# THE ANGLE-ENVELOPE METHOD OF ANALYZING SHEAR TESTS

Earth Sciences Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

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16. ABSTRACT

The Angle-envelope Method of interpreting shear tests results was first introduced at the 13th Symposium on Rock Mechanics held at the University of Illinois in August 1971. This short discussion has been prepared to provide additional detail and to help clarify the method. The Angle-envelope Method provides a designer with a range of sliding friction angles, phi ($\phi$), and an initial shear value obtained at a predetermined normal load. A designer, depending upon his requirements, is able to select a phi angle which can be used in conjunction with an initial shear value to provide an apparent cohesion most appropriate to his problem. Test data may be interpreted using this proposed method in addition to the conventionally obtained linear regression results. An appendix contains a glossary of terms concerning shear and sliding resistance testing as interpreted and used by the author.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS-- / *shear tests/ shear stress/ stress/ *sliding resistance/ friction/ cohesion/ *rock mechanics/ strength/ characteristics/ rock properties

b. IDENTIFIERS-- / angle-envelope method/ sliding tests/ shear tests/ cohesion intercept

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UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

# FOREWORD

In reading through numerous articles and papers on the subject of shear tests and shear strength, it has been observed that probably all of the assumptions and/or ideas presented in this paper have at one time or another been stated directly or indirectly by various authors. Many papers stress the fact that although there are numerous ways of obtaining and/or estimating shear strength, cohesion, tan phi, etc., for all kinds of rock or rock masses, the engineering expertise and judgment of the user is the final and most important of all the parameters. With this in mind, the following discussion was prepared.

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# DISCUSSION

In rock mechanics, the shear strength of rock is an important parameter to be considered for design purposes. Much information by various authors has been published on shear tests, apparatus, and the interpretation of results obtained. All seem in agreement that shear is not a simple phenomenon in rock masses and discuss at length "i" angles, "d" distances, cohesion, maximum strengths, residual strengths, roughness, etc. All of these factors, in all probability, contribute to the shear strength of a given rock. It is not the intent of this paper to discount any of the above-mentioned items, but to try to provide a method for determining a set of values pertaining to a rock or rock mass that a design engineer, with engineering judgment, can apply to his situation to best design his structure. It is hoped this paper will improve communications between design and rock mechanics engineers.

It is felt that there are four different types of shear strengths for a given rock mass which are determined by three separate test procedures. These types are all related, but appear to be relatively independent of each other at this time. Further study may reveal valuable correlations between them.

The first type is triaxial shear strength which is determined by a triaxial shear test whereby a specimen is failed by an axial pressure

($S_1$), while being constrained by a lateral pressure ($S_3$). A series of tests run on a number of specimens at differing lateral pressures, produces data which can be converted into values for cohesion and an internal friction coefficient. (Since there is some ambiguity in the meaning of terms, the appendix provides a glossary of terms as used in this paper.) The data can be used to develop a PSR (principal stress relationship) curve in addition to Mohr's envelope. The solution to Mohr's envelope can be linear ($\tau = C + a\sigma$) where: $\tau$ = shear stress, C = intercept on $\tau$ axis at $\sigma = 0$, a = slope of line, and $\sigma$ = axial stress; or curvilinear conforming to perhaps a parabolic or exponential curve.

The second and third types of shear strengths are also concerned with a rock mass; but in these, the shear plane is determined by the shear apparatus or testing machine. Type 2 shear strength is through relatively homogeneous, isotropic rock and type 3, which is essentially the same as type 2, is shear strength along a seam, healed joint, bedding plane, or some such feature of the rock under test. Some persons refer to types 2 and 3 as "break bond" or "direct shear" tests. A fourth type of shear strength is that which may be developed along a joint or fracture which has virtually no cohesion, e.g., a specimen which falls apart along the joint when picked up. These joints may mate or fit together perfectly and exhibit a considerable amount of shear strength. This is a sliding resistance or sliding friction test.

Another test procedure which may be used to determine type 2, 3, or 4 shear strengths is the torsional shear test. In this test, a casing is attached to the upper portion of a circular specimen and the rock failed by application of a torque.

Type 1 shear strength will not be discussed since interpretation of these data are well documented. Torsional testing will not be discussed; however, the following method may be applicable to analysis of the results. A method for interpreting data from type 2, 3, and 4 specimens tested by conventional methods in a shear box or direct shear type machine will be presented. As stated earlier, this will provide the design engineer with values he can use rather than becoming involved with mathematical equations involving multiple parameters.

