

Mechanical Behavior of Cement

API TECHNICAL REPORT 10TR7
FIRST EDITION, DECEMBER 2017



AMERICAN PETROLEUM INSTITUTE

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Introduction

Understanding cement mechanical behavior allows oil and gas wells to be better designed for long-term integrity. This document outlines the terminology and common test procedures used to evaluate the mechanical behavior of cement. Testing protocols were compiled from several laboratories within the industry. Cooperative testing helped to check repeatability of testing techniques. Testing was also partially used to guide specifics within any recommended procedures. Curing conditions are dependent on the expected downhole conditions and testing temperature was only considered at atmospheric conditions. Only test methods that are widely used at this time are presented here, such as:

- uniaxial compression test,
- direct and indirect tension test,
- triaxial test,
- acoustic test.

The parameters derived from these tests include:

- unconfined compressive strength,
- Young's modulus,
- Poisson's ratio,
- bulk modulus,
- tensile strength,
- shear failure envelope,
- dynamic Young's modulus,
- dynamic Poisson's ratio.

Cement is used in wellbore construction to provide structural support and prevent annular fluid flow. Cement slurry is pumped in the annulus outside of the tubular. This slurry hydrates into a porous solid. It is important that cement placement is designed and executed successfully for the cemented annulus to initially protect and support the tubular string as well as provide zonal isolation. It is also important that the cement's hardened properties be designed correctly for it to continue to perform long-term. An initially good cement sheath can become compromised when subjected to stress changes experienced in a well (Thiercelin et al., 1998; Bosma et al., 1999; Bois et al., 2012). Changes in stress can result from changes in pressure, temperature, and other fluctuations such as formation compaction and creep caused through wellbore operations (drilling, stimulation, workover, etc.) and production (reservoir depletion). Therefore, it is important to characterize the hardened cement's properties to facilitate estimations of the stress-strain responses of the cement during wellbore operations. These estimates can provide the information necessary for designing a cement system that can withstand the thermal and mechanical stresses the cement sheath may have to endure during its useful life.

There are two common ways to determine the properties of hardened cement. One technique is via “static” measurements using a load frame that yields values of static Young's modulus, static Poisson's ratio, compressive strength, and tensile strength; the second technique uses acoustic measurements that give values of dynamic Young's modulus and dynamic Poisson's ratio. There is not a general correlation between static and dynamic measurements over a wide variety of cement compositions. However, correlations may be established for a limited range of compositions (Reddy et al., 2007). The two methods will be addressed separately with emphasis on the “static” method.

Mechanical Behavior of Cement

1 Scope

The mechanical testing described in this document will provide the necessary cement property data for use in cement sheath integrity simulations. The compressive strength tests and nondestructive sonic determination of compressive strength of cement defined in API 10B-2 do not provide suitable data for cement sheath integrity simulations. The methods of API 10B-2 provide information on the strength of cement to ensure that the cement is suitable for general well construction applications and to determine when sufficient strength is developed to allow well operations to continue.

2 Normative References

This document contains no normative references. For a list of documents and articles associated with this publication, see the Bibliography.

3 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1

effective stress

The part of stress that impacts the mechanical behavior of a material body. Effective stress is calculated by subtracting the pore pressure from the total stress.

3.2

elasticity

The ability of a material to change its form as a result of an applied stress and return to its original form once the stress is removed.

3.3

failure criteria

The prediction or estimation of the failure of a material and the conditions under which it fails under the action of external loads.

3.4

isotropic

Identical properties in all directions.

3.5

load frame

A fixture used to test a material and measure its properties in compression or tension.

3.6

Mohr's circle

The two-dimensional graphical representation of the stresses in a material body.

3.7

Poisson's ratio

ν

A measure of a material's tendency to expand when it experiences compression in a perpendicular direction and can be further described as the negative ratio of transverse strain to axial strain.

3.8

stress

An applied pressure or system of pressures that strains or deforms a body.

3.9**strain**

The measure of the relative deformation that results from applied stress.

3.10**tensile strength**

σ_T

The maximum stress a material can withstand before failing, while being stretched.

3.11**triaxial**

Involves three axes. In the context of this document it refers to a material's response in three dimensions.

3.12**unconfined compressive strength**

UCS

The maximum stress a material can withstand before failing, while being compressed without confining pressure.

