Mechanical properties of intact rock and joints

Mechanical properties of rock that are of most importance to engineering design are elastic properties and strength. In this regard, field-scale rock masses are composite materials that are composed of numerous joints (discontinuities) and blocks of intact rock between joints. Deformation of this composite under changing loads is largely determined by: (1) intact rock elastic moduli and strength and (2) stiffness and strength of joints. These properties may be determined by laboratory tests on relatively small samples that have dimensions of the order of inches or centimeters. Confining pressure, rate of loading, temperature, time, and peculiarities of testing apparatus are often observed to affect test results on strength but have only a minor influence on elastic moduli. Within the engineering design domain and range of environmental variables, the effect of confining pressure on strength is most significant. Rock includes an enormous variety of materials from volcanic glass to reef coral, from fresh granite to welded tuff, from pegmatite to porphyry, limestone to marble, shale to slate, sandstone to quartzite, peat to coal, and so on. Not too surprisingly, there are exceptions and departures from the norms.

Rock types based on genetic or geological classification systems seldom relate to engineering properties. Although one may intuitively suppose that there is an association of property values with rock types, there is often little correlation. Some sedimentary rocks have high strength, while some igneous rocks have low strength, and so on. However, there are several rock classification systems available for engineering purposes that allow for preliminary estimates of excavation stability or safety. The most popular engineering classification systems are the rock mass rating (RMR) and quality (Q) systems. These classification systems characterize rock masses by a single number based on a combination of laboratory measurements and field observations, that is, on intact rock properties, joint properties, joint spacing, and whether water is present. The purpose of classification schemes is to assist in determining tunnel support requirements in advance of excavation. While rock and joint properties determined by laboratory testing do not automatically lead to elastic moduli and strengths of field-scale rock masses, they form an essential part of any site-specific database needed for design, even at the earliest stages of site evaluation.

The American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM) have published standards for conducting a variety of laboratory tests. ISRM also has published suggested standards for field tests and measurements ***in situ***. These standards give meaning to rock properties test results and allow for comparisons amongst rock types and testing laboratories. Various tabulations of rock properties data may be found in the references.

Elastic moduli of intact rock

Elastic moduli of isotropic media commonly determined in laboratory testing are Young's modulus E and Poisson's ratio ν. Shear modulus G is usually computed from E and ν. These moduli may be determined statically and dynamically, although static elastic moduli are determined most often. Measurements are usually done on cylindrical test specimens prepared from a diamond drill core obtained during site exploration. An additional measurement of lateral displacement allows for the determination of Poisson's ratio. Figure 1 is a schematic of a laboratory test for Young's modulus.

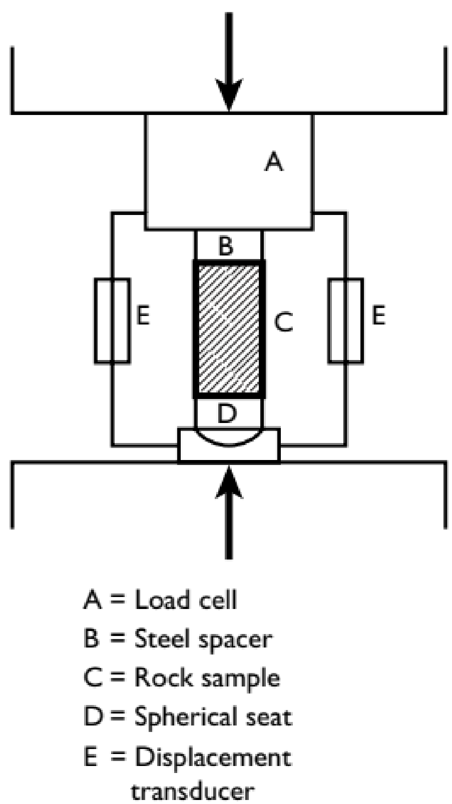

Figure 1 Schematic of apparatus for measuring Young's modulus and Poisson's ratio on an intact rock test cylinder.

