# UNIVERSIDAD NACIONAL DE INGENIERÍA

## FACULTAD DE INGENIERIA GEOLOGICA, MINERA Y METALURGICA

TESIS

# “CORRELACIÓN DEL $m_i$ EN RELACIÓN AL COCIENTE DE LA RESISTENCIA DE COMPRESIÓN UNIAXIAL Y TRACCIÓN INDIRECTA”

PARA OBTENER EL GRADO ACADÉMICO DE MAESTRO EN GESTIÓN MINERA

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# DEDICATORIA

Dedicado a mi Esposa Dery por su permanente apoyo y a mis hijos Erick, Edgar y Luana por ser mi motivación y a mi madre que gracias a ella soy el profesional y persona que soy.

# AGRADECIMIENTO

A Dios, quien me ha guiado y me ha dado la fortaleza de seguir adelante.

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# RESUMEN

La presente investigación tiene como finalidad la determinación del parámetro $m_i$ sin la realización del ensayo de compresión triaxial, el procedimiento del ensayo de compresión triaxial se requiere de una prensa que puede ser mecánica o servocontrolada. Así como un equipo que permite realizar un esfuerzo de confinamiento a la probeta para el cual se requiere otros accesorios conocidos como las celdas Hooke.

De acuerdo con la metodología de esta investigación que es de tipo aplicada, diseño cuasi experirnental, se realizara la determinación del parámetro $m_i$ solo con el desarrollo del ensayo de compresión Uniaxial con el cual se determina el esfuerzo compresivo y de la determinación del esfuerzo de tracción por medio del ensayo de tracción indirecta llamado Método Brasilero.

Se han desarrollado ensayos de compresión triaxial en los que se han determinado el parámetro $m_i$ , y a la vez se han realizado en las mismas muestras los ensayos de compresión uniaxial y de tracción para utilizar los factores de corrección y así poder comparar los valores del $m_i$ obtenido por el ensayo de compresión triaxial y el $m_i$ determinado por el ensayo de compresión uniaxial y ensayo de tracción. Los ensayos se han realizado sobre muestras de roca de algunas litologías y grado de alteración diferentes ya que en nuestro país como sabemos tiene una alto grado de tectonismo.

# ABSTRACT

The purpose of this investigation is to determine the parameter mi without performing the triaxial compression test; the triaxial compression test procedure requires a press that can be mechanical or servo-controlled. As well as a piece of equipment that allows a confinement effort to be made to the test tube, for which other accessories known as Hooke cells are required.

According to the methodology of this research, which is of an applied type, quasi-experimental design, the determination of the parameter mi will be carried out only with the development of the Uniaxial compression test with which the compressive stress and the determination of the tensile stress are determined. through the indirect tensile test called the Brazilian Method.

Triaxial compression tests have been developed in which the parameter mi has been determined, and at the same time uniaxial compression and traction tests have been carried out on the same samples to use the correction factors and thus be able to compare the values of mi obtained. by the triaxial compression test and the mi determined by the uniaxial compression test and tensile test. The tests have been carried out on rock samples of different lithologies and degrees of alteration, since in our country, as we know, it has a high degree of tectonism.

# INTRODUCCION

Un laboratorio de Mecánica de Rocas se encarga de realizar diversos ensayos físico-mecánicos a muestras de roca, las muestras pueden ser bloques rocosos o testigos diamantinos. Los ensayos que se realizan en estas muestras, determinan valores de parámetros que permiten desarrollar e implementar estudios geomecánicas en las diferentes labores que se desarrollar en múltiples actividades principalmente civiles y mineras.

Los ensayos de rocas se desarrollan bajo ciertos estándares o normas ASTM y/o ISRM, y con los parámetros calculados permite elaborar los análisis de estabilidad, sostenimiento de las labores que se desarrollan en una unidad minera y que son analizadas por los geomecánicos que influyen en las operaciones unitarias como la perforación, voladura, planeamiento y seguridad en las labores mineras.

Dentro de estos ensayos físico-mecánicos se encuentran los ensayos de compresión Uniaxial que determina el parámetro de esfuerzo compresivo, el ensayo de Tracción (método brasilero) que determina el parámetro de esfuerzo de tracción ambos ensayos se desarrollan utilizando una prensa hidráulica como equipo de ejecución.

El ensayo de compresión triaxial de determina los parámetros de $m_i$, cohesión y Angulo de fricción interna este ensayo se desarrolla utilizando equipos como una prensa hidráulica, celdas Hook y un equipo de confinamiento, lo que implica que el laboratorio de mecánica de rocas debe de contar con una mayor infraestructura y por ende una mayor inversión.

El presente trabajo tiene como finalidad permitir que en los laboratorios de mecánica de rocas existentes en las empresas mineras que cuenten con equipos básicos, como una prensa hidráulica puedan determinar el valor del parámetro mi, el cual es importante para la determinación de estudios de sostenimiento y seguridad de las labores existentes, sin tener la necesidad de contar con las celdas Hook ni el equipo de confinamiento lo que implica un ahorro en la adquisición de equipos.

# CAPITULO I

# GENERALIDADES

## 1.1. Antecedentes bibliográficos

### Internacional

A. Basu • D. A. Mishra • K. Roychowdhury (2013), " Rock failure modes under uniaxial compression, Brazilian, and point load tests", Department of Geology and Geophysics, Indian Institute of Technology Kharagpur, Kharagpur 721302, India.

Se analizo un estudio integral sobre las formas de falla de las muestras de roca a escala de laboratorio y es importante la ayuda para el soporte diseñado en base a la naturaleza de una obra de ingeniería. Con la debida necesidad, ese artículo analiza los modos de falla de unas tres litologías como son el granito, esquisto y arenisca bajo pruebas de compresión uniaxial, brasileña y de carga puntual en relación con las resistencias correspondientes. La naturaleza del modo de falla principal cambia desde división axial hasta corte a lo largo de un solo plano y fractura múltiple en el caso de muestras de granito y arenisca a medida que aumenta la resistencia a la compresión uniaxial (UCS). Los especímenes de granito y arenisca fallaron principalmente después de un tipo de fractura central o múltiple, mientras que los especímenes de esquisto fallaron principalmente por activación de capas en combinación con fracturas centrales o no centrales en todo el rango de resistencia a la tracción brasileña determinada. En el caso del granito y la arenisca, el modo de falla múltiple central corresponde a una alta resistencia a la tracción. Se presentaron descripciones de diferentes modos de falla bajo carga puntual. Se encontró que los especímenes de granito y arenisca generalmente fallan a través de los materiales rocosos en uno o más planos de extensión.

Tuvo como finalidad analizar, comparar y evaluar las relaciones que hay entre diferentes litologías como en este caso se desarrolló con granitos y areniscas, teniendo como relación de análisis los ensayos de compresión uniaxial, el ensayo de tracción indirecta y el ensayo de carga puntual.

Miguel Vera Barrientos, Ramiro León Fagnilli (2015) "Correlaciones empíricas entre ensayos de compresión uniaxial no confinado (ucs), resistencia a la tracción indirecta (bts) y ensayos de carga puntual (plt)", Laboratorio de mecánica de rocas Universidad de Santiago de Chile Chile.

Los resultados de un ensayo de compresión uniaxial son relevantes en la determinación de las propiedades de la roca. Este estudio trata de resolver en forma empírica, las correlaciones entre el ensayo de carga puntual, Is(50), que se determina la estimación de la resistencia de las rocas, considerado por su fácil preparación de muestras, su bajo costo, además el ensayo de tracción indirecta o ensayo brasilero, ambos en función del ensayo de compresión.

Existen normas internacionales como ASTM D5731-14, D7012-14 y D3967-08 que nos dan los lineamientos y normas en las que se realizan estos ensayos.

El estudio encontró las correlaciones entre los ensayos Is(50) PLT y BTS respecto de los datos de UCS para un tipo de roca definida como brecha sub volcánica de composición riolítica de la cordillera de los Andes Central, obteniendo un error promedio del 0,15% para el primer caso, para el caso de la tracción indirecta el error aumenta a un 0,43%.

En la actualidad existen diversas ecuaciones de regresión tanto para resistencia a la UCS no confinada como para BTS en base al ensayo de ICP. Todos ellos concluyen que los factores asociados a los tipos de roca en su composición influyen en el resultado de los ensayos, al usar las diferentes ecuaciones se observa una baja correlación y en algunos casos poca confianza en los resultados.

Feijoo Calle Ernesto Patricio+Padrón Suarez Jhenifer Cristina+ (April 18, 2020) Rock resistivity and its relation to unconfined compressive strength in a mine Mining engineering Universidad Ciencia y Tecnología

En este estudio se propuso un método de campo para correlacionar los valores de la resistencia a la compresión simple (RCS) y la resistividad en rocas, ya que en los proyectos mineros, muchas veces, resulta complicado determinar el valor de la RCS, para lo cual es indispensable enviar muestras al laboratorio, originando tiempo y costos a la empresa.

Si correlacionamos los valores de la resistividad de la roca con la RCS, podemos ya no se enviarían muestras de forma continua para su análisis. Este trabajo se lo desarrolló sobre la base de muestras y probetas de una zona especifica

**Nacional**

Edgar Christian Jhonathan Tisnado Valdivia 1, Wilber Pastor Contreras 2, Stive Spencer Velarde Ochoa 3, Ivan Laura Nina (2016) Comparación De Valores Típicos De Parámetros De Resistencia De Las Rocas Volcánicas en El Sector De Totorani –Puno XVIII Congreso Peruano de Geología, En este trabajo se determinó la valides de las propiedades geomecanicas de rocas para contrastar información obtenida sobre los parámetros de resistencia de muestras de roca intacta de una litología especifica, Para este estudio los ensayos se realizaron en el Laboratorio de Mecánica de Rocas de la Facultad de Ingeniería de Minas Universidad Nacional del Altiplano de Puno y al Laboratorio de la Escuela de Ingeniería de Minas de la Universidad Nacional Jorge Basadre Grohmann de Tacna. Para este trabajo fue necesario realizar diferentes pruebas físico mecánicas de roca como los ensayos que son los ensayos triaxiales, Compresion uniaxial y tracción método indirecto (método brasilero) ISRM (Sociedad Internacional de Mecánica de Rocas) y ASTM (Sociedad Americana de Pruebas de Materiales).

Cristhian Germán Saucedo Abanto (2017) “Curvas de relación de la resistencia a compresión del concreto (F’c) y la velocidad de onda medida con ultrasonido en muestras de concreto de las cuales se desconoce sus características de diseño” Tesis Universidad Nacional de Cajamarca En este trabajo se determinaron correlación entre la resistencia a compresión y la velocidad del pulso ultrasónico en concretos variando la relación agua/cemento y el uso de los agregados.

Realizaron ensayos a compresión y de ultrasonido a 3, 7, 14, 21 y 28 días de edad de las probetas de concreto. En esta investigación llegaron a la conclusión que existía una marcada relación entre la resistencia a compresión y la velocidad de ultrasonido.

Por ello este trabajo de investigación correlacionara los ensayos de compresión uniaxial y de tracción indirecta para el cálculo del mi para una determinada sección litológica. Igualmente se determinará el mejor modelo matemático que nos dé mejor aproximación a la obtención del parámetro.

## 1.2. Descripción de la realidad problemática

En algunas unidades mineras de nuestro país cuentan con laboratorios que desarrollan ensayos de Mecánica de Rocas. Generalmente no todos los laboratorios no cuentan con el equipo y accesorios necesarios para el desarrollo del ensayo de compresión triaxial. Pero si cuentan por lo menos con una prensa hidráulica la cual permite desarrollar el ensayo de Compresión simple y ensayos de tracción indirecta (método brasilero).

Para el análisis de sostenimiento y seguridad de las operaciones mineras se requiere la determinación de uno de los parámetros que se obtiene del desarrollo del ensayo de compresión triaxial que es el parámetro del $\mathbf{m_i}$ **.**

Las unidades mineras actualmente tienen que esperar tiempos prolongados para obtener estos valores que son útiles para el para el control de las labores mineras existentes.

Estos tiempos se acortan de manera considerable con la determinación de este parámetro por medios indirectos, teniendo como resultados el esfuerzo compresión y el esfuerzo de tracción.