3.13**Young's modulus****modulus of elasticity**

E

Property of a linear elastic solid material that represents the material's stiffness, which can be further described as the ratio of stress to strain.

4 Expansion and Explanation of Defined Terms**4.1 General**

To facilitate communication and avoid confusion, it is important to provide clear definitions to the mechanical parameters discussed in this report. Note that only the parameters directly related to mechanical testing of cement are provided here. More details about the principals discussed in this document can be found by referring to a book on solid mechanics (Timoshenko and Goodier, 1970) and, more specifically, on rock mechanics, such as Jaeger et al. (2007), Fjaer et al. (2008), or Aadnøy and Looyeh (2011).

4.2 Stress**4.2.1 General**

At a point located in a solid, stress is defined by a force, F , and the surface, A , through which the force is acting on the solid.

First, define the load vector, p , which is defined as the ratio of the force, F , to the area, A , as given by:

$$p = \frac{1}{A} F \quad (1)$$

Second, look at what occurs at a specific point on the surface. The area is allowed to shrink down to the point, so that the magnitude A goes to zero. The load vector at that point can be defined by:

$$p(x, n) = \lim_{dA \rightarrow 0} \frac{1}{dA} F \quad (2)$$

where

$x = (x_1, x_2, x_3)$ is the coordinate vector of the point;

n is the normal vector to the surface plane.

The load vector has three components in a three-dimensional system. In general it may vary from point to point and be different on different planes that pass through the point.

Third step is to define the stress σ_{ij} at a point x as the projection of the load vector $p(x, n_j)$ on vector n_j . Hence, stress is defined as a force applied to a surface per unit area.

The convention used in this document is that stress is positive if in compression and negative when in tension.

In particular, normal stress (σ_n) is the stress component normal to a given plane and shear stress (τ) is the stress component parallel to a given plane (see Figure 1) as defined by:

$$\sigma_n = \lim_{dA \rightarrow 0} \frac{dF_n}{dA} \quad (3)$$

$$\tau = \lim_{dA \rightarrow 0} \frac{dF_s}{dA} \quad (4)$$

If the stress does *not* depend on the point selected on the surface plane, this gives the following simplified formulas:

$$\sigma_n = \frac{F_n}{A} \quad (5)$$

$$\tau = \frac{F_s}{A} \quad (6)$$

Engineering stress units are megapascals (MPa) [pounds-force per square inch (psi)].

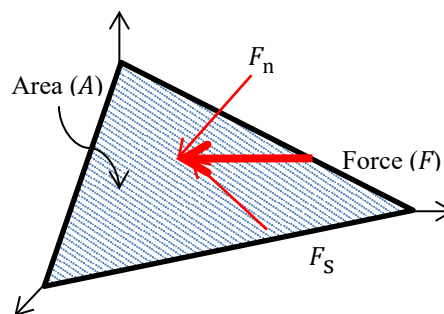


Figure 1—Force Applied to a Surface Area

4.2.2 Axial Stress

For a cylindrical test specimen subjected to uniaxial load along its axis, the axial stress (σ_a) can be represented as:

$$\sigma_a = \frac{\text{Force}}{\text{Area}} = \frac{F}{A_0} \quad (7)$$

The axial compressive force (F) is applied normal to the flat surface (area A_0) of the cement test specimen (see Figure 2).

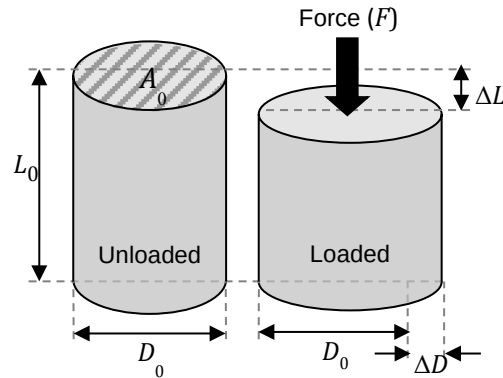


Figure 2—Cylindrical Test Specimen

4.2.3 Radial Stress

The radial direction is perpendicular to the axis of a cylindrical specimen. Pressure applied in this direction is referred as radial stress (σ_r) (see Figure 3).

