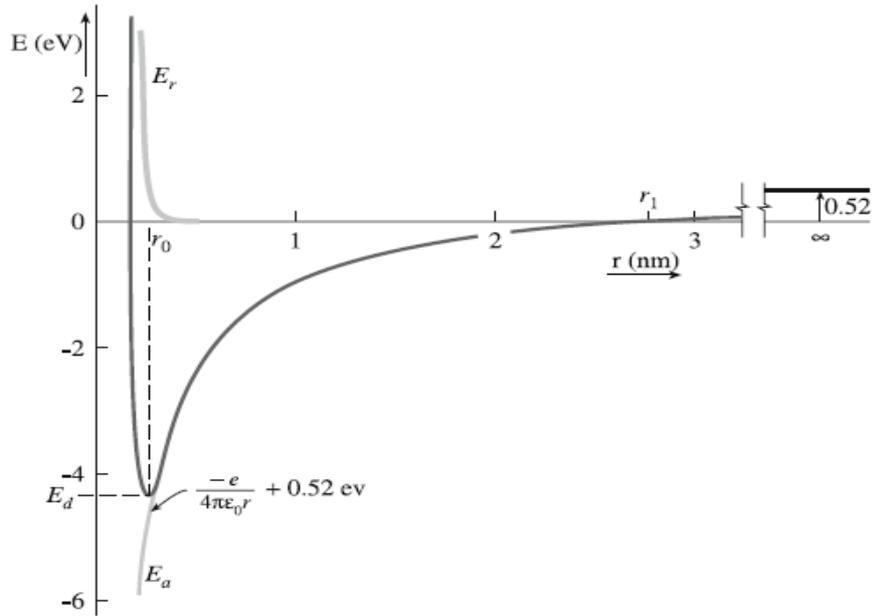


FIGURE E (a) Bond-energy curve for KCl. At infinite separation, the energy is that required to form K_g and Cl_g^- from the corresponding atoms.

$$\frac{F}{r_0^2} = \sigma = \frac{S_0(r-r_0)}{r_0^2} = \frac{S_0}{r_0} \left(\frac{r-r_0}{r_0} \right) = \mathcal{E}\epsilon$$

where σ and ϵ are stress and strain, respectively. Moduli obtained from this approach are approximate because they relate to two atoms only, ignoring the effects of neighboring atoms. As the interatomic spacing, and in some cases the bonding, varies with direction in a single crystal, Young's modulus is dependent upon the direction of stress in relation to the crystal axes. Single crystals are elastically anisotropic. As the temperature of a material is increased it is generally found that Young's modulus slowly decreases as shown for single-crystal aluminum oxide (corundum) in Figure F. As we approach absolute zero, the slope of the curve approaches zero as required by the third law of thermodynamics. (The entropy of any pure substance in complete internal equilibrium is zero.) An empirical relationship that fits the data for several ceramics is

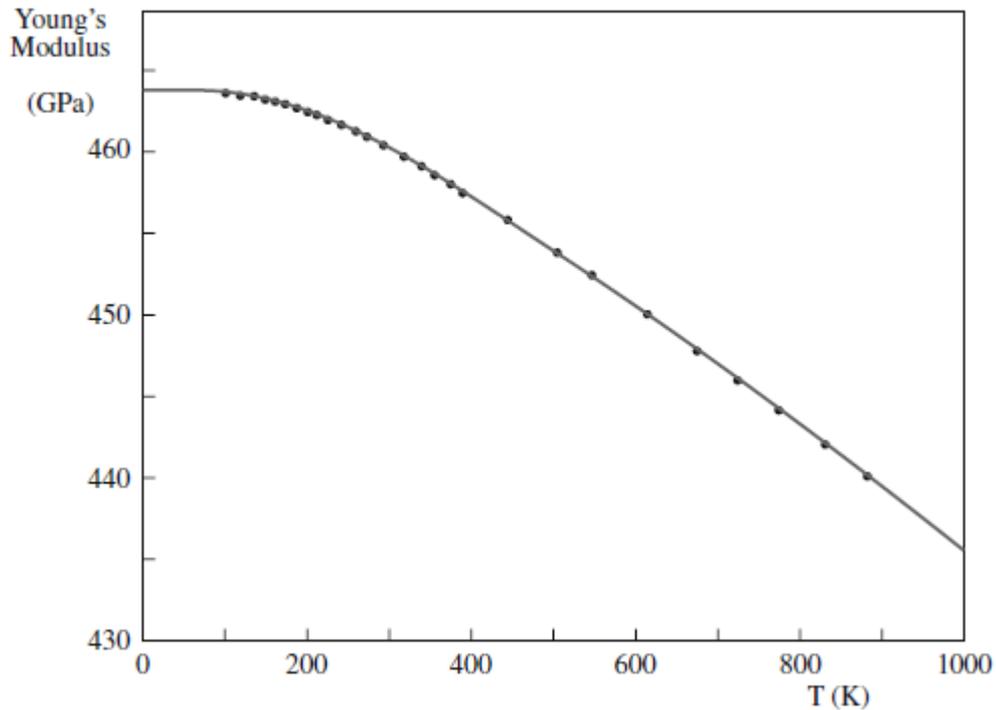


FIGURE F: Temperature dependence of Young's modulus for corundum.

$$E = E_0 - bT \exp\left(\frac{-T_0}{T}\right)$$

E_0 is Young's modulus at absolute zero and b and T_0 are empirical constants; T_0 is about half the Debye temperature. (The Debye temperature is the temperature at which the elastic vibration frequency of the atoms in a solid is the maximum.) As the temperature is increased the separation between the atoms is increased and the force necessary for further increases is slightly decreased. For polycrystalline ceramics there is an additional effect due to grain boundaries. At high temperatures there is a rapid decrease in the measured values of Young's moduli as shown in Figure G. This has been attributed to nonelastic effects such as grain boundary sliding and grain boundary softening. So Young's modulus of a bulk ceramic is continuing to change but we are measuring changes due to the grain boundaries.