The "Angle-envelope Method" was first presented at the 13th U.S. Symposium on Rock Mechanics held at the University of Illinois, in 1971. The concept will be presented by giving some typical data and working through an example of the analysis.

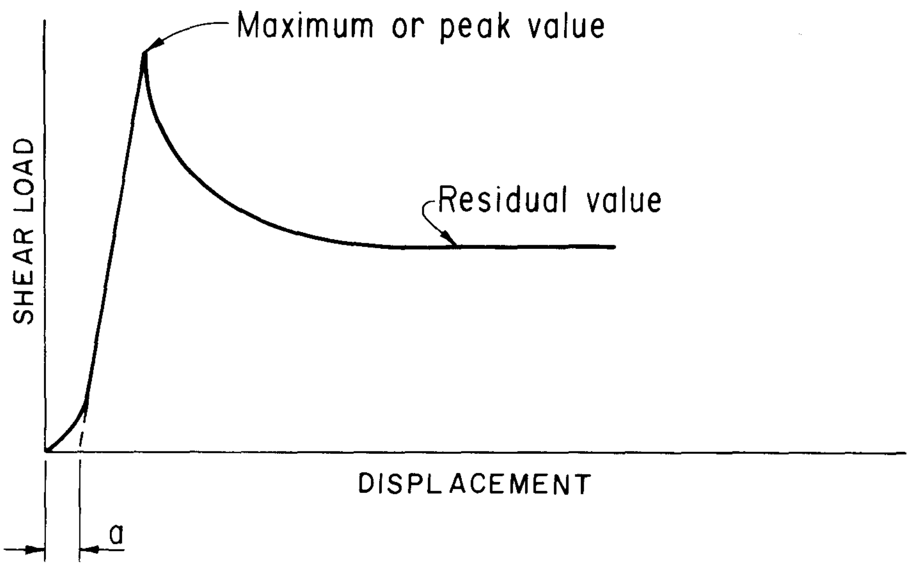


Figure 1. Typical load vs displacement curve for intact specimen, initial or first run.

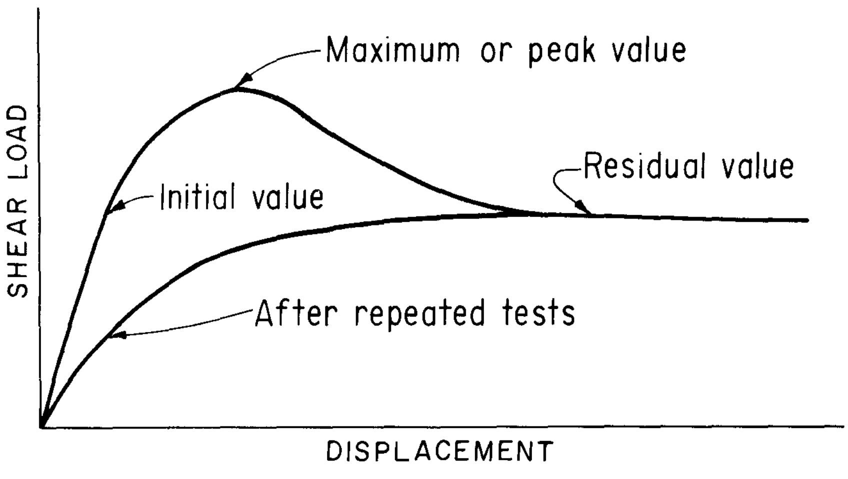


Figure 2. Typical load vs displacement curve for subsequent sliding friction tests.

Figures 1 and 2 show typical data obtained during the course of a shear test. Other authors state that the small flat starting portion of the curve in figure 1 labeled "a", can be related to closing of very small fissures and may or may not appear depending on the rock type. It may also be caused by taking up slack in the test machine. After the initial portion, the curve depicts a stress-strain relationship such as for an elastic material, until failure, which is generally a very sudden brittle-type fracture. Results from subsequent sliding friction tests generally appear as in figure 2. If the small flat part, "a", appears here also, it is probably due to machine slack mentioned previously. Two tests at different normal loads are necessary and three or more are preferable for determining the angle of sliding friction (phi or $\phi$).