## 1.3. Formulación del problema

### 1.3.1. Problema General

- ¿Influirá la correlación y determinación del mi mediante los ensayos de Compresión Uniaxial y ensayos de tracción indirecta sin desarrollar el ensayo de compresión triaxial?

### 1.3.2. Problemas específicos

- ¿En qué medida se controla y se mejora el grado de seguridad en las labores mineras?
- ¿En qué medida se controla y se mejora la determinación de parámetros de estabilidad de labores mineras sin requerir ensayos triaxiales?.

## 1.4. JUSTIFICACIÓN E IMPORTANCIA DE LA INVESTIGACIÓN

Existen diversos laboratorios de Mecánica de rocas en entidades públicas y privadas los cuales requieren sus servicios las empresas consultoras, así como las mineras en la realización de ensayos de compresión triaxial para determinar los parámetros del mi. Lo cual se requiere para el desarrollo de este ensayo una máquina de confinamiento y celdas Hook. Por ello las empresas deben de esperar un tiempo prolongado en la obtención de estos valores para el control geomecánico de las labores existentes, con esta investigación se podrá:

a. Determinar el valor del mi si contar con el equipo de confinamiento.
b. Tener un control geomecánico en más corto plazo ya que solo se requerirá una prensa hidráulica para la determinación del mi
c. El nivel de riesgo disminuiría ya que habrá un rápido control geomecánico de las labores mineras.

### 1.4.1. Justificación práctica

Presenta una justificación práctica, debido a que la determinación del parámetro Mi se realizara de manera más sencilla utilizando ensayos de Compresión Uniaxial y ensayos de tracción indirecta en las que solo se requiere una prensa hidráulica.

### 1.4.2. Justificación económica

Presenta una justificación económica, debido a que se busca la reducción de los costos de inversión en la adquisición de equipos y accesorios de confinamiento.

## 1.5. Objetivos

### 1.5.1. Objetivo General

- Determinar de forma indirecta el valor del $m_i$ , sin realizar el ensayo de compresión triaxial y sin usar un equipamiento de confinamiento de testigos los accesorios correspondientes.

### 1.5.2. Objetivos específicos

- Realizar ensayos de compresión simple y tracción indirecta en laboratorios de las empresas mineras.
- Determinar el mi mediante la correlación de los resultados del ensayo de compresión simple y ensayo de tracción indirecta.

## 1.6. Hipótesis

### 1.6.1. Hipótesis General

- ¿Se determinará el valor del mi sin desarrollar el ensayo de compresión triaxial?

### 1.6.2. Hipótesis específicas

- Con la implementación de una prensa hidráulica se desarrollan los ensayos de compresión simple y tracción indirecta y se podrá simular indirectamente un ensayo de compresión triaxial.

- Con la determinación del mi por este método se disminuye el tiempo en la toma de decisiones en los sistemas de seguridad en las labores mineras.

## 1.7. Variables

Tabla 1.1. Variables e indicadores

| | |
|---|---|
| **Variable independiente: X**<br>X1: Correlacionar el valor mi sin desarrollar el ensayo de compresión triaxial. | **Indicadores de X:**<br>X1: Adquisición de equipo manual de una prensa hidráulica. |
| **Variable dependiente: Y**<br>Y1: Desarrollo del ensayo de compresión simple.<br>Y2: Desarrollo del ensayos de tracción indirecta (método brasilero) | **Indicadores de Y:**<br>Y1: Determinación del esfuerzo compresivo.<br>Y2: Determinación del esfuerzo a la tracción. |

*Fuente: Elaboración Propia*

## 1.8. Periodo de análisis

El presente trabajo en la determinación de la correlación del valor mi, tendrá un periodo de recopilación de datos y el análisis de 06 meses en su implementación y desarrollo de la tesis.

# CAPÍTULO II

# EL MARCO TEÓRICO Y MARCO CONCEPTUAL

## 2.1. Bases teóricas

### 2.1.1. Ensayos de mecánica de rocas

Para la determinación y análisis de estudios de estabilidad de macizos rocosos se requiere conocer, entender y manejar, algunas metodologías y ensayos de propiedades físicas y mecánicas de la roca. Los ensayos realizados en el laboratorio de mecánica de rocas sirven a las especialidades de Ingeniería de Minas y Geológica, y con el apoyo de normas ASTM y sugerencias de la Sociedad Internacional de Mecánica de Rocas, así como el desarrollo de un registro de fotos que sirve para la interpretación de la forma de rotura de la muestra para la posterior elaboración del informe de resultados.

El objetivo principal de los ensayos de mecánica de rocas es determinar las propiedades físicas y mecánicas de la roca como: densidad, porosidad, absorción, resistencia a la compresión, resistencia a la tracción, compresión triaxial, determinación de módulos elásticos, abrasión, permeabilidad, entre otros

Los ensayos que se realizan se deben de prepara probetas que dependiendo del tipo de ensayo a realizarse deben de tener diferentes dimensiones.

Para la preparación de probetas de los ensayos de Compresión Triaxial y Uniaxial, deben de tener las siguientes consideraciones.

-Cilíndricos circulares

-L/D: Entre 2 y 2.5
-La Relación entre el diámetro del testigo y el diámetro del grano mas grande de la roca debe ser como mínimo de 10 a 1.
-La superficie del testigo debe ser lisa y libre de irregularidades abruptas, con todos sus elementos alineados sin desviarse mas de 0.5 mm a lo largo del testigo.
-Las bases deben ser paralelas entre si, sin desviarse mas de 0.025 mm y perpendiculares con respecto al eje longitudinal del cilindro sin apartarse mas de 0.05 mm en 50 mm.
-No se permiten testigos que estén cubiertos con otro material o que tengan algún tratamiento superficial diferente al de la maquina refrendadora.

-El diámetro debe ser medido con aproximación a 0.1 mm y ser el promedio de las medidas de dos diámetros perpendiculares entre si y tomadas en 3 partes del testigo.

-La altura debe ser tomada con aproximación al mm.

- La condición de humedad del testigo puede tener un efecto significativo en la resistencia que pueda alcanzar la roca. Los testigos no deben ser almacenados por más de 30 días. Una buena práctica es tratar de conservar las condiciones de humedad natural del testigo hasta el momento del ensayo.

- El número de testigos a ensayar depende del número de las diferentes presiones de confinamiento con las que se desea ensayar.

- Para el Ensayo de Tracción método brasilero la probeta debe tener las consideraciones anteriores, pero será un disco circular con una relación espesor-diámetro (t/D) entre 0,2 y 0,75

### 2.1.2. Ensayo de Compresión Triaxial

El propósito de este ensayo es la de determinar la resistencia a la compresión de un testigo cilíndrico de roca bajo una presión de confinamiento.

Tiene como objetivo determinar los parámetros de resistencia al corte (cohesión y ángulo de fricción interna) y la constante mi de la roca intacta. Se usara para simular condiciones de un macizo rocoso subterráneo.

Representa las condiciones de las rocas in situ sometidas a esfuerzos confinantes, mediante la aplicación de presión hidráulica uniforme alrededor de la probeta mediante el siguiente procedimiento:

1. La celda es ensamblada con el testigo instalado en la chaqueta y entre las platinas. El testigo, las platinas y los asientos esféricos deben estar alineados entre sí. Los asientos esféricos estarán ligeramente lubricados con grasa o aceite.

2. La celda triaxial se llena con aceite permitiendo que el aire salga por la conexión de escape. Se debe asegurar que la chaqueta no tenga fisuras ni huecos en de cada ensayo, de manera que el aceite no penetre en el testigo.

Fig. 2. 1. La celda Hooke.
*Fuente: Laboratorio Mecánica de Rocas UNI*

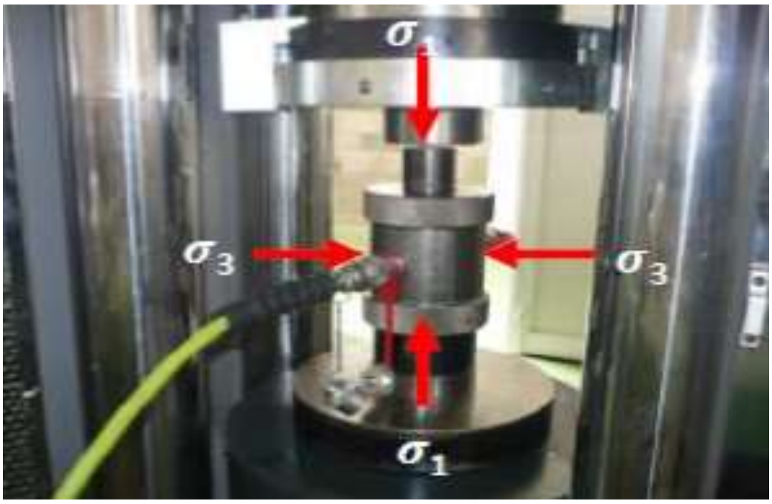

Fig. 2.2 Esfuerzos de Confinamiento
*Fuente: Laboratorio Mecánica de Rocas UNI*

3. Se establece la presión de confinamiento en el nivel predeterminado y se mantiene constante, entonces se aplica la carga normal. El máximo valor de carga axial y su correspondiente presión de confinamiento se registran.

Fig. 2.3 Equipo para generar presión de confinamiento
*Fuente: Laboratorio Mecánica de Rocas UNI*

4. Se repite el procedimiento para otro valor de presión de confinamiento.

Permite determinar la envolvente o línea de resistencia del material rocoso ensayado a partir de la que se obtienen los valores de sus parámetros resistentes cohesión y ángulo de fricción

En un ensayo de compresión triaxial:

- La carga axial y su esfuerzo principal correspondiente simulan el esfuerzo principal mayor que actúa en la corteza ($\sigma_1$).
- La tensión radial producida por la presión hidráulica representa el esfuerzo principal menor ($\sigma_3$).

Para obtener un valor de resistencia a la compresión triaxial mencionamos necesariamente la presión de confinamiento aplicada en el ensayo, necesaria para encontrar una relación entre $\sigma_1 = f(\sigma_3)$ , donde:

- $\sigma_1$ : Resistencia a la compresión axial
- $\sigma_3$ : Presión de confinamiento

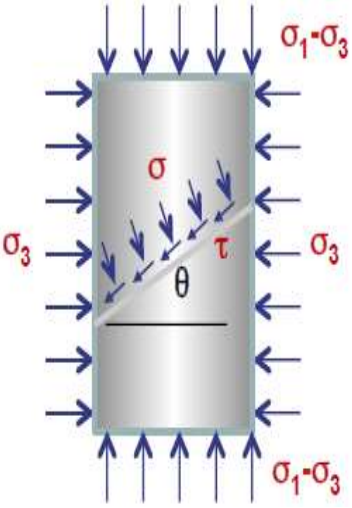

Fig. 2.4 Distribución de esfuerzos
*Fuente: Elaboración propia*

Cada par de valores $\sigma_1$ y $\sigma_3$ permiten construir.

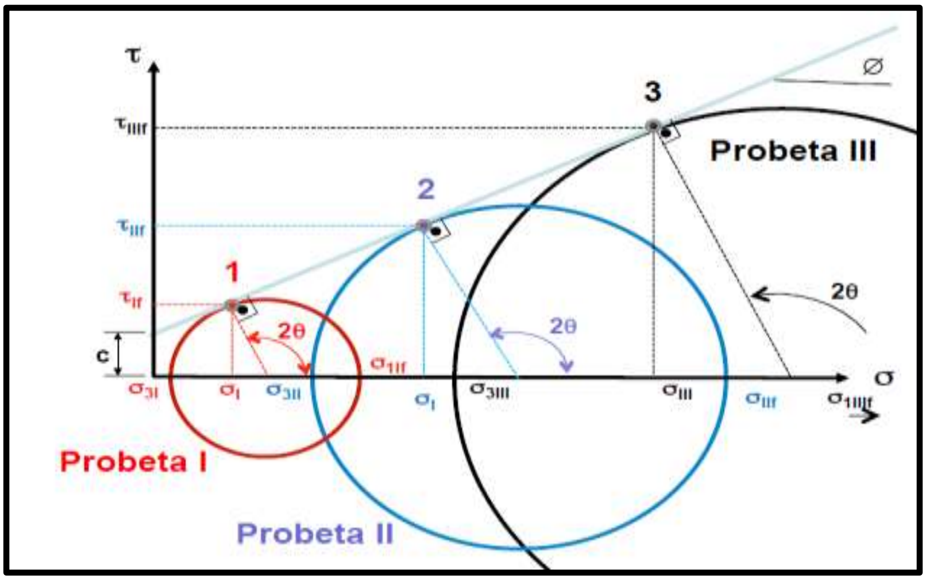

Fig. 2.5 El grafico del círculo de Mohr
*Fuente: Elaboración propia*

Se definen diferentes criterios de rotura pero los más usados son:

-**Criterio lineal de Mohr-Coulomb:** Si bien fue pensado inicialmente para suelos se adecua a rocas y es usado por su sencillez.