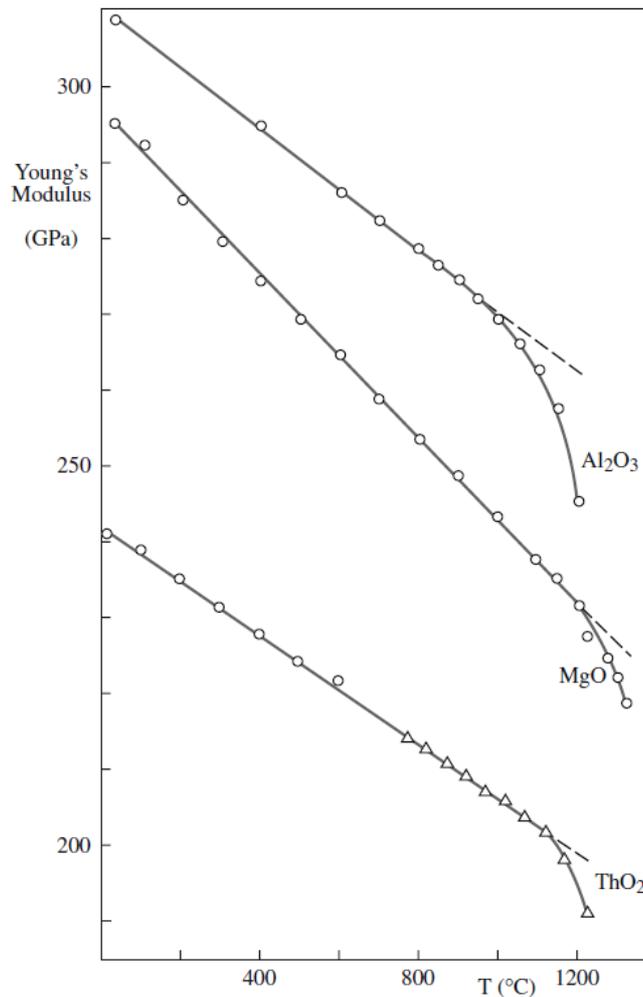


FIGURE G Temperature dependence of Young's modulus of several polycrystalline ceramics.

Measurement of Young's modulus

How is Young's modulus measured? One way is to compress the material with a known compressive force, and measure the strain. Young's modulus is then given by $E = (\sigma/\epsilon) \sim$, each defined as described earlier. But this is not generally a good way to measure the modulus. For one thing, if the modulus is large, the extension u may be too small to measure with precision. And, for another, if anything else contributes to the strain, like creep (which we will discuss in a later chapter), or deflection of the testing machine itself, then it will lead to an incorrect value for E - and these spurious strains can be serious.

A better way of measuring E is to measure the natural frequency of vibration of a round rod of the material, simply supported at its ends (Fig. H) and heavily loaded by a mass M at the middle (so that we may neglect the mass of the rod itself). The frequency of oscillation of the rod, f cycles per second (or hertz), is given by

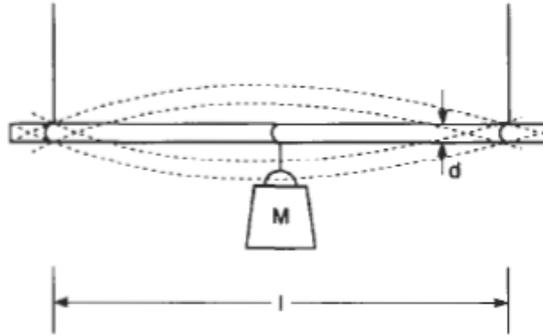


Fig. H: A vibrating bar with a central mass, M.

$$f = \frac{1}{2\pi} \left\{ \frac{3\pi E d^4}{4I^3 M} \right\}^{1/2}$$

where I is the distance between the supports and d is the diameter of the rod. From this,

$$E = \frac{16\pi M I^3 f^2}{3d^4}$$

Use of stroboscopic techniques and carefully designed apparatus can make this sort of method very accurate.

The best of all methods of measuring E is to measure the velocity of sound in the material. The velocity of longitudinal waves, v_l , depends on Young's modulus and the density, ρ :

$$v_l = \left(\frac{E}{\rho} \right)^{1/2}$$

v_l is measured by 'striking' one end of a bar of the material (by glueing a piezo-electric crystal there and applying a charge-difference to the crystal surfaces) and measuring the time sound takes to reach the other end (by attaching a second piezo-electric crystal there). Most moduli are measured by one of these last two methods.

References:

- 1- "Engineering Materials 1 An Introduction to their Properties and Applications", by Michael F. Ashby and David R. H. Jones
- 2- ASTM manuals.
- 3- "ceramic materials", C. Barry & M. G. Norton.
- 4- " Materials Engineering, Science, Processing and Design", by Michael Ashby, Hugh Shercliff and David Cebon.