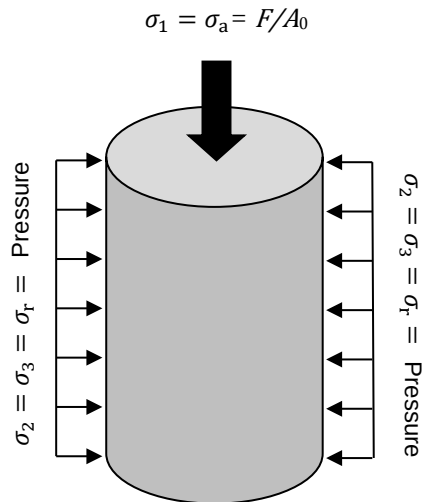


Figure 3—Cylinder Test Specimen Subject to Radial Stress

4.3 Strain

4.3.1 General

In the mechanics of rigid bodies, the fundamental kinematic variable is displacement, which is the vector that quantifies the change in the position of a given particle of the solid. The position of each particle is labeled by its location, relative to some coordinate system, in some state that is taken to be the initial state of the solid. This position point can be denoted as $x = (x_1, x_2, x_3)$. When loads are applied to the solid, the particle initially located at point x is displaced to a new location denoted by $x' = (x'_1, x'_2, x'_3)$. The vector that connects the original position x and the final position x' is known as the displacement at x . This vector is denoted in vector notation by $u = (u, v, w)$.

To be consistent with the sign convention used for stresses, the displacement vector shall be defined according to:

$$u = x - x' \quad (8)$$

In general, the displacement varies from point to point, so that each component (u, v, w) varies with all three position coordinates, x , y , and z .

The use of strain rather than displacement is somewhat analogous to the use of stress rather than the more physically obvious variable, the load force. Hence, strain is essentially a measure of the relative displacement of nearby particles, rather than a measure of their absolute displacement.

The basic concept behind strain can be introduced in a one-dimensional context by considering a short one-dimensional bar, initially of length L , which is being deformed to a final length L' . The mean strain (ϵ_{mean}) undergone by this bar is defined by the fractional decrease in the length of the bar as shown by:

$$\epsilon_{\text{mean}} = \frac{L - L'}{L} \quad (9)$$

According to this definition, the strain is a positive number if the bar becomes shorter, and vice versa.

The strain (ϵ) at the point x is found by taking the limit of an infinitesimally short bar, which is mathematically equivalent to letting the initial length of the bar go to zero, and is described by:

$$\epsilon = \lim_{L \rightarrow 0} \frac{L - L'}{L} \quad (10)$$

This type of strain is called normal strain and is a change in length per unit of length in a given direction.

There also exists another type of strain, called the shear strain (γ), which measures angular distortion, rather than stretching. It is equal to one-half of the increase in the angle initially formed by two infinitesimal perpendicular line segments and is described by:

$$\gamma = \lim_{\Delta L \rightarrow 0} \frac{\theta - \frac{\pi}{2}}{2} \quad (11)$$

For a cylindrical specimen under uniaxial compression (axial stress) or triaxial compression (axial and radial stresses), the two normal strains can be conveniently measured experimentally. They are the axial strain and the transverse (or radial) strain.

Strain is a dimensionless unit that can also be expressed in millimeters per millimeters (inches per inches). However, engineering strain units are commonly presented as a percentage (%).

4.3.2 Axial Strain

For the cylindrical specimen (see Figure 3), the amount of axial dimensional change (ΔL) relative to the original length (L_0) in the direction of primary axial stress is defined as the axial strain (ε_a) and is shown by:

$$\varepsilon_a = \frac{\Delta L}{L_0} \quad (12)$$

4.3.3 Transverse (or Radial) Strain

For the cylindrical specimen (see Figure 3), the amount of diametrical dimensional change (ΔD) relative to the original diameter (D_0) in a direction perpendicular to the primary axial stress is defined as the transverse (or radial) strain (ε_t) and is shown by:

$$\varepsilon_t = \frac{\Delta D}{D_0} \quad (13)$$

4.4 Elasticity

4.4.1 General

Elasticity is the property of a material to return to its original shape when unloaded. Elastic deformation is reversible.

Linear elasticity is a material property to deform elastically and proportionally to stress: stress–strain curves are linear.

4.4.2 Elastic Limit

The elastic limit is the stress or deformation limit where the material transitions from elastic behavior to nonelastic behavior. The elastic limit is not necessarily associated with sample failure as defined in 4.5, 4.6, or 4.9 and can be related to irreversible behavior due to plasticity, for example.