Table 1 shows data which would be provided from figures 1 and 2. Run number 1 is the initial or first test conducted on the specimen (fig. 1) and is very important because the values obtained from it are most indicative of the strength of the intact undisturbed rock. Rock specimens cannot be remolded like soil and since no two specimens are exactly alike, very seldom do any two provide nearly identical results. For these reasons, care must be exercised to conduct this test as carefully as possible. This first test is usually performed with a normal stress approximating the value that the engineering structure will provide, whether it is the thrust of an arch dam or the downward force of a gravity dam or bridge abutment. If enough specimens are available, as from a drill hole, they can be tested at many different normal stresses to provide greater confidence in the values for shear strength, cohesion, and tan $\phi$. However, for large field tests, the costs involved are usually very high and few sites or specimens are tested; therefore, extra care should be taken to obtain reliable data from each specimen.

TABLE 1. - Typical values for a sandstone specimen; area = 3.16 in$^2$

| Run number | N (psi) | S (psi) |
|---|---|---|
| 1 (initial) | 100 | 355 |
| 2 | 100 | 120 |
| 3 | 200 | 190 |
| 4 | 300 | 266 |

Runs numbered 2, 3, and 4 in table 1 are subsequent sliding friction tests and results generally appear as shown in figure 2. The series is conducted with increasing normal loads as shown in table 1. Here again, lower normal loads are of the same magnitude as those applied to the rock by structures and these are run first. In addition, higher normal loads will also cause an increasing amount of damage to the sliding surfaces as more and more shearing of asperities takes place which tends to smooth the surface and lower the shear resistance. Results from four or more runs provide data which are then analyzed for use by designers. Figure 3 shows the data from table 1 in graphical form. Figure 4 shows the results as they appear on the computer output sheet.

The assumptions on which the Angle-envelope analysis is based are as follows:

1. After the initial shear test (run number 1), "cohesion" is zero and results from subsequent sliding friction tests should indicate this. This is accomplished by radiating lines from the origin (zero cohesion) through the maximum and minimum values of shear strength (fig. 3).

2. Sliding resistance or friction is independent of area but cohesion is not. To provide a value of cohesion and shear strength in engineering units, all shear and normal values are divided by the area of the specimen at the expected shear plane. Subsequent test points on figure 3 become dimensionless ratios used as the tangent of friction angles.