-**Criterio no lineal de Hoek-Brown:** Método que se ha ido actualizando y se utiliza para estudiar de manera clara la rotura de un medio rocoso mediante la introducción de variables geotécnicas y geológicas

$$\sigma_1' = \sigma'_3 + \sigma_{Ci} \cdot \left( m \frac{\sigma'_3}{\sigma_{Ci}} + s \right)^{0.5}$$

Fig. 2.6 La ecuación de Hoek-Brown para roca intacta

*Fuente: Elaboración propia*

- $\boldsymbol{\sigma_1\ y\ \sigma_2}$ son los esfuerzos principales mayor y menor en el momento de rotura
- $\boldsymbol{\sigma_{ci}}$ es la resistencia a la compresión uniaxial
- $\boldsymbol{m}$ y $\boldsymbol{s}$ son constantes del material que dependen de las propiedades de la roca.

### 2.1.3. Ensayo de Compresión Simple

La Resistencia compresiva de roca intacta es el esfuerzo medido sobre una probeta generalmente cilíndrica la roca, ese esfuerzo es el máximo que puede tolerar una muestra de material antes de fracturarse.

Se conoce también como la resistencia a la compresión no confinada de un material porque el esfuerzo de confinamiento se fija en cero.

Los especímenes o probetas de ensayo serán cilindros circulares rectos dentro de las tolerancias especificadas.

La probeta tendrá una proporción longitud a diámetro (L/D) de 2.0 a 2.5 a esta relación se le llama esbeltes y con un diámetro no inferior a 1 7/8 pulgadas (47 mm).

Generalmente se debe de registrar los siguientes datos.

- Fuente de la muestra incluido el nombre del proyecto y la ubicación.
- Descripción litológica de la roca.
- Condición de humedad del espécimen antes del ensayo.
- Diámetro del espécimen y altura, de acuerdo con los requerimientos de dimensión.
- Temperatura a la cual se llevó a cabo el ensayo.

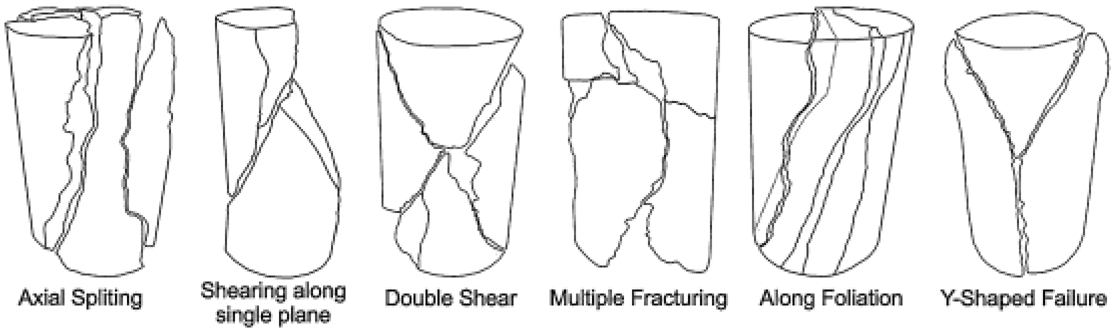

Fig. 2.7 Tipos de rotura compresión uniaxial

*Fuente: Bieniawski 1967*

Fig. 2.8 Ejemplos de Roturas de ensayos UCS

*Fuente: Indian Institute of Technology Kharagpur*

### 2.1.4. Ensayo de Tracción (Método Brasilero)

El ensayo de tracción indirecta o ensayo brasileño obedece a la norma ASTM D3967 (**American Society for Testing and Materials** o **ASTM International)** el cual en su norma se refiere al significado, uso y alcance que tiene este método.

Este ensayo consiste en someter a compresión diametral una probeta cilíndrica, aplicando una carga de manera uniforme a lo largo de dos líneas o generatrices opuestas hasta alcanzar la rotura. Esta configuración de carga provoca un esfuerzo de tracción relativamente uniforme en todo el diámetro del plano de carga vertical, este esfuerzo inducido de tracción es la que determina la rotura de la probeta en el plano diametral.

Aplicar una carga de compresión en continuo aumento para producir una velocidad aproximadamente constante de carga o de deformación de tal manera que la rotura ocurrirá dentro de 1 a 10 min de carga, que debe estar entre 0,05 y 0,35 MPa / s (500 y 3000 psi / min) de velocidad de carga, dependiendo del tipo de roca.

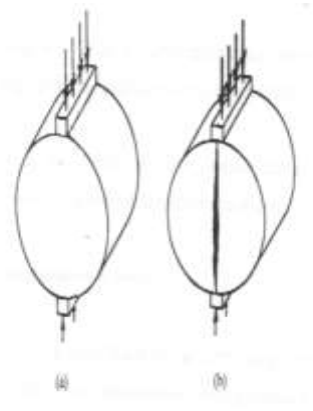

Fig. 2.9 Distribución de carga y rotura en el ensayo de tracción

*Fuente: Elaboración propia*

Para el calculo del esfuerzo de tracción se determina mediante el promedio de valores de 3 o mas probetas.

Fig. 2.10 Posición de probeta en equipo de prensa hidráulica

*Fuente: Laboratorio de Mecánica de rocas UNI*

$$T_I = -\frac{2P}{\pi * t * D}$$

$T_i$ =Resistencia a la tracción indirecta de la roca o mineral en (Kg/cm$^2$).

P = Carga última de rotura de la probeta (Kg).

D = Diámetro de la probeta (cm).

L = Longitud de la probeta (cm).

Π = Constante.

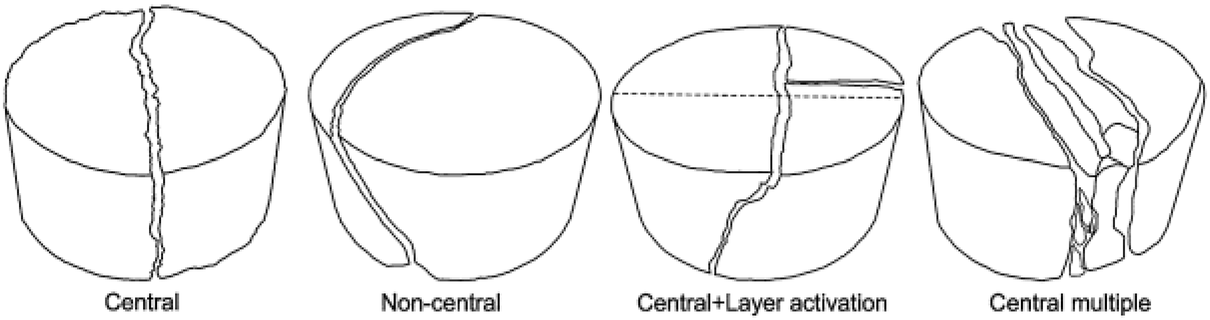

Fig. 2.11 Tipos de rotura del ensayo de tracción indirecta.

*Fuente: Indian Institute of Technology Kharagpur*

## 2.2. Marco Conceptual

### 2.2.1. Esfuerzo y deformación.

Se denomina esfuerzo al conjunto de fuerzas que afectan a un cuerpo material y tienden a deformarlo. Los esfuerzos tectónicos pueden ser básicamente de tres tipos:

a) Compresión: producido por fuerzas que actúan convergentemente en una misma dirección. Como consecuencia se produce un acortamiento de la corteza

b) Distensión (tensión, estiramiento o tracción): producida por fuerzas divergentes que actúan en una misma dirección. Como consecuencia se produce un estiramiento de la corteza

c) Cizallamiento: originado por fuerzas paralelas que actúan en sentidos opuestos.

### 2.2.2. Glosario

**ASTM**: (American Society for Testing and Materials o ASTM International), es una organización de estándares internacionales que desarrolla y publica acuerdos voluntarios de normas técnicas para una amplia gama de materiales, productos, sistemas y servicios

**Esfuerzo compresivo**: Esfuerzo que resulta de la aplicación de un par de fuerzas colineales convergentes sobre un plano perpendicular a la línea de aplicación de tales fuerzas

**Esfuerzo cortante**: Esfuerzo resultante de la aplicación de un par de fuerzas no colineales sobre un plano paralelo a ellas

**Esfuerzo de tracción**: Esfuerzo que resulta de la aplicación de un par de fuerzas colineales divergentes sobre un plano perpendicular a la línea de aplicación de tales fuerzas

**Esfuerzo in situ**: Esfuerzo a que está sometido un terreno antes de ser excavado

**Esfuerzos principales**: Esfuerzos (deformaciones) normales a cada uno de los tres planos, mutuamente perpendiculares, en los que los esfuerzos de cizalladura son nulos

**Índice de calidad de roca**, RQD: Calificación la calidad de una masa de roca propuesta por Deere con base en el estado de los núcleos de perforación de diámetro NX. Numéricamente el RQD se define como la relación porcentual entre a) la sumatoria de las longitudes de los trozos de núcleos mayores de 10 centímetros, y b) la longitud total de la perforación.

**Roca o Roca Intacta**: Agregado solido, formado por uno o varios minerales, que están presentes en la corteza terrestre igualmente se refiere a un elemento de roca que no presenta discontinuidades que se puedan observar.

**Macizo Rocoso:** es la forma en que se presentan las rocas en el medio natural. Se define por la roca y la estructura que a la vez contiene planos de estratificación.

**Estructura:** Los macizos rocosos generalmente son atravesados por diversos caracteres geológicos estructurales y discontinuidades de variado origen geológico, como pliegues, fallas, estratificación y diaclasas.

# CAPÍTULO III

# METODOLOGIA DE LA INVESTIGACIÓN

## 3.1. Tipo, nivel y diseño de investigación, técnicas e instrumentos para recoger datos, técnicas de procesamiento de datos

### 3.1.1 Tipo

La presente tesis es de tipo de investigación “APLICADA”, ya que en campo se demostrará los procedimientos, herramientas y equipos aplicados para desarrollar dicho plan.

### 3.1.2 Nivel

La presente tesis es de nivel “DESCRIPTIVO”, ya que en campo señalaremos los procesos en el estudio para desarrollar en dicho plan

### 3.1.3. Diseño de Investigación

La presente tesis tiene como diseño de investigación EXPERIMENTAL Y CUANTITATIVA, ya que en laboratorio se desarrollara los ensayos para la determinación de los valores de mi en los ensayos de compresión triaxial, comparando los valores correlacionados de los ensayos de compresión simple y tracción. Desarrollados en dicho plan.

## 3.2. Desarrollo del trabajo de tesis

Hoek-Brown (1980), propuso un criterio para estimar el esfuerzo deruptura del macizo rocoso a través de la realización de ensayos triaxiales y una caracterización del macizo rocoso,

La ecuación de Hoek-Brown para roca intacta se define como:

$$\sigma_1' = \sigma'_3 + \sigma_{Ci} \cdot \left( m \frac{\sigma'_3}{\sigma_{Ci}} + s \right)^{0.5}$$

Fig. 3.1 La ecuación de Hoek-Brown para roca intacta

*Fuente: Elaboración propia*

Donde σ1 y σ3 representan el mayor y menor esfuerzo principal respectivamente, mi es una constante que depende de la roca intacta, σci es el esfuerzo a la compresión uniaxial.

$m = m_i$ y $s= 1$

La constante a estudiar mi es normalmente obtenida de un grupo de ensayos triaxiales con distintos confinamientos. El valor de mi depende de las características de la roca y de los minerales existentes en la muesra, de la textura y tamaño de grano, es decir su determinación debe ser única para cada tipo de roca a estudiar.