Young's modulus

Cores prepared with smooth ends and with a length-to-diameter ratio (L/D) of two are loaded axially in compression. A cycle of loading and unloading is done first to ensure the proper functioning of the system and to seat the apparatus. Subsequent cycles of loading and unloading show greater reproducibility, narrower loops, and steeper plots of axial force versus displacement. Data are obtained after seating the apparatus and test cylinder. If strain gages are attached to the test specimen, then a plot of axial stress as a function of axial strain allows for the determination of Young's modulus. Strain gages have the advantage of reacting directly to the rock but are more expensive than the use of displacement transducers. Figure 2 presents the results of the laboratory test for Young's modulus for a variety of rock types. The range of test results indicates that variability is to be expected. Ranges of Young's modulus according to rock type indicates a wide range for a given rock type and no correlation of modulus with rock type.

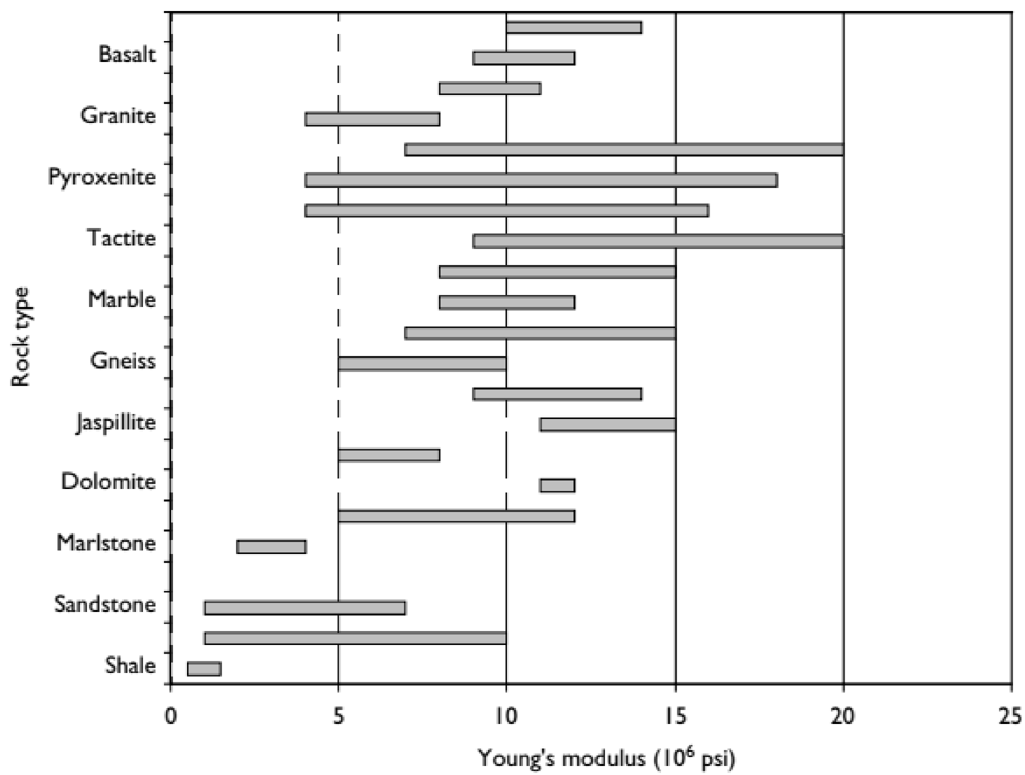

Figure 2 Laboratory test data for Young's modulus.

Coal is a rock type that is in a class by itself because of its organic constitution and commercial importance. A wide range for Young's modulus from 1 to over 51 GN/m^2 (0.15 to 7.4 × 106 psi). This large range is caused, in part, by directional dependencies (anisotropy), but mainly by coal rank that ranges from sub-bituminous to anthracite. A likely range of Young's modulus for most bituminous coal is perhaps 2 to 5 GN/m^2 (0.29 to 0.73 × 106 psi). However, recognition of anisotropy may be important at any particular site.

The theory behind the test for Young's modulus is Hooke's law which in consideration of the uniaxial loading reduces to $\sigma a = E\varepsilon a$ for the axial direction. Thus, a plot of axial stress versus axial strain does indeed allow Young's modulus to be determined by simply measuring the slope of the plot. The plot is usually curved, as shown in Figure 3 where compression is positive. The slope of a tangent to the stress-strain curve defines a *tangent modulus E*t. A line drawn from the origin to a point on the curve defines a *secant modulus E*s. Measurement of the tangent modulus at 50% of the unconfined compressive strength defines Young's modulus for engineering design.