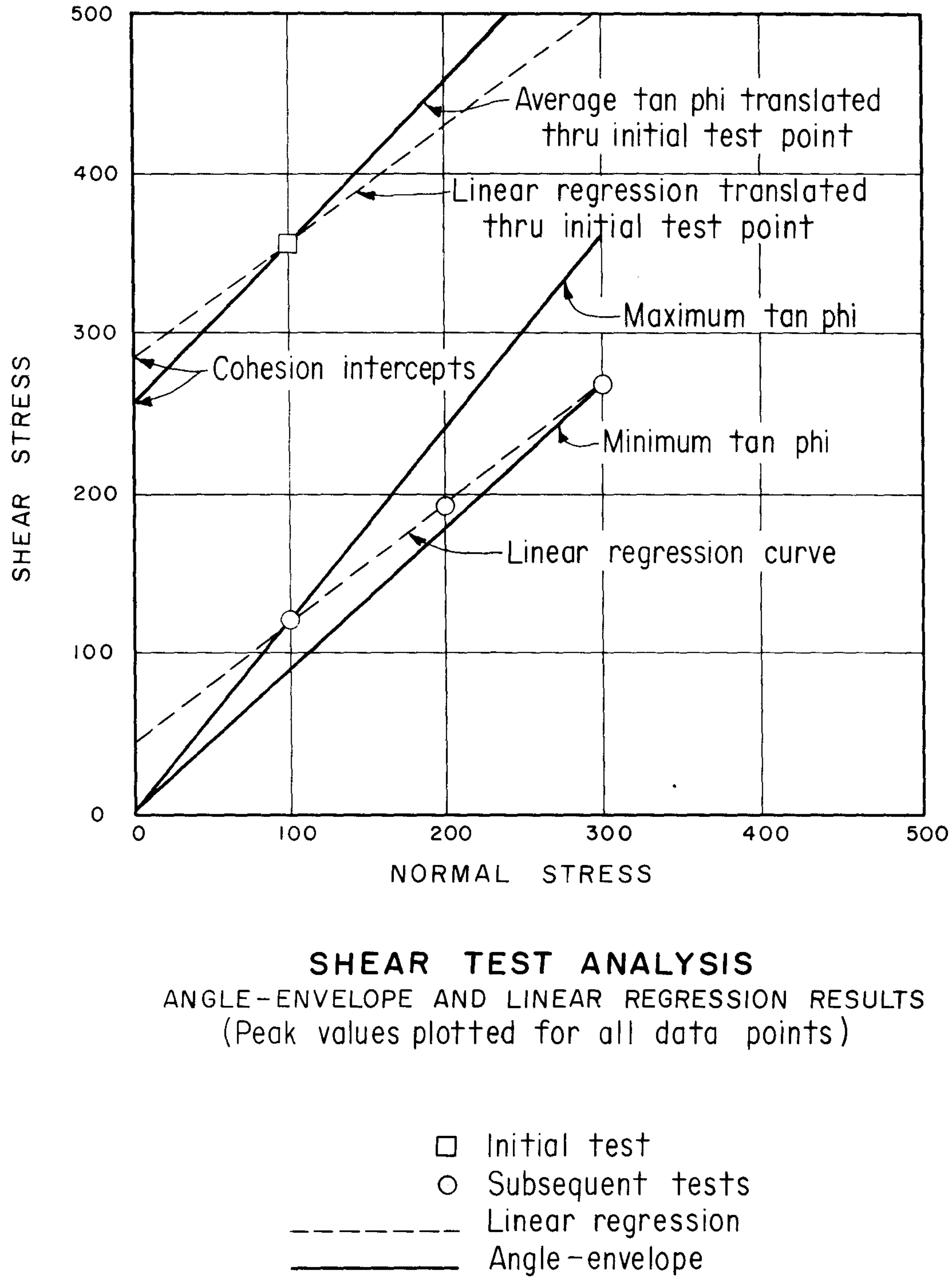


Figure 3. Graph of Angle-envelope and linear regression results for one specimen.

SHEAR TEST ANALYSIS

ANGLE-ENVELOPE AND LINEAR REGRESSION RESULTS

EXAMPLE SPECIMEN

SPECIMEN NUMBER XXXX-YYYY AREA = 3.16 $in^2$

| RUN NUMBER | N | S |
|---|---|---|
| 1 | 100 | 355 |
| 2 | 100 | 120 |
| 3 | 200 | 190 |
| 4 | 300 | 266 |

* LINEAR REGRESSION RESULTS *

S = 46.5 + 0.72854(N) CORRELATION = 0.9997

PHI = 36.1 DEGREES COHESION = 281.9 PSI

* ANGLE-ENVELOPE RESULTS *

PHI MAX = 50.3 DEGREES (1.20367)

PHI MIN = 41.6 DEGREES (0.88692)

PHI AVG = 45.4 DEGREES (1.01362)

COHESION (MAX PHI) = 234.40 PSI

COHESION (MIN PHI) = 266.08 PSI

COHESION (AVG PHI) = 253.41 PSI

Figure 4. Typical computer output of results.

3. The contribution of shear to sliding resistance is minimal after the initial test. Friction, not cohesion, is the major contributor to final results.

4. Dilatency (movement perpendicular to the failure plane) is undoubtedly present at low normal loads and, to a lesser degree, at higher normal loads where more shearing of asperities occurs. It is felt, however, that the "i" angle is contained in the value of tan $\phi$ (e.g. tan $(\phi' + i)$) and should not be separated as it is present throughout the rock being tested. For large specimens, the concept of "i" angle becomes a geometrical consideration more than a shear-related parameter depending upon the direction of the forces applied to the rock mass as related to the orientation of joints and fracture patterns.

With these assumptions, it can be seen that the plot in figure 3 provides a minimum and maximum value for tan $\phi$. Up to now in this discussion, no factor of safety has been applied or implied by any of the results. The expertise and the experience of both the rock mechanics and design engineers must be utilized to select the best value of tan $\phi$ to use for design of the structure under consideration. The failure criteria line, oriented at the selected angle, is then translated until it passes through the first run maximum or peak shear strength value. Following the line back to the $N = 0$

abscissa, a value for the "cohesion" of the rock is obtained. "Cohesion" is underlined because it is not known if this is really the proper term to be used. It may be more properly named "apparent cohesion" or "inherent shear strength" or some other term, known to be extrapolated from the measured data, but probably never attained during shear tests or in an in situ rock mass. The load imposed on a shear feature may never be zero unless an unusual stress field is encountered whereby the structure forces the load on the fault or joint to zero. To this calculated value of cohesion, a safety factor may be applied to provide a logical and valid criteria to use in design formulas. In essence then, the "Angle-envelope" method does not provide a single equation of a line through a series of points (as does the linear regression or Coulomb solution) which when translated to the initial test, provides a value of cohesion. Rather, a range or envelope of friction angles is defined, any of which may be translated to provide a cohesion for a given shear strength.