Una aproximación al valor de la constante mi se puede

$$M_i = UCS / BTS$$

Tabla 3.1 Ensayos de compresión Triaxial

:

| **Sondaje** | **Muestra** | **Diámetro (cm)** | **Altura (cm)** | **Confin. (MPa)** | **Esfuerzo Rotura (MPa)** | **Resistencia Compresiva MPa** | ***mi*** | **Cohesión *"c"* (MPa)** | **Ang. de Fricción Interno (°)** |
|---|---|---|---|---|---|---|---|---|---|
| *NZ-22-012* | *M-15* | *6.04* | *12.40* | *2* | *115.1* | ***101.12*** | ***12.83*** | ***16.04*** | ***56.13*** |
| *NZ-22-012* | *M-16* | *6.04* | *12.43* | *4* | *128.5* | | | | |
| *NZ-22-012* | *M-17* | *6.04* | *12.32* | *6* | *140.0* | | | | |
| *NZ-22-012* | *M-26* | *6.11* | *12.20* | *2* | *114.4* | ***100.54*** | ***12.70*** | ***16.03*** | ***55.98*** |
| *NZ-22-012* | *M-27* | *6.11* | *12.46* | *4* | *127.7* | | | | |
| *NZ-22-012* | *M-28* | *6.11* | *12.45* | *6* | *139.1* | | | | |
| *NZ-22-012* | *M-29* | *6.08* | *12.24* | *2* | *104.7* | ***89.93*** | ***13.56*** | ***13.91*** | ***56.81*** |
| *NZ-22-012* | *M-30* | *6.08* | *12.34* | *4* | *117.6* | | | | |
| *NZ-22-012* | *M-31* | *6.08* | *12.50* | *6* | *130.3* | | | | |
| *NZ-22-012* | *M-37B* | *6.10* | *12.45* | *2* | *105.0* | ***91.00*** | ***12.72*** | ***14.49*** | ***55.94*** |
| | | *6.10* | *12.23* | *4* | *117.5* | | | | |
| | | *6.10* | *12.22* | *6* | *129.5* | | | | |
| *NZ-22-012* | *M-40A* | *6.10* | *12.28* | *2* | *113.1* | ***100.07*** | ***11.42*** | ***16.73*** | ***54.48*** |
| *NZ-22-012* | *M-40B* | *6.10* | *12.64* | *4* | *124.3* | | | | |
| *NZ-22-012* | *M-40C* | *6.10* | *12.59* | *6* | *136.2* | | | | |
| *NZ-22-012* | *M-55A* | *6.11* | *12.50* | *2* | *114.1* | ***101.69*** | ***10.88*** | ***17.38*** | ***53.80*** |
| *NZ-22-012* | *M-55B* | *6.11* | *12.45* | *4* | *125.4* | | | | |
| *NZ-22-012* | *M-55C* | *6.11* | *12.54* | *6* | *136.4* | | | | |
| *NZ-22-016* | *M-11* | *6.11* | *12.21* | *2* | *113.9* | ***101.33*** | ***11.12*** | ***17.14*** | ***54.12*** |
| | | *6.11* | *12.27* | *4* | *125.6* | | | | |
| | | *6.11* | *12.25* | *6* | *136.5* | | | | |
| *NZ-22-016* | *M-24* | *6.11* | *12.21* | *2* | *115.8* | ***103.96*** | ***10.41*** | ***18.12*** | ***53.17*** |
| | | *6.11* | *12.27* | *4* | *127.3* | | | | |
| | | *6.11* | *12.28* | *6* | *137.4* | | | | |
| *NZ-22-016* | *M-30* | *6.11* | *12.46* | *2* | *114.0* | ***100.51*** | ***12.13*** | ***16.35*** | ***55.35*** |
| | | *6.11* | *12.39* | *4* | *126.4* | | | | |
| | | *6.11* | *12.50* | *6* | *138.0* | | | | |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

Tabla 3.2 Ensayos de compresión Uniaxial

| **Sondaje** | **Muestra** | ***Diámetro (cm)*** | ***Altura (cm)*** | ***Carga de rotura (kN)*** | ***Resistencia a la Compresión Uniaxial (kg/cm2)*** | ***Resistencia a la Compresión Uniaxial (MPa)*** |
|---|---|---|---|---|---|---|
| *NZ-22-012* | *M-02* | *6.07* | *12.34* | *124.7* | ***440*** | ***43.2*** |
| *NZ-22-012* | *M-07* | *6.06* | *12.30* | *284.7* | ***1009*** | ***98.9*** |
| *NZ-22-012* | *M-10* | *6.07* | *12.19* | *347.7* | ***1226*** | ***120.2*** |
| *NZ-22-012* | *M-12* | *6.07* | *12.24* | *761.5* | ***762*** | ***263.4*** |
| *NZ-22-012* | *M-14* | *6.10* | *12.24* | *575.6* | ***2010*** | ***197.0*** |
| *NZ-22-012* | *M-18* | *6.08* | *12.52* | *88.7* | ***313*** | ***30.7*** |
| *NZ-22-012* | *M-20* | *6.08* | *12.50* | *587.1* | ***2070*** | ***202.9*** |
| *NZ-22-012* | *M-37A* | *6.10* | *12.72* | *482.6* | ***1693*** | ***166.0*** |
| *NZ-22-012* | *M-42* | *6.09* | *12.26* | *323.2* | ***1133*** | ***111.0*** |
| *NZ-22-012* | *M-45* | *6.11* | *12.21* | *302.4* | ***1052*** | ***103.1*** |
| *NZ-22-012* | *M-57* | *6.13* | *12.35* | *288.7* | ***999*** | ***97.9*** |
| *NZ-22-012* | *M-60* | *6.12* | *12.58* | *313.6* | ***1091*** | ***107.0*** |
| *NZ-22-016* | *M-01* | *6.08* | *12.45* | *120.3* | ***424*** | ***41.6*** |
| *NZ-22-016* | *M-03* | *6.11* | *12.40* | *214.6* | ***748*** | ***73.3*** |
| *NZ-22-016* | *M-06* | *6.10* | *12.38* | *184.7* | ***646*** | ***63.3*** |
| *NZ-22-016* | *M-09* | *6.10* | *12.46* | *75.8* | ***265*** | ***26.0*** |
| *NZ-22-016* | *M-15* | *6.11* | *12.53* | *538.3* | ***1878*** | ***184.2*** |
| *NZ-22-016* | *M-18* | *6.08* | *12.37* | *171.3* | ***603*** | ***59.1*** |
| *NZ-22-016* | *M-20* | *6.10* | *12.39* | *283.5* | ***991*** | ***97.2*** |
| *NZ-22-016* | *M-23* | *6.11* | *12.38* | *530.8* | ***1850*** | ***181.3*** |
| *NZ-22-016* | *M-27* | *6.11* | *12.38* | *214.7* | ***748*** | ***73.3*** |
| *NZ-22-016* | *M-34* | *6.11* | *12.61* | *147.2* | ***514*** | ***50.4*** |
| *NZ-22-016* | *M-35* | *6.11* | *12.61* | *446.3* | ***1559*** | ***152.8*** |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

Tabla 3.3 Ensayos de Tracción Indirecta (método brasilero)

| Sondaje | Muestra | Diámetro (cm) | Altura (cm) | Carga (kN) | Resist. a la tracción (kg/cm$^2$) | Resist. a la tracción (MPa) |
|---|---|---|---|---|---|---|
| NZ-22-012 | M-06 | 6.09 | 3.10 | 37.9 | 130 | 12.8 |
| | | 6.09 | 3.09 | 37.5 | 129 | 12.7 |
| | | 6.09 | 3.01 | 32.7 | 116 | 11.4 |
| | | | | **Promedio** | **125** | **12.3** |
| NZ-22-012 | M-08 | 6.06 | 3.11 | 45.6 | 157 | 15.4 |
| | | 6.06 | 3.08 | 48.1 | 167 | 16.4 |
| | | 6.06 | 3.10 | 49.7 | 172 | 16.8 |
| | | | | **Promedio** | **165** | **16.2** |
| NZ-22-012 | M-19 | 6.08 | 3.05 | 35.6 | 125 | 12.2 |
| | | 6.08 | 3.19 | 35.0 | 117 | 11.5 |
| | | 6.08 | 3.09 | 34.8 | 120 | 11.8 |
| | | | | **Promedio** | **121** | **11.8** |
| NZ-22-012 | M-21 | 6.09 | 3.02 | 71.0 | 251 | 24.6 |
| | | 6.09 | 3.10 | 72.8 | 250 | 24.5 |
| | | 6.09 | 3.07 | 74.0 | 257 | 25.2 |
| | | | | **Promedio** | **253** | **24.8** |
| NZ-22-012 | M-24 | 6.08 | 3.22 | 44.8 | 148 | 14.6 |
| | | 6.08 | 3.11 | 45.8 | 157 | 15.4 |
| | | 6.08 | 3.13 | 42.8 | 146 | 14.3 |
| | | | | **Promedio** | **151** | **14.8** |
| NZ-22-012 | M-44 | 6.09 | 3.11 | 42.5 | 146 | 14.3 |
| | | 6.09 | 3.23 | 43.6 | 144 | 14.1 |
| | | 6.09 | 3.33 | 42.0 | 134 | 13.2 |
| | | | | **Promedio** | **141** | **13.9** |
| NZ-22-012 | M-50 | 6.11 | 3.07 | 35.4 | 123 | 12.0 |
| | | 6.11 | 3.10 | 37.2 | 128 | 12.5 |
| | | 6.11 | 3.04 | 36.8 | 129 | 12.6 |
| | | | | **Promedio** | **126** | **12.4** |
| NZ-22-012 | M-54 | 6.11 | 3.12 | 53.0 | 181 | 17.7 |
| | | 6.11 | 3.16 | 51.8 | 174 | 17.1 |
| | | 6.11 | 3.13 | 53.9 | 183 | 17.9 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | **Promedio** | **179** | **17.6** |
| NZ-22-016 | M-06 | 6.10 | 3.05 | 28.4 | 99 | 9.7 |
| | | 6.10 | 3.08 | 25.6 | 88 | 8.7 |
| | | 6.10 | 3.03 | 26.7 | 94 | 9.2 |
| | | | | **Promedio** | **94** | **9.2** |
| NZ-22-016 | M-08 | 6.10 | 3.05 | 23.9 | 83 | 8.2 |
| | | 6.10 | 3.00 | 23.1 | 82 | 8.0 |
| | | 6.10 | 3.00 | 23.8 | 84 | 8.3 |
| | | | | **Promedio** | **83** | **8.2** |
| NZ-22-016 | M-12 | 6.10 | 3.27 | 30.9 | 101 | 9.9 |
| | | 6.10 | 3.03 | 28.0 | 98 | 9.6 |
| | | 6.10 | 3.12 | 27.7 | 95 | 9.3 |
| | | | | **Promedio** | **98** | **9.6** |
| NZ-22-016 | M-14 | 6.10 | 3.08 | 48.2 | 167 | 16.3 |
| | | 6.10 | 3.25 | 49.2 | 161 | 15.8 |
| | | 6.10 | 3.28 | 52.1 | 169 | 16.6 |
| | | | | **Promedio** | **166** | **16.2** |
| NZ-22-016 | M-22 | 6.10 | 3.16 | 32.0 | 108 | 10.6 |
| | | 6.10 | 3.15 | 32.2 | 109 | 10.7 |
| | | 6.10 | 3.07 | 32.0 | 111 | 10.9 |
| | | | | **Promedio** | **109** | **10.7** |
| NZ-22-016 | M-26 | 6.11 | 3.49 | 33.1 | 101 | 9.9 |
| | | 6.11 | 3.38 | 31.8 | 100 | 9.8 |
| | | 6.11 | 3.20 | 30.2 | 100 | 9.8 |
| | | | | **Promedio** | **100** | **9.8** |
| NZ-22-016 | M-35 | 6.10 | 3.00 | 40.2 | 143 | 14.0 |
| | | 6.10 | 3.04 | 39.8 | 139 | 13.7 |
| | | 6.10 | 3.06 | 41.8 | 145 | 14.3 |
| | | | | **Promedio** | **142** | **14.0** |