4.4.3 Elastic Constants

4.4.3.1 General

Many elastic materials have a tendency to deform linearly (or approximately linearly) as long as the stress does not exceed the material's elastic limit. This linear-elastic behavior is described by Hooke's law, which states that strain is a linear function of stress. Elastic constants, which represent the material's elastic properties, are conveniently defined to link stress and strain. Some of the most commonly used elastic constants are Young's modulus, Poisson's ratio, shear modulus, and bulk modulus. For isotropic materials, the material's elastic properties are fully described by any two of these elastic constants (all the others can be calculated theoretically). At moderate stress levels cement can be assumed to exhibit linear-elastic behavior and therefore its elastic constants are often reported. Young's, shear, and bulk moduli are typically expressed in gigapascals (GPa) or pounds-force per square inch (psi).

4.4.3.2 Determination of Elastic Properties

All elastic properties can be determined in several ways when the stress–strain curves like the one in Figure 4 are not fully linear, as follows.

- Tangent: determined from linear regression on the stress–strain test data over a stress range (see Figure 4A).

- Chord: the slope of a line connecting any two points on the stress–strain curve (see Figure 4B).
- Secant: the slope of a line from any point on the stress–strain curve relative to the zero stress point (uniaxial test) or zero net stress point (triaxial test) (see Figure 4C).

The secant is the least preferred method because the stress–strain curve may not be linear near zero stress.

For a perfectly linear-elastic material, tangent, secant, and chord Young's parameters are all identical. However, the experimental determination of all the elastic parameters should be made over the same stress range.

The elastic properties can be determined while the sample is being loaded (as shown in the Figure 4 example) or unloaded (not shown). The range used for determining the tangent or chord modulus can be prescribed, for example: 25 % to 40 %, or 10 % to 50 % of the axial stress to maximum stress before failure. However, the end user should use a range close to the value that the information will be used and that the sample exhibits linear behavior.