If the joint is a type 4 (falls apart), the initial test shear strength value usually will fall inside the maximum and minimum tan $\phi$ envelope, especially if the initial normal load is greater than the lowest sliding normal load. An exception would occur for specimens having very rough sliding surfaces which would have a large "apparent cohesion" value. In probably 95 percent of the tests run, the lowest normal load provides the highest sliding friction value. Likewise, 95 percent of the lowest tan $\phi$'s are at the highest normal load. This implies that roughness of asperities (or "i" angle, or dilation) is a much greater factor at these low loads where the shear strength of these features does not come into play. It must be remembered, though, that a much higher shear load must be applied to cause displacement at the higher normal load.

On figure 3, all of the plotted points are peak values which are selected as indicated on figures 1 and 2. Some feel that the peak or maximum value may be justifiably used for the initial shear strength value but residual values should be used to determine the sliding friction angles. This is probably a good conservative scheme, but the design engineer must realize what values are used and guard against on overly conservative design resulting if additional safety factors are applied to already conservative values.

Figure 3 also shows typical results based on the Coulomb linear regression criteria. As can be seen, the results are not radically different from angle-envelope results. Tan $\phi$ is usually less than the minimum tan $\phi$ obtained from the Angle-envelope method. The exception is type 4 joints where linear regression often provides a negative intercept on the N = 0 axis. This cannot occur with the Angle-envelope analysis as an open or type 4 joint is assumed to have zero cohesion.

# APPENDIX

Definitions of various words used in the text as interpreted by the author.

1. Angle-envelope analysis method - the method described in this paper whereby shear test results are presented as a range of friction angles, the most appropriate value of which may be translated until it passes through an initial run shear strength to obtain cohesion for design purposes.

2. Apparent cohesion - (see cohesion).

3. Area - (of specimen) - the planar area measured at the shear failure.

4. Asperities - (see roughness, dilatency, "i" angle) the bumps and hollows that make up the sheared surface.

5. Break-bond - (see direct shear test).

6. Cohesion - shear strength at zero normal load (obtained through extrapolation of data measured at other normal loads).

7. "d" distance - the distance between the two jigs or holding devices to which shear and normal loads are applied, measured generally perpendicular to joint or feature. The shear zone is restricted to the material located within the "d" distance.

8. Dilatency - the tendency for a specimen to expand, before failure, when a shear load causes displacement. Measured parallel with normal load - related to "i" angle.

9. Direct shear test - a test whereby an intact specimen is subjected to a biaxial stress field until shear failure occurs in a predetermined location (as opposed to a triaxial shear test).

10. First test - (see initial test) first run conducted on a specimen.

11. Friction angle - (see sliding friction).

12. "i" angle - a portion of the sliding friction angle, that is produced by specimen geometry rather than true friction, e.g., tan $(\phi' + i)$. Calculated by: i = arc tan (vertical displacement/horizontal displacement). Should be zero for smooth surfaces.

13. Inherent shear strength - (see cohesion) possibly a better term for cohesion when applied to an intact specimen.

14. Initial shear value - (see fig. 2) the point on the shear load vs displacement curve where the line starts to curve or deviate from a straight line. Generally at or near maximum for initial tests (see 15 below). May be used by some design engineers as a value to determine various calculated parameters when no sliding movement can be tolerated.

15. Initial test - the first test run on a specimen to determine the shear strength at a given normal load.

16. Internal friction coefficient - The tan $\phi$ value obtained from a series of triaxial shear tests. Calculated by use of Mohr's envelope.

17. Joint - a term used in this paper to indicate the failure surface either before or after testing. May be an open joint, healed joint, filled joint, seam, fracture, etc.

18. Linear regression - the mathematical method of determining the equation of a straight line that minimizes the square of the distances from the line to a series of points.