Fuente: Laboratorio de Mecánica de Rocas UNI

## ENSAYOS COMPLETOS DE INVESTIGACION

Tabla 3.4 Ensayos de compresión Triaxial

| **Muestra** | **Diámetro (cm)** | **Altura (cm)** | **Confin. (MPa)** | **Esfuerzo Rotura (MPa)** | **Resistencia Compresiva MPa** | ***mi*** | **Cohesión *"c"* (MPa)** | **Ang. de Fricción Interno (°)** |
|---|---|---|---|---|---|---|---|---|
| *MINERAL* | *4.07* | *8.24* | *2* | *126.9* | ***110.08*** | ***15.8*** | ***20.77*** | ***49.44*** |
| | *4.07* | *8.36* | *4* | *142.1* | | | | |
| | *4.07* | *8.25* | *6* | *156.2* | | | | |
| *INTRUSIVO* | *4.10* | *8.42* | *2* | *198.3* | ***169.65*** | ***28.72*** | ***25.01*** | ***57.98*** |
| | *4.10* | *8.34* | *4* | *223.7* | | | | |
| | *4.10* | *8.35* | *6* | *246.9* | | | | |
| *CALIZA* | *4.07* | *8.34* | *2* | *95.8* | ***79.37*** | ***15.54*** | ***15.60*** | ***48.31*** |
| | *4.07* | *8.36* | *4* | *109.5* | | | | |
| | *4.07* | *8.43* | *6* | *123.4* | | | | |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

Tabla 3.5 Ensayos de compresión Uniaxial

| **Muestra** | ***Diámetro (cm)*** | ***Altura (cm)*** | ***Carga de rotura (kN)*** | ***Resistencia a la Compresión Uniaxial (kg/cm2)*** | ***Resistencia a la Compresión Uniaxial (MPa)*** |
|---|---|---|---|---|---|
| *MINERAL* | *4.08* | *8.29* | *144.2* | ***1127*** | ***110.5*** |
| *INTRUSIVO* | *4.10* | *8.35* | *223.6* | ***1731*** | ***169.7*** |
| *CALIZA* | *4.07* | *8.31* | *93.9* | ***738*** | ***72.4*** |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

Tabla 3.6 Ensayos de Tracción Indirecta (método brasilero)

| **Muestra** | **Diámetro (cm)** | **Altura (cm)** | **Carga (kN)** | **Resist. a la tracción (kg/cm$^2$)** | **Resist. a la tracción (MPa)** |
|---|---|---|---|---|---|
| *MINERAL* | *5.40* | *2.93* | *5.6* | *23* | *2.3* |
| | *5.40* | *2.86* | *6.5* | *27* | *2.7* |
| | *5.40* | *2.87* | *8.2* | *34* | *3.4* |
| | | | ***Promedio*** | ***28*** | ***2.8*** |
| *INTRUSIVO* | *5.40* | *2.91* | *27.3* | *113* | *11.1* |
| | *5.40* | *2.88* | *26.3* | *110* | *10.8* |
| | *5.40* | *2.89* | *25.4* | *106* | *10.4* |
| | | | ***Promedio*** | ***109*** | ***10.7*** |
| *CALIZA* | *5.40* | *2.89* | *12.8* | *53* | *5.2* |
| | *5.40* | *2.91* | *11.5* | *48* | *4.7* |
| | *5.40* | *2.87* | *12.2* | *51* | *5.0* |
| | | | ***Promedio*** | ***51*** | ***5.0*** |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

# CAPÍTULO IV

# RESULTADOS DE LA INVESTIGACIÓN

## 4.1. Análisis de los resultados de la investigación

Se han analizado mas de 200 datos de resultados de las muestras de Esfuerzos del ensayo de compresión simple, tracción indirecta y luego se compararon con los resultados del valor del $m_i$ del ensayo de compresión triaxial.

En la tabla se puede observar que en algunas muestras el porcentaje de variación es de +/- 3.33 % y en algunos casos +/- 18.52 % en relación al $m_i$ del triaxial.

Se pudo determinar que las roturas de las muestras en el caso del ensayos de tracción no fueron de tipo diametral, por lo que pudo influir en el resultado respectivo.

Tabla 4.1 Cuadro de resultados

| MUESTRA | UCS | BTS | UCS/BTS | TX - Mi | % |
|---|---|---|---|---|---|
| | Mpa. | Mpa. | | | |
| RP2705 | 94.9 | 6.0 | 15.74 | 16.26 | -3.33 |
| CX2910 | 79.6 | 5.2 | 15.26 | 12.43 | 18.52 |
| RP1925 | 109.5 | 6.9 | 15.78 | 14.28 | 9.50 |
| CX2452 | 92.0 | 6.1 | 15.03 | 16.54 | -10.07 |

*Fuente: Elaboración Propia*

Para el caso comparativo de datos entre BTS y UCS con el calculo de mi de un ensayo triaxial existe un 10.35 % de error.

Tabla 4.2 Ensayos de compresión Triaxial

| **Muestra** | **Diámetro (cm)** | **Altura (cm)** | **Confin. (MPa)** | **Esfuerzo Rotura (MPa)** | **Resistencia Compresiva MPa** | ***mi*** | **Cohesión *"c"* (MPa)** | **Ang. de Fricción Interno (°)** |
|---|---|---|---|---|---|---|---|---|
| *RP2800* | *4.02* | *8.11* | *2* | *227.7* | ***198.84*** | ***28.74*** | ***34.48*** | ***53.20*** |
|  | *4.01* | *8.18* | *4* | *254.0* |  |  |  |  |
|  | *4.01* | *8.18* | *6* | *277.6* |  |  |  |  |
| *RP2705* | *4.01* | *8.20* | *2* | *121.7* | ***104.60*** | ***16.26*** | ***19.19*** | ***47.98*** |
|  | *4.01* | *8.22* | *4* | *137.4* |  |  |  |  |
|  | *4.01* | *8.23* | *6* | *151.3* |  |  |  |  |
| *CX2452* | *4.03* | *8.05* | *2* | *136.6* | ***119.11*** | ***16.54*** | ***21.8*** | ***48.15*** |
|  | *4.02* | *8.21* | *4* | *152.7* |  |  |  |  |
|  | *4.02* | *8.07* | *6* | *167.2* |  |  |  |  |
| *CX3389* | *4.04* | *8.05* | *2* | *129.9* | ***110.54*** | ***18.37*** | ***19.93*** | ***49.16*** |
|  | *4.03* | *8.13* | *4* | *145.8* |  |  |  |  |
|  | *4.03* | *8.31* | *6* | *162.8* |  |  |  |  |
| *CX2910* | *4.01* | *8.18* | *2* | *78.6* | ***65.21*** | ***12.43*** | ***12.54*** | ***45.27*** |
|  | *4.01* | *8.18* | *4* | *90.7* |  |  |  |  |
|  | *4.01* | *8.15* | *6* | *101.4* |  |  |  |  |
| *TJ2822* | *3.97* | *8.10* | *2* | *129.7* | ***109.90*** | ***19.33*** | ***19.69*** | ***49.64*** |
|  | *3.97* | *8.24* | *4* | *147.7* |  |  |  |  |
|  | *3.97* | *7.88* | *6* | *163.4* |  |  |  |  |
| *TJ2027* | *4.06* | *8.12* | *2* | *155.2* | ***132.33*** | ***22.47*** | ***23.33*** | ***51.03*** |
|  | *4.06* | *8.39* | *4* | *175.4* |  |  |  |  |
|  | *4.06* | *8.18* | *6* | *194.1* |  |  |  |  |
| *RP1925* | *4.06* | *8.19* | *2* | *96.3* | ***81.31*** | ***14.28*** | ***15.24*** | ***46.69*** |
|  | *4.06* | *8.34* | *4* | *110.7* |  |  |  |  |
|  | *4.06* | *8.11* | *6* | *122.1* |  |  |  |  |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

Tabla 4.3 Ensayos de Tracción Indirecta (método brasilero)

| Muestra | Diámetro (cm) | Altura (cm) | Carga (kN) | Resist. a la tracción (kg/cm$^2$) | Resist. a la tracción (MPa) |
|---|---|---|---|---|---|
| *RP2800* | *7.39* | *4.01* | *48.7* | *107* | *10.5* |
| | *7.39* | *3.99* | *46.9* | *103* | *10.1* |
| | *7.39* | *3.91* | *47.8* | *107* | *10.5* |
| | | | ***Promedio*** | ***106*** | ***10.4*** |
| *RP2705* | *7.39* | *4.08* | *28.4* | *61* | *6.0* |
| | *7.39* | *4.96* | *31.2* | *55* | *5.4* |
| | *7.39* | *3.88* | *30.1* | *68* | *6.7* |
| | | | ***Promedio*** | ***62*** | ***6.0*** |
| *CX2452* | *4.02* | *2.11* | *8.0* | *61* | *6.0* |
| | *4.02* | *2.11* | *8.5* | *65* | *6.4* |
| | *4.02* | *2.09* | *7.9* | *61* | *6.0* |
| | | | ***Promedio*** | ***62*** | ***6.1*** |
| *CX3389* | *4.04* | *2.08* | *8.5* | *66* | *6.4* |
| | *4.04* | *2.10* | *8.8* | *67* | *6.6* |
| | *4.04* | *2.19* | *8.0* | *59* | *5.8* |
| | | | ***Promedio*** | ***64*** | ***6.3*** |
| *CX2910* | *4.01* | *2.18* | *7.1* | *53* | *5.2* |
| | *4.01* | *2.19* | *7.0* | *52* | *5.1* |
| | *4.01* | *2.20* | *7.5* | *55* | *5.4* |
| | | | ***Promedio*** | ***53*** | ***5.2*** |
| *TJ2822* | *4.00* | *2.09* | *8.2* | *64* | *6.2* |
| | *4.00* | *2.09* | *8.0* | *62* | *6.1* |
| | *4.00* | *2.07* | *8.9* | *70* | *6.8* |
| | | | ***Promedio*** | ***65*** | ***6.4*** |
| *RP1925* | *4.06* | *2.02* | *9.0* | *71* | *7.0* |
| | *4.06* | *2.03* | *8.5* | *67* | *6.6* |
| | *4.06* | *2.05* | *9.5* | *74* | *7.3* |
| | | | ***Promedio*** | ***71*** | ***6.9*** |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

Tabla 4.4 Ensayos de compresión Uniaxial

| **Muestra** | ***Diámetro (cm)*** | ***Altura (cm)*** | ***Carga de rotura (kN)*** | ***Resistencia a la Compresión Uniaxial (kg/cm2)*** | ***Resistencia a la Compresión Uniaxial (MPa)*** |
|---|---|---|---|---|---|
| *RP2800* | *4.01* | *8.09* | *246.1* | ***1990*** | ***195.1*** |
| *RP2705* | *4.02* | *8.14* | *120.3* | ***968*** | ***94.9*** |
| *CX3389* | *4.06* | *8.09* | *121.6* | ***958*** | ***93.9*** |
| *CX2910* | *4.01* | *7.99* | *100.6* | ***812*** | ***79.6*** |
| *BP2331* | *4.04* | *8.14* | *104.3* | ***831*** | ***81.4*** |
| *TJ2027* | *4.07* | *8.05* | *156.8* | ***1228*** | ***120.4*** |
| *TJ3033* | *4.06* | *8.21* | *121.6* | ***959*** | ***94.1*** |
| *RP1925* | *4.06* | *8.19* | *141.6* | ***1117*** | ***109.5*** |
| *CX2452* | *4.03* | *8.10* | *117.3* | ***939*** | ***92.0*** |
| *TJ2822* | *3.98* | *8.15* | *120.7* | ***992*** | ***97.3*** |

*Fuente: Laboratorio de Mecánica de Rocas UNI*

# CONCLUSIONES

- Se concluye que los resultados experimentales el cálculo del Mi por medio del esfuerzo compresivo y el esfuerzo de tracción tiene una aproximado de un 10.35 %.
- Los valores obtenidos tienen una variabilidad el cual esta en relación a la litología de la muestra y del grado de tectonismo que presenta la muestra.
- La aproximación del valor de Mi tiene relación al correcto desarrollo de los ensayos de compresión uniaxial y de tracción (método Brasilero), para ello los proceso que están reglamentados por las normas ASTM y equipos deben de estar debidamente calibrados.

## RECOMENDACIONES

- La recomendación principal es de realizar más ensayos, pero analizando muestras por cada litología existente en nuestro medio.
- Realizar varios ensayos de UCS, BTS y TX de una misma muestra que tenga el mismo grado de alteración en toda la muestra.
- Registrar las muestras y sus resultados mediante un mapeo por regiones metalogénicas y geológicas de nuestro país.