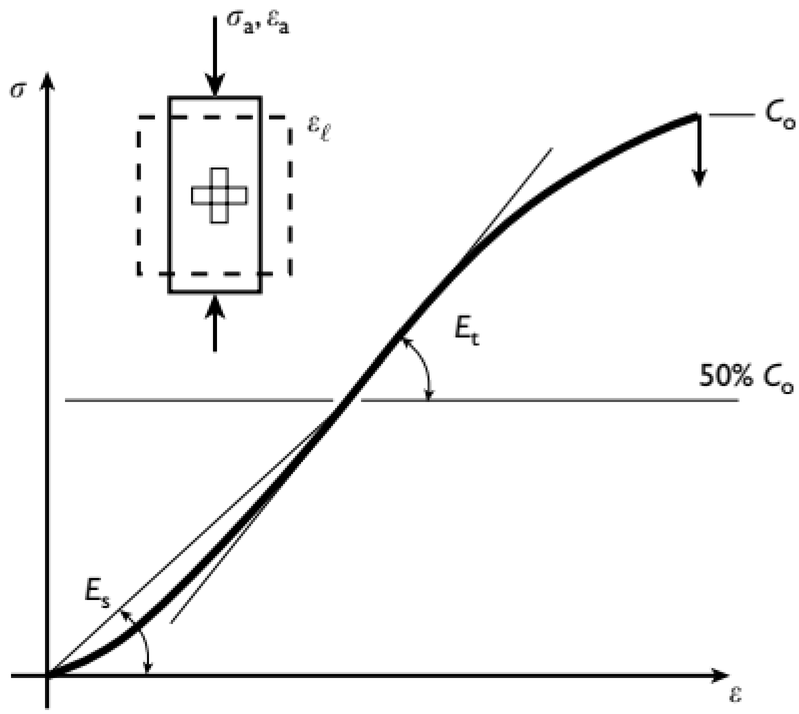

Figure 3 An axial stress-strain plot for Young's modulus.

Measurements of axial force and displacement using displacement transducers instead of strain gages allow for a more economical determination of Young's modulus. However, care must be taken to account for the displacement of steel spacers, spherical seats, and other materials in series with the test specimen. This accounting is easily done graphically, as shown in Figure 4, where a total force-displacement plot and a force-displacement plot without the test specimen are presented. The displacement of the test specimen is the difference between the two plots at the considered level of force. According to Hooke's law $\sigma a = F/A = E\varepsilon a = EU/L$ where F, U, A, and L are force, displacement, the cross-sectional area of the test specimen, and test specimen length, respectively. Again, data reduction is done at about 50% of the unconfined compressive strength of the material.

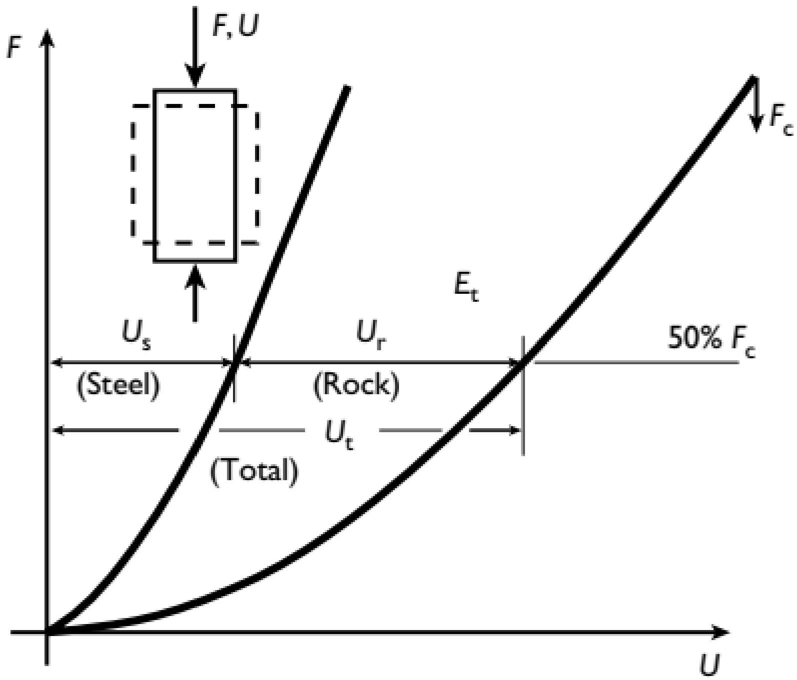

Figure 4 Force–displacements plot for steel and steel plus rock total.