19. Maximum value - (peak value) on figures 1 and 2, this is the highest point on the curve as indicated. May be used by designers in lieu of initial shear value.

20. Normal force - the force applied to the specimen perpendicular to the shear plane. Force and load are interchangeable but force generally denotes a direction.

21. Normal load - the load in pounds, kilograms, etc., applied to the specimen.

22. Normal stress - the normal force divided by the planar area of the shear zone.

23. Peak value - (see figs. 1 and 2) see maximum strength value.

24. Phi ($\phi$) - the friction angle = arc tan (S/N).

25. Residual strength value - (see fig. 2) - portion of load vs displacement curve where displacement continues with no change in load. May be used by designers in lieu of initial or maximum value.

26. Roughness - the bumpiness or irregularity of the sheared surface - related to "i" angle, asperities, dilatency.

27. Shear force - the force applied to the specimen parallel to the shear plane.

28. Shear load - the load applied to the specimen which ultimately causes failure or displacement. For some in situ tests this load must be adjusted as it is applied at an angle to reduce overturning moments.

29. Shear test - Generally denotes a direct shear test as opposed to a triaxial or torsional shear test.

30. Shear strength - the value which denotes the ability of a rock of a given area to withstand an applied shear force. Is usually reported as the ultimate or maximum shear stress obtainable.

31. Shear stress - same as shear strength above except that it can range from zero to ultimate dependent on the variables involved.

32. Sliding friction - a dimensionless ratio, generally expressed as a tangent of an angle which relates the shear load to normal load, e.g., phi = arc tan (S/N).

33. Sliding resistance - essentially the same as sliding friction angle or coefficient of internal friction from triaxial tests. Calculated from shear load divided by normal load.

34. Tan phi ($\phi$) - (see phi), a way of stating the sliding friction angle or coefficient of internal friction. Calculated from shear load divided by normal load.

35. Triaxial shear test - a test in which a specimen is confined by a lateral pressure and then failed by axial loading. Yields a PSR curve and Mohr's envelope shear strength results.

# CONVERSION FACTORS–BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-72) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, it gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table 1

QUANTITIES AND UNITS OF SPACE

| Multiply | By | To obtain |
|---|---|---|
| | **LENGTH** | |
| Mil | 25.4 (exactly) | Micron (μ) |
| Inches (in) | 25.4 (exactly) | Millimeters (mm) |
| Inches | 2.54 (exactly)* | Centimeters (cm) |
| Feet (ft) | 30.48 (exactly) | Centimeters |
| Feet | 0.3048 (exactly)* | Meters (m) |
| Feet | 0.0003048 (exactly)* | Kilometers (km) |
| Yards (yd) | 0.9144 (exactly) | Meters (m) |
| Miles (statute) (mi) | 1,609.344 (exactly)* | Meters |
| Miles | 1.609344 (exactly) | Kilometers (km) |
| | **AREA** | |
| Square inches (in$^2$) | 6.4516 (exactly) | Square centimeters (cm$^2$) |
| Square feet (ft$^2$) | *929.03 | Square centimeters |
| Square feet | 0.092903 | Square meters (m$^2$) |
| Square yards (yd$^2$) | 0.836127 | Square meters |
| Acres | *0.40469 | Hectares (ha) |
| Acres | *4,046.9 | Square meters (m$^2$) |
| Acres | *0.0040469 | Square kilometers (km$^2$) |
| Square miles (mi$^2$) | 2.58999 | Square kilometers |
| | **VOLUME** | |
| Cubic inches (in$^3$) | 16.3871 | Cubic centimeters (cm$^3$) |
| Cubic feet (ft$^3$) | 0.0283168 | Cubic meters (m$^3$) |
| Cubic yards (yd$^3$) | 0.764555 | Cubic meters (m$^3$) |
| | **CAPACITY** | |
| Fluid ounces (U.S.) (oz) | 29.5737 | Cubic centimeters (cm$^3$) |
| Fluid ounces (U.S.) | 29.5729 | Milliliters (ml) |
| Liquid pints (U.S.) (pt) | 0.473179 | Cubic decimeters (dm$^3$) |
| Liquid pints (U.S.) | 0.473166 | Liters (l) |
| Quarts (U.S.) (qt) | *946.358 | Cubic centimeters (cm$^3$) |
| Quarts (U.S.) | *0.946331 | Liters (l) |
| Gallons (U.S.) (gal) | *3,785.43 | Cubic centimeters (cm$^3$) |
| Gallons (U.S.) | 3.78543 | Cubic decimeters (dm$^3$) |
| Gallons (U.S.) | 3.78533 | Liters (l) |
| Gallons (U.S.) | *0.00378543 | Cubic meters (m$^3$) |
| Gallons (U.K.) | 4.54609 | Cubic decimeters (dm$^3$) |
| Gallons (U.K.) | 4.54596 | Liters (l) |
| Cubic feet (ft$^3$) | 28.3160 | Liters |
| Cubic yards (yd$^3$) | *764.55 | Liters |
| Acre-feet | *1,233.5 | Cubic meters (m$^3$) |
| Acre-feet | *1,233,500 | Liters |