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# ANEXOS

# ANEXO 01

## MATRIZ DE CONSISTENCIA

## “ CORRELACION DEL mi EN RELACION AL COCIENTE DE LA RESISTENCIA DE COMPRESION UNIAXIAL Y TRACCION INDIRECTA”

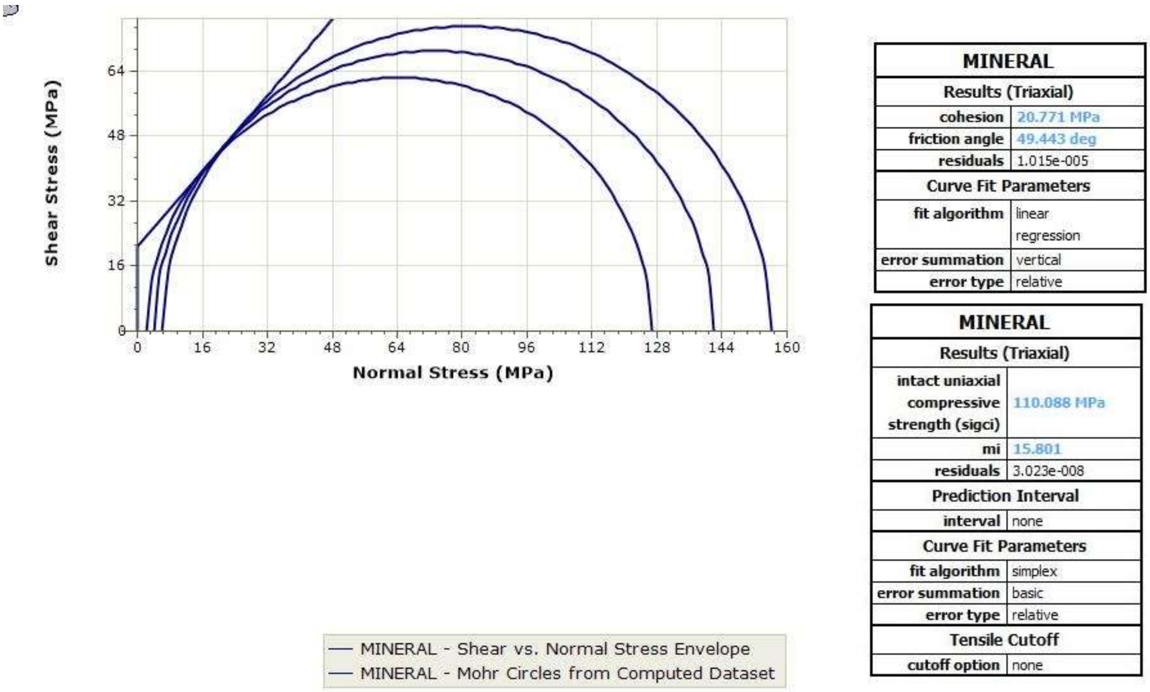
# ANEXO 1
# MATRIZ DE CONSISTENCIA
## “CORRELACION DEL mi EN RELACION AL COCIENTE DE LA RESISTENCIA DE COMPRESION UNIAXIAL Y TRACCION INDIRECTA”

| FORMULACIÓN DEL PROBLEMA | OBJETIVOS | HIPOTESIS | VARIABLES | INDICADORES | DISEÑO METODOLOGICO |
|---|---|---|---|---|---|
| **Problema general**<br>¿Cómo influye la correlación y determinación del mi sin desarrollar el ensayo de compresión triaxial?<br>**Problemas específicos**<br>1. ¿En qué medida se controla y se mejora el grado de seguridad en las labores mineras?<br>2. ¿En qué medida se controla y se mejora el sostenimiento en las labores mineras?<br>3. ¿En qué medida se controla y se mejora la determinación de parámetros de estabilidad de labores mineras sin requerir ensayos triaxiales en laboratorios especializados? | **Objetivo general**<br>Determinar cómo influye la determinación indirecta del mi en la toma de decisiones en la seguridad de operaciones mineras<br>**Objetivos específicos**<br>1. Realizar ensayos de compresión simple y tracción indirecta en laboratorios de las empresas mineras.<br>2. Determinar el mi mediante la correlación de los resultados del ensayos de compresión simple y ensayo de tracción indirecta | **Hipótesis general**<br>¿Se determinará el valor del mi sin desarrollar el ensayo de compresión triaxial?<br>**Hipótesis especificas**<br>1. Con la implementación de una prensa hidráulica se desarrollan los ensayos de compresión simple y tracción indirecta y se podrá simular indirectamente un ensayo de compresión triaxial.<br>2. Con la determinación del mi por este método se disminuye el tiempo en la toma de decisiones en los sistemas de seguridad en las labores mineras. | **Variable independiente: X**<br>X1= Correlacionar el valor mi sin desarrollar el ensayo de compresión triaxial<br>**Variable dependiente: Y**<br>Y1: Desarrollo del ensayo de compresión simple<br>Y2: Desarrollo del ensayos de tracción indirecta (método brasilero) | **Indicadores de X:**<br>X1:<br>Adquisición de equipo manual de una prensa hidráulica<br>**Indicadores de Y:**<br>Y1: Determinación del esfuerzo compresivo<br>Y2: Determinación del esfuerzo de tracción. | **Tipo de Investigación**<br>Aplicada<br>**Nivel de Investigación**<br>Descriptiva<br>**Diseño de la Investigación**<br>Cuasiexperimental, Cuantitativa<br>**Población**<br>Laboratorio de Mecánica de Rocas de la Universidad Nacional de Ingeniería<br>**Muestra**<br>**La Muestra esta compuesta por:**<br>**Muestras de Litologias diferentes.**<br>La técnica a emplearse será la de: Observación y Análisis<br>**Instrumento**<br>Prensa Hidraulica |

# ANEXO 02 – Gráficos, Fotos

# Cap. III

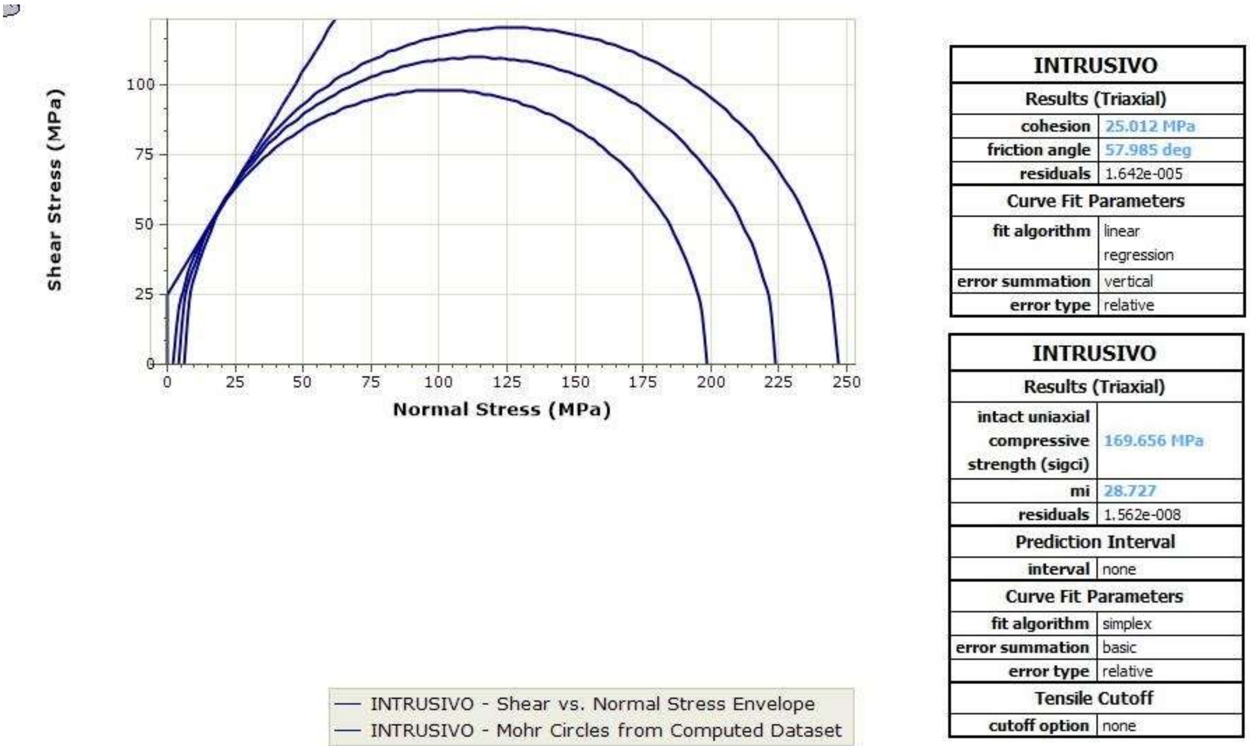
**GRAFICOS DE ENSAYOS TRIAXIALES Y FOTOS DE LAS MUESTRAS QUE MUESTRAN LOS TIPO DE ROTURAS DE LAS MUESTRAS DEL CAPITULO III**



| MINERAL | |
|---|---|
| **Results (Triaxial)** | |
| **cohesion** | 20.771 MPa |
| **friction angle** | 49.443 deg |
| **residuals** | 1.015e-005 |
| **Curve Fit Parameters** | |
| **fit algorithm** | linear regression |
| **error summation** | vertical |
| **error type** | relative |

| MINERAL | |
|---|---|
| **Results (Triaxial)** | |
| **intact uniaxial compressive strength (sigci)** | 110.088 MPa |
| **mi** | 15.801 |
| **residuals** | 3.023e-008 |
| **Prediction Interval** | |
| **interval** | none |
| **Curve Fit Parameters** | |
| **fit algorithm** | simplex |
| **error summation** | basic |
| **error type** | relative |
| **Tensile Cutoff** | |
| **cutoff option** | none |

---



| INTRUSIVO | |
|---|---|
| **Results (Triaxial)** | |
| **cohesion** | 25.012 MPa |
| **friction angle** | 57.985 deg |
| **residuals** | 1.642e-005 |
| **Curve Fit Parameters** | |
| **fit algorithm** | linear regression |
| **error summation** | vertical |
| **error type** | relative |

| INTRUSIVO | |
|---|---|
| **Results (Triaxial)** | |
| **intact uniaxial compressive strength (sigci)** | 169.656 MPa |
| **mi** | 28.727 |
| **residuals** | 1.562e-008 |
| **Prediction Interval** | |
| **interval** | none |
| **Curve Fit Parameters** | |
| **fit algorithm** | simplex |
| **error summation** | basic |
| **error type** | relative |
| **Tensile Cutoff** | |
| **cutoff option** | none |