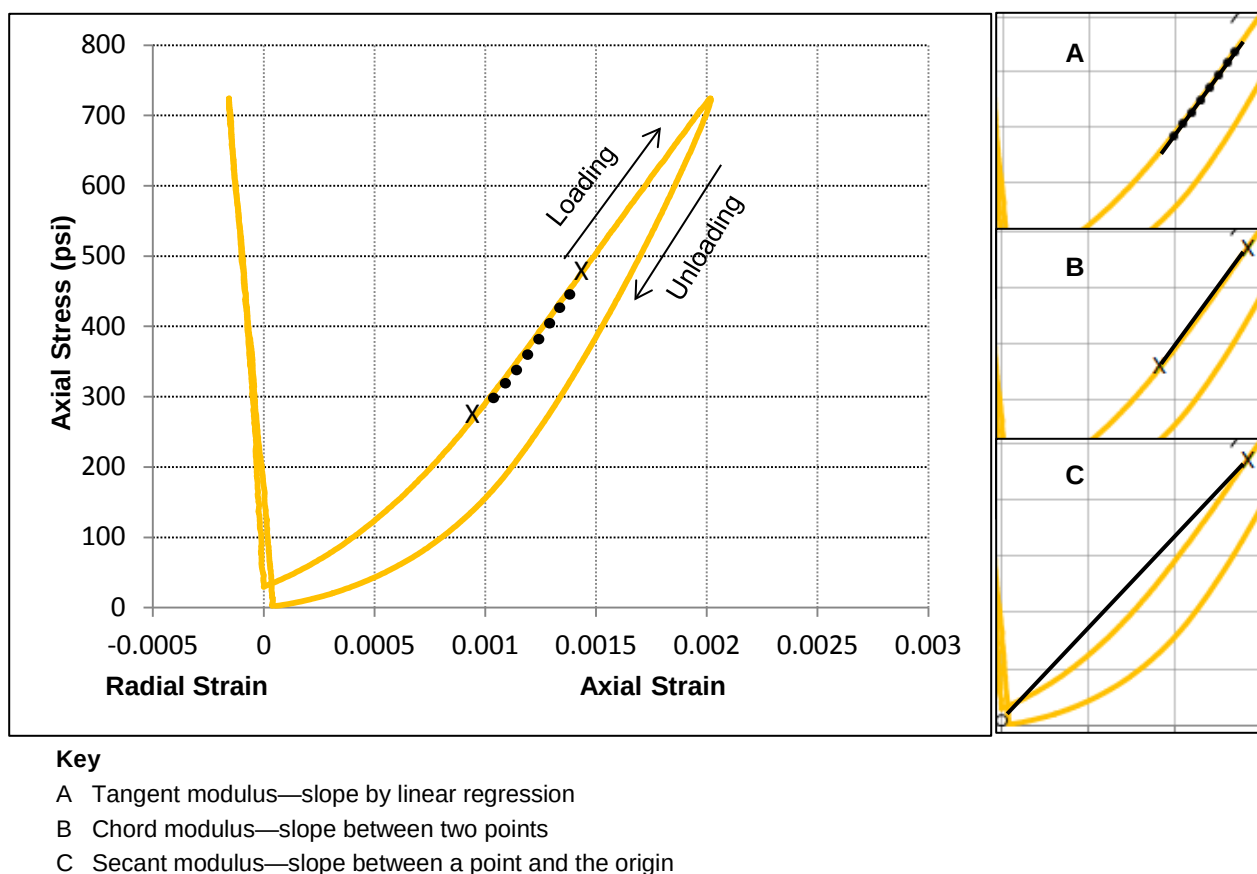


Figure 4—Elasticity Test Result Examples

4.4.3.3 Young's Modulus

Young's modulus (E) is defined below by the ratio of the change in axial stress (σ_a) to the resulting change in axial strain (ε_a) during an unconfined compressive test:

$$E = \frac{\sigma_a}{\varepsilon_a} \quad (14)$$

Young's modulus is expressed in gigapascals (pounds-force per square inch).

4.4.3.4 Poisson's Ratio

When a material is compressed in one direction, it usually tends to expand in directions perpendicular to the direction of compression. To characterize such behavior of a cylinder using previously defined normal strains in 4.3, Poisson's ratio (ν) is defined as the ratio of radial strain (ε_t) to axial strain (ε_a):

$$\nu = \frac{-\varepsilon_t}{\varepsilon_a} \quad (15)$$

Poisson's ratio is dimensionless.

NOTE Minus sign for the Poisson's ratio formula is required because the two strain values in Equation (15) are of opposite sign.

4.4.3.5 Shear Modulus

Shear modulus (G) is the sample's stiffness against shear stress. It is defined below by the ratio of the shear stress and the resultant angle (θ) of deformation (twice the relate shear strain):

$$G = \frac{\tau}{\theta} \quad (16)$$

However, for isotropic materials, it can also be obtained by combining any other two elastic properties, Young's modulus (E) and Poisson's ratio (ν):

$$G = \frac{E}{2(1 + \nu)} \quad (17)$$

Shear modulus is expressed in gigapascals (pounds-force per square inch).

4.4.3.6 Bulk Modulus

When a material is subjected to hydrostatic stress (equal stresses in all directions), its bulk modulus (K) can be determined below by the ratio of the hydrostatic stress (σ_p) and the volumetric strain (change of volume over the initial volume, ε_{vol}):

$$K = \frac{\sigma_p}{\varepsilon_{vol}} \quad (18)$$

However, for isotropic materials, it can also be defined by combining any other two elastic properties Young's modulus (E) and Poisson's ratio (ν):

$$K = \frac{E}{3(1 - 2\nu)} \quad (19)$$

4.5 Unconfined Compressive Strength (UCS)

UCS is the stress at which the cement specimen fails in a compression test without confining pressure. It is determined experimentally by destructively testing the cement sample. The maximum stress recorded during the test is the UCS and is described as:

$$UCS = MAX\{\sigma_a(unconfined)\} \quad (20)$$

NOTE Materials can deviate from linear elastic relationship at stresses less than the UCS.

4.6 Tensile Strength (σ_T)

The tensile strength is the stress at which the cement specimen fails in a tensile test. It can be determined by either direct method or indirect method.

The direct tension test is performed by applying a direct pull apart force to a specimen, which gives the direct tensile strength (σ_{TD}) of the specimen.

The indirect tension test (also called Brazilian test) can be performed by applying a diametrical compressive force along the length of a cylindrical specimen, which gives the splitting tensile strength (σ_{TS}) of the specimen.

NOTE Other indirect tension test methods, such as three- or four-point flexural tests, are used for testing concrete rectangular specimens, which are not covered in this document.