Table II

QUANTITIES AND UNITS OF MECHANICS

| Multiply | By | To obtain |
|---|---|---|
| **MASS** | | |
| Grains (1/7,000 lb) (gr) | 64.79891 (exactly) | Milligrams (mg) |
| Troy ounces (480 grains) | 31.1035 | Grams (g) |
| Ounces (avdp) (oz) | 28.3495 | Grams |
| Pounds (avdp) (lb) | 0.45359237 (exactly) | Kilograms (kg) |
| Short tons (2,000 lb) | 907.185 | Kilograms |
| Short tons (2,000 lb) | 0.907185 | Metric tons |
| Long tons (2,240 lb) | 1,016.05 | Kilograms (kg) |
| **FORCE/AREA** | | |
| Pounds per square inch (lb/in$^2$) | 0.070307 | Kilograms per square centimeter (kg/cm$^2$) |
| Pounds per square inch | 6894.76 | Pascals (Pa), or Newtons per square meter (N/m$^2$) |
| Pounds per square foot (lb/ft$^2$) | 4.88243 | Kilograms per square meter (kg/m$^2$) |
| Pounds per square foot | 47.8803 | Pascals (Pa), or Newtons per square meter (N/m$^2$) |
| **MASS/VOLUME (DENSITY)** | | |
| Ounces per cubic inch (oz/in$^3$) | 1.72999 | Grams per cubic centimeter (g/cm$^3$) |
| Pounds per cubic foot (lb/ft$^3$) | 16.0185 | Kilograms per cubic meter (kg/m$^3$) |
| Pounds per cubic foot | 0.0160185 | Grams per cubic centimeter (g/cm$^3$) |
| Tons (long) per cubic yard | 1.32894 | Grams per cubic centimeter |
| **MASS/CAPACITY** | | |
| Ounces per gallon (U.S.) (oz/gal) | 7.4893 | Grams per liter (g/l) |
| Ounces per gallon (U.K.) | 6.2362 | Grams per liter |
| Pounds per gallon (U.S.) (lb/gal) | 119.829 | Grams per liter |
| Pounds per gallon (U.K.) | 99.779 | Grams per liter |
| **BENDING MOMENT OR TORQUE** | | |
| Inch-pounds (in-lb) | 0.011521 | Meter-kilograms (m-kg) |
| Inch-pounds | 1.12985 x $10^6$ | Centimeter-dynes (cm-dyn) |
| Foot-pounds (ft-lb) | 0.138255 | Meter-kilograms (m-kg) |
| Foot-pounds | 1.35582 x $10^7$ | Centimeter-dynes |
| Foot-pounds per inch (ft-lb/in) | 5.4431 | Centimeter-kilograms per centimeter (cm-kg/cm) |
| Ounce-inches (oz-in) | 72.008 | Gram-centimeters (g-cm) |
| **VELOCITY** | | |
| Feet per second (ft/s) | 30.48 (exactly) | Centimeters per second (cm/s) |
| Feet per second | 0.3048 (exactly)* | Meters per second (m/s) |
| Feet per year (ft/yr) | *0.965873 x $10^{-6}$ | Centimeters per second |
| Miles per hour (mi/h) | 1.609344 (exactly) | Kilometers per hour (km/hr) |
| Miles per hour | 0.44704 (exactly) | Meters per second |
| **ACCELERATION*** | | |
| Feet per second$^2$ (ft/s$^2$) | *0.3048 | Meters per second$^2$ (m/s$^2$) |
| **FLOW** | | |
| Cubic feet per second (second-feet) (ft$^3$/s) | *0.028317 | Cubic meters per second (m$^3$/s) |
| Cubic feet per minute (ft$^3$/m) | 0.4719 | Liters per second (l/s) |
| Gallons (U.S.) per minute (gal/min) | 0.06309 | Liters per second |
| **FORCE*** | | |
| Pounds (lb) | *0.453592 | Kilograms (kg) |
| Pounds | *4.4482 | Newtons (N) |
| Pounds | *4.4482 x $10^5$ | Dynes (dyn) |