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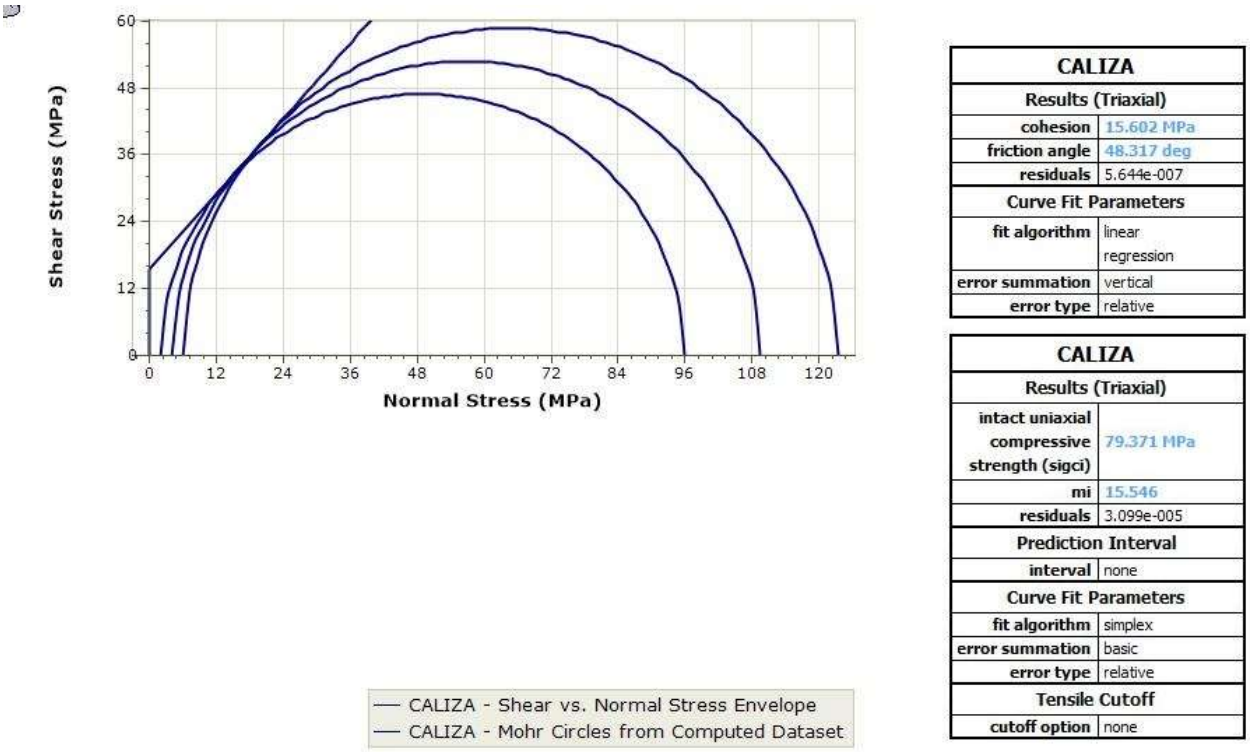


| CALIZA | |
|---|---|
| **Results (Triaxial)** | |
| **cohesion** | 15.602 MPa |
| **friction angle** | 48.317 deg |
| **residuals** | 5.644e-007 |
| **Curve Fit Parameters** | |
| **fit algorithm** | linear regression |
| **error summation** | vertical |
| **error type** | relative |

| CALIZA | |
|---|---|
| **Results (Triaxial)** | |
| **intact uniaxial compressive strength (sigci)** | 79.371 MPa |
| **mi** | 15.546 |
| **residuals** | 3.099e-005 |
| **Prediction Interval** | |
| **interval** | none |
| **Curve Fit Parameters** | |
| **fit algorithm** | simplex |
| **error summation** | basic |
| **error type** | relative |
| **Tensile Cutoff** | |
| **cutoff option** | none |

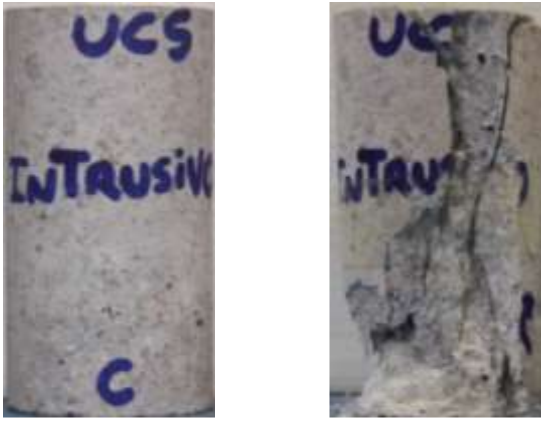
## ***FOTOS: COMPRESION UNIAXIAL***

**_Muestra: MINERAL_**

**_Antes_** **_Después_**

**_Muestra: INSTRUSIVO_**

**_Antes_** **_Después_**



**_Muestra: CALIZA_**

**_Antes_** **_Después_**

## FOTOS: COMPRESION TRIAXIAL

### Muestra: MINERAL

***Antes***

***Después***

### Muestra: INSTRUSIVO

***Antes***

***Después***

***Muestra: CALIZA***

***Antes***

***Después***

## ***FOTOS: TRACCION INDIRECTA***

***Muestra: MINERAL***
***Antes***

***Después***

***Muestra: INTRUSIVO***
***Antes***

***Después***

***Muestra: CALIZA***

***Antes***

***Después***

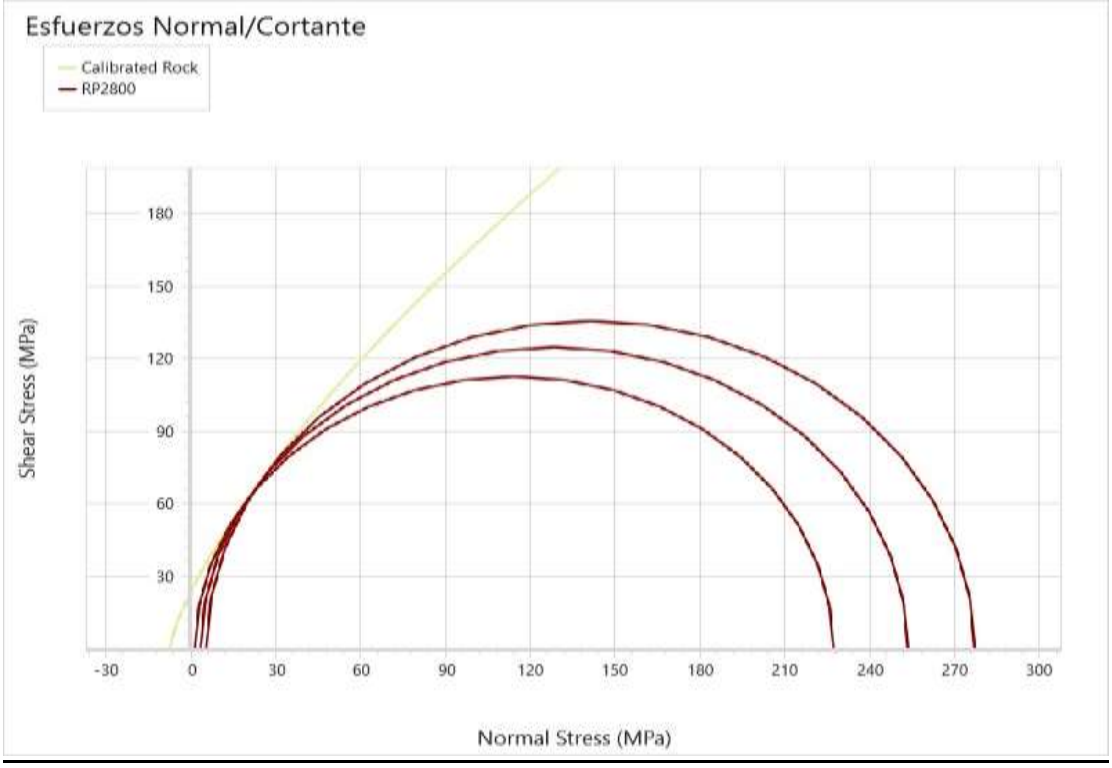
# ANEXO 03 – Graficos, Fotos

# Cap. IV

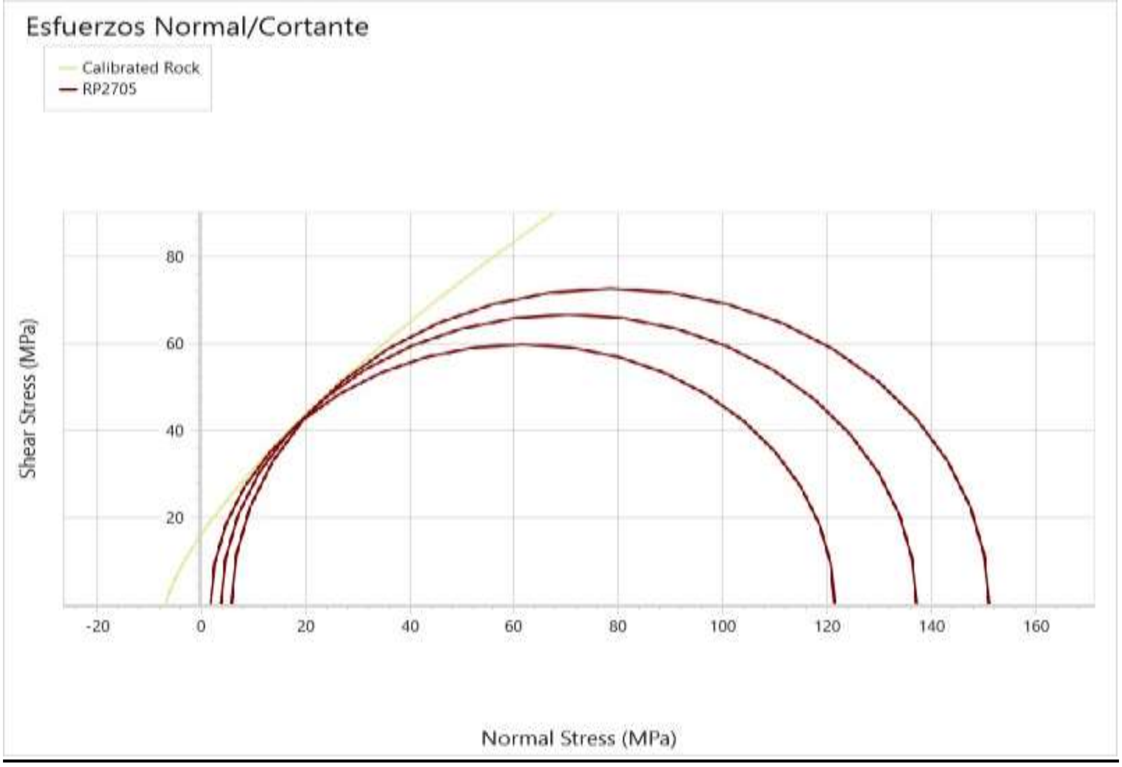
**GRAFICOS DE ENSAYOS TRIAXIALES Y FOTOS DE LAS MUESTRAS QUE MUESTRAN LOS TIPO DE ROTURAS DE LAS MUESTRAS DEL CAPITULO IV**