4.7 Mohr's Circle

Introduced by Cauchy, stress at a point in a solid body is physically represented as a second order tensor. It has components consisting of both shear and normal stresses. Analysis of the stress state in the simple test specimen exposed to normal stresses of σ_1 and σ_3 at the boundary actually results in both shear and normal stresses at a point within the specimen.

Mohr found that the transformation equation relating the shear and normal stresses takes the form of a circle. Once this "Mohr's circle" is defined, the stress at a point is fully understood. This concept is important for cement testing because physical observations of failed specimens subjected to normal stresses are often found to fail in shear. This is especially true when cement is tested in a confined state. The normal stresses at the time of failure are points on the x-axis.

In the example Figure 5, the confining pressure (σ_3) is the smallest principal stress and the beginning of each half circle and the maximum stress at failure (σ_1) is the end of each half circle. Each circle has a radius equal to $\tau_{max} = (\sigma_1 - \sigma_3)/2$, the maximum shear stress experienced during the test. Center of the Mohr circle is positioned on the x-axis at a stress value equal to $(\sigma_1 + \sigma_3)/2$. Without confining pressure (green circle, $\sigma_3 = 0$), the Mohr circle diameter σ_1 is equal to the UCS.

It is also possible to draw a Mohr circle with tensile stresses. In that case the tensile test can be represented by a circle with negative stress and a diameter equal to the tensile strength (σ_T).

The apex of the Mohr circle, τ_{max} , establishes the failure limit. The failure limit for each case is used to establish a failure envelope. Subsequently, any stress state that is represented by a Mohr circle can be compared to the failure envelope. If the circle crosses the envelope then a failure is expected.

4.8 Effective Stress

Terzaghi has shown that the stress at the origin of the end of the elastic behavior in porous media is not the total stress applied to the solid, but an effective stress which involves material pore pressure (P_{pore}), is defined as follows:

$$\sigma'_n = \sigma_n - P_{pore} \quad (21)$$

$$\tau' = \tau \quad (22)$$

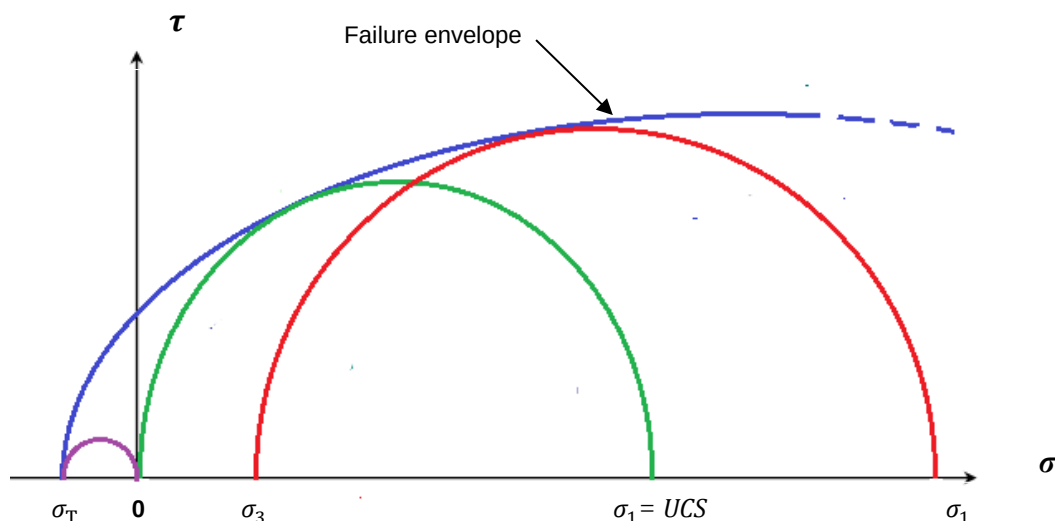


Figure 5—Mohr Circles and Mohr Failure Envelope

4.9 Failure Criteria

4.9.1 General

As there are, in general, more than one stress component that is different from zero, failure is checked using a criterion, which is a function of stress components and other variables, depending on the case. Failure occurs when the function becomes null or positive as described by:

$$f\{\sigma_{ij}, C_k\} \geq 0 \quad (23)$$

These criteria separate the elastic from the failed regions; the failure can be due to shear and tensile mechanisms.