Table II—Continued

| Multiply | By | To obtain |
|---|---|---|
| **WORK AND ENERGY*** | | |
| British thermal units (Btu) | *0.252 | Kilogram calories (kg-cal) |
| British thermal units (Btu) | 1,055.06 | Joules (J) |
| Btu per pound | 2.326 (exactly) | Joules per gram (J/g) |
| Foot-pounds (ft-lb) | *1.35582 | Joules (J) |
| **POWER** | | |
| Horsepower (hp) | 745.700 | Watts (w) |
| Btu per hour (Btu/hr) | 0.293071 | Watts |
| Foot-pounds per second (ft-lb/sec) | 1.35582 | Watts |
| **HEAT TRANSFER** | | |
| Btu in./hr ft$^2$ degree F (k, thermal conductivity) | 1.442 | Milliwatts/cm degree C |
| Btu in./hr ft$^2$ degree F (k, thermal conductivity) | 0.1240 | Kg cal/hr m degree C |
| Btu ft/hr ft$^2$ degree F | *1.4880 | Kg cal m/hr m$^2$ degree C |
| Btu/hr ft$^2$ degree F (C, thermal conductance) | 0.568 | Milliwatts/cm$^2$ degree C |
| Btu/hr ft$^2$ degree F (C, thermal conductance) | 4.882 | Kg cal/hr m$^2$ degree C |
| Degree F hr ft$^2$/Btu (R, thermal resistance) | 1.761 | Degree C cm$^2$/milliwatt |
| Btu/lb degree F (c, heat capacity) | 4.1868 | J/g degree C |
| Btu/lb degree F | *1.000 | Cal/gram degree C |
| Ft$^2$/hr (thermal diffusivity) | 0.2581 | Cm$^2$/sec |
| Ft$^2$/hr (thermal diffusivity) | *0.09290 | M$^2$/hr |
| **WATER VAPOR TRANSMISSION** | | |
| Grains/hr ft$^2$ (water vapor) transmission) | 16.7 | Grams/24 hr m$^2$ |
| Perms (permeance) | 0.659 | Metric perms |
| Perm-inches (permeability) | 1.67 | Metric perm-centimeters |

Table III

OTHER QUANTITIES AND UNITS

| Multiply | By | To obtain |
|---|---|---|
| Cubic feet per square foot per day (seepage) | *304.8 | Liters per square meter per day |
| Pound-seconds per square foot (viscosity) | *4.8824 | Kilogram second per square meter |
| Square feet per second (viscosity) | *0.092903 | Square meters per second |
| Fahrenheit degrees (change)* | 5/9, then subtract 17.78 | Celsius or Kelvin degrees |
| Volts per mil | 0.03937 | Kilovolts per millimeter |
| Lumens per square foot (foot-candles) | 10.764 | Lumens per square meter |
| Ohm-circular mils per foot | 0.001662 | Ohm-square millimeters per meter |
| Millicuries per cubic foot | *35.3147 | Millicuries per cubic meter |
| Milliamps per square foot | *10.7639 | Milliamps per square meter |
| Gallons per square yard | *4.527219 | Liters per square meter |
| Pounds per inch | *0.17858 | Kilograms per centimeter |

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ABSTRACT

The Angle-envelope Method of interpreting shear test results was first introduced at the 13th Symposium on Rock Mechanics held at the University of Illinois in August 1971. This short discussion has been prepared to provide additional detail and to help clarify the method. The Angle-envelope Method provides a designer with a range of sliding friction angles, phi ($\phi$), and an initial shear value obtained at a predetermined normal load. A designer, depending upon his requirements, is able to select a phi angle which can be used in conjunction with an initial shear value to provide an apparent cohesion most appropriate to his problem. Test data may be interpreted using this proposed method in addition to the conventionally obtained linear regression results. An appendix contains a glossary of terms concerning shear and sliding resistance testing as interpreted and used by the author.

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