Various criteria have been developed to predict and describe rock-like material failure. They all are written in terms of Terzaghi effective stresses. Two of these key failure mechanisms are briefly described below in 4.9.2 and 4.9.3.

4.9.2 Mohr–Coulomb Criterion

This criterion assumes that failure occurs when the effective shear stress is significantly higher along a plane in comparison with the effective normal stress applied to this plane. This creates a fault zone that ultimately develops through the failure plane. Eventually, the two faces of the failure plane will move with respect to each other. The criterion takes the form of a linear function of shear stress (τ) and normal stress (σ_n) applied to the plane (see Figure 6), which is described by:

$$\tau = c + \sigma_n \tan \varphi \quad (24)$$

where

c is the cohesion of the material;

φ is the friction angle by analogy to fault sliding Coulomb criterion.

The uniaxial compressive strength (UCS) is related to the cohesion (c) and friction angle (φ) by:

$$UCS = \frac{2c \cos \varphi}{1 - \sin \varphi} \quad (25)$$

This behavior is usually exhibited by isotropic brittle materials like cement.

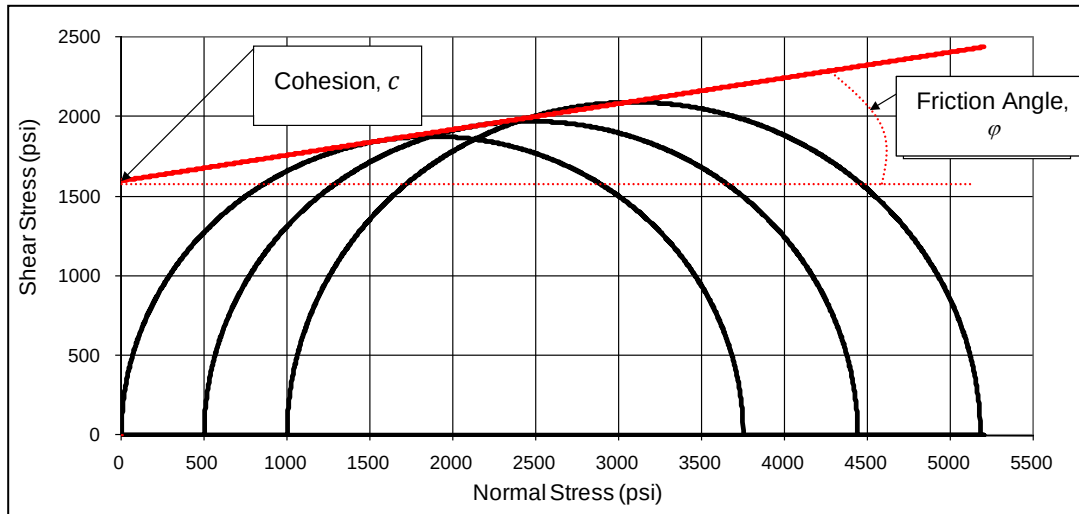


Figure 6—Mohr's Circles for Confined Tests Bounded by the Mohr–Coulomb Shear Failure Criteria

4.9.3 Drucker–Prager Criterion

This criterion relies on the second invariant of the stress deviator tensor, J_2 , and the effective average stress ($\sigma'_m = \sigma_m - P_0$) and is described by:

$$\alpha I_1 + \sqrt{J_2} - \beta = 0 \quad (26)$$

where

α and β are related to the cohesion, c , and the angle of internal friction, φ ;

I_1 is the first invariant of stress and $I_1 = \sigma_1 + \sigma_2 + \sigma_3$;

J_2 is the deviatoric invariant.

Under triaxial conditions where the axial stress, σ_1 , is larger than the confining pressure, σ_3 , the deviatoric invariant J_2 , and the effective average stress, σ'_m , are expressed respectively by:

$$\sqrt{J_2} = \frac{1}{3}(\sigma_1 - \sigma_3) \quad (27)$$

$$\sigma'_m = \sigma_m - P_0 = \frac{1}{3}(\sigma_1 + 2\sigma_3) - P_0 \quad (28)$$

where

P_0 is the pore pressure;

σ_m is the average stress.

5 Mechanical Testing Specimen Preparation

5.1 Cement Slurry Preparation

Cement slurries should be mixed in accordance with procedures described in API 10B-2 when possible. Considerations include the following.

- Before preparation of cement specimens, cement slurry design should be checked to achieve minimum free fluid and sedimentation.