## GRAFICOS: ENSAYO COMPRESION TRIAXIAL

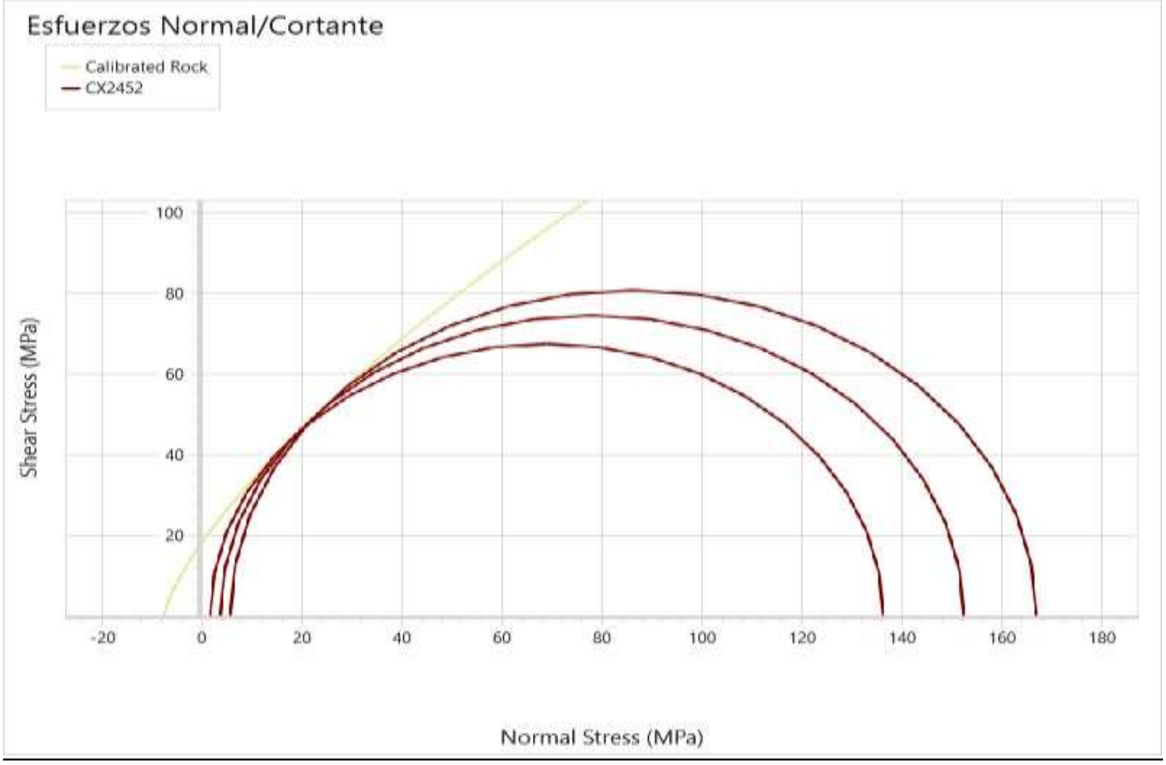
### MUESTRA: RP2800



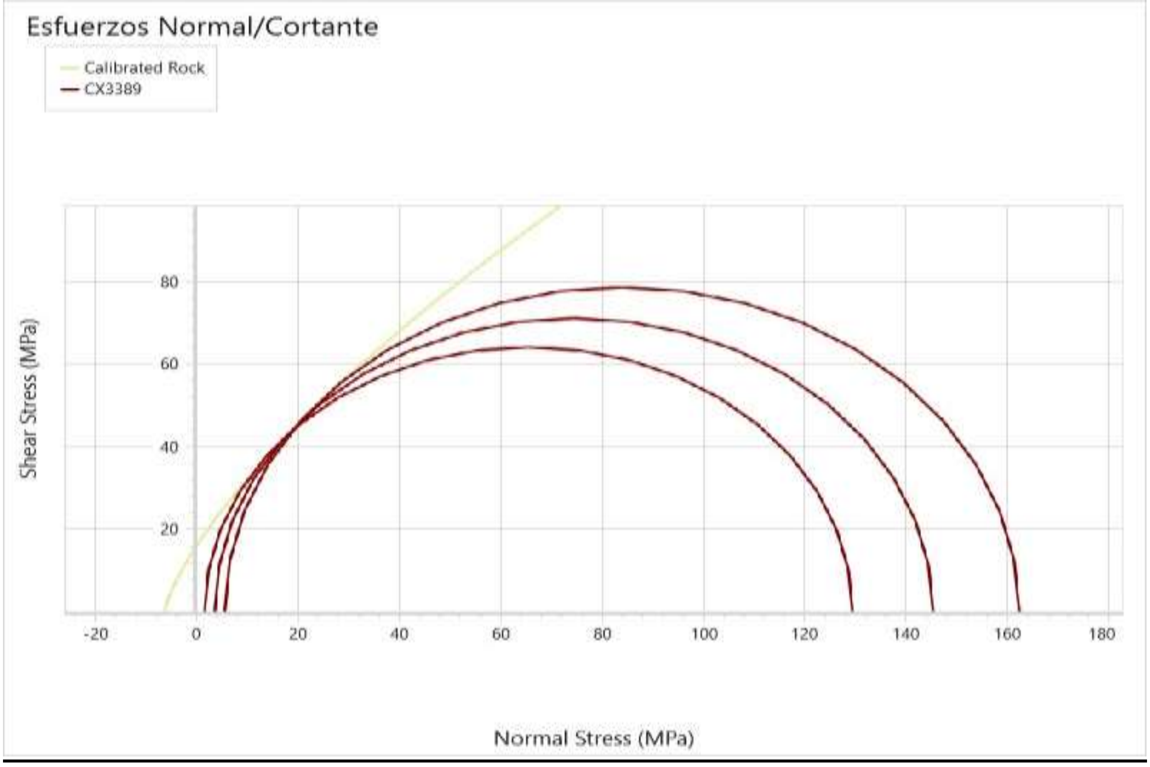
### MUESTRA: RP2705



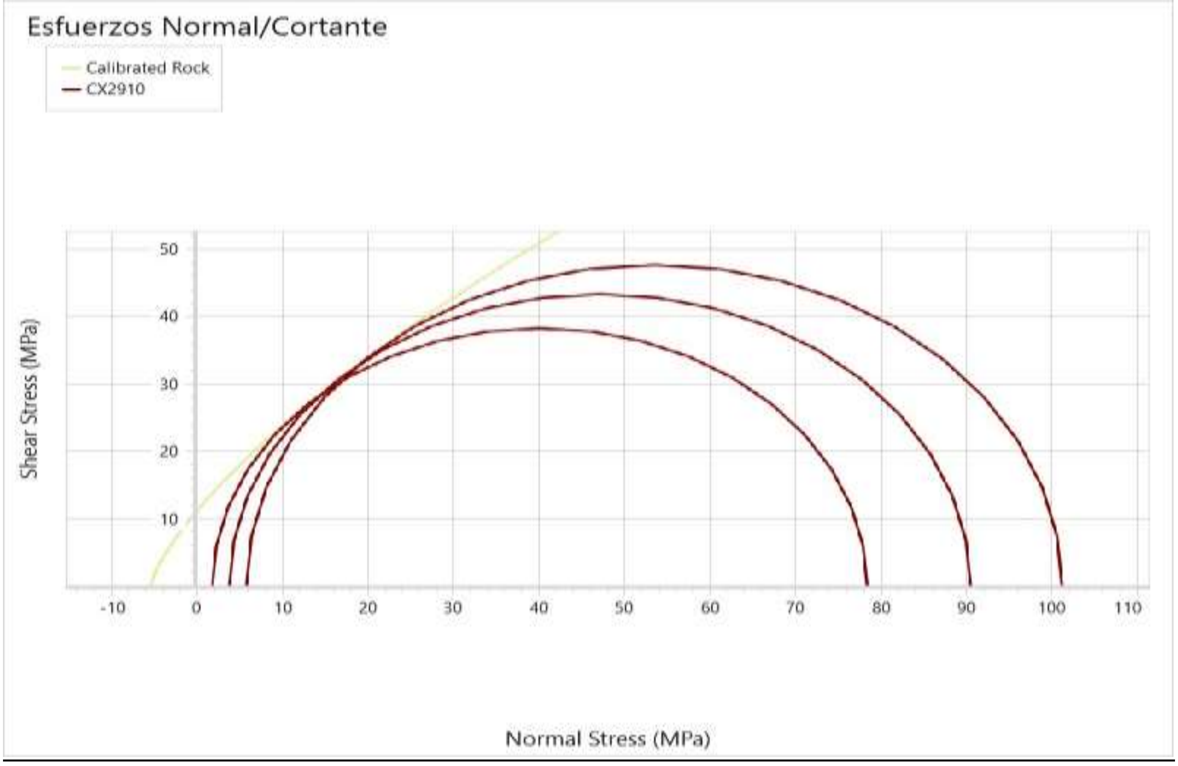
***MUESTRA: CX2452***



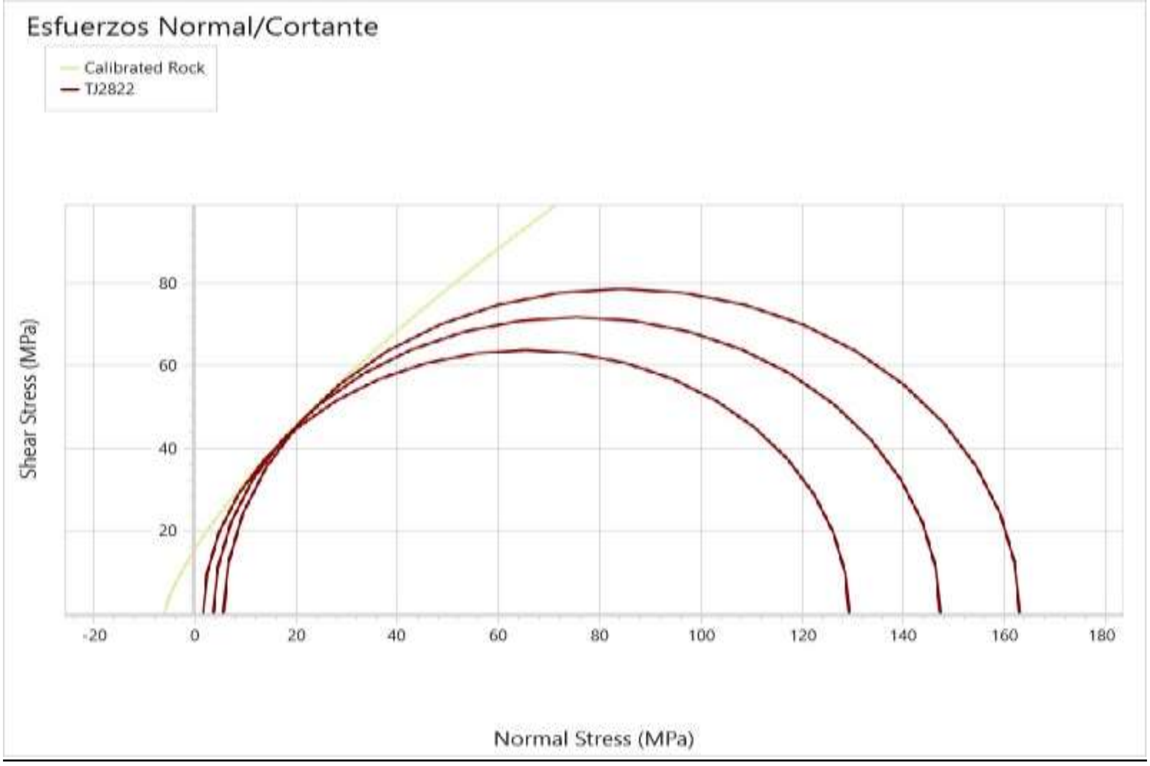
***MUESTRA: CX3389***



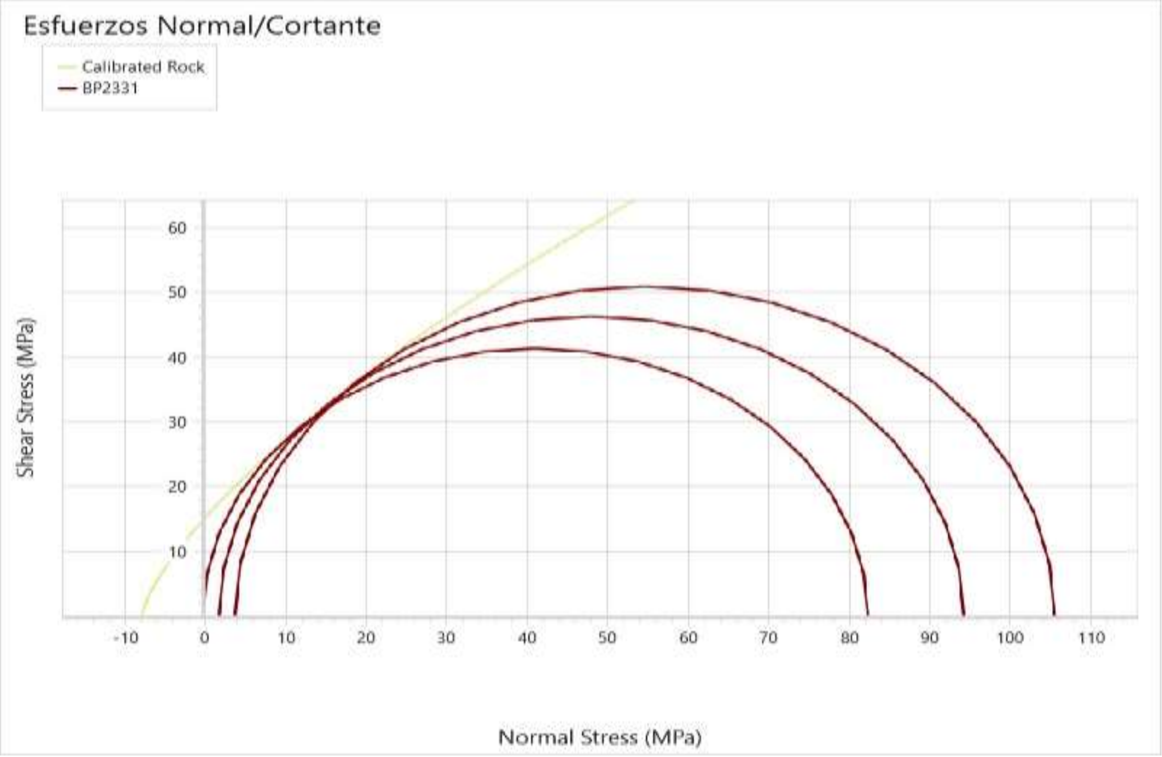
***MUESTRA: CX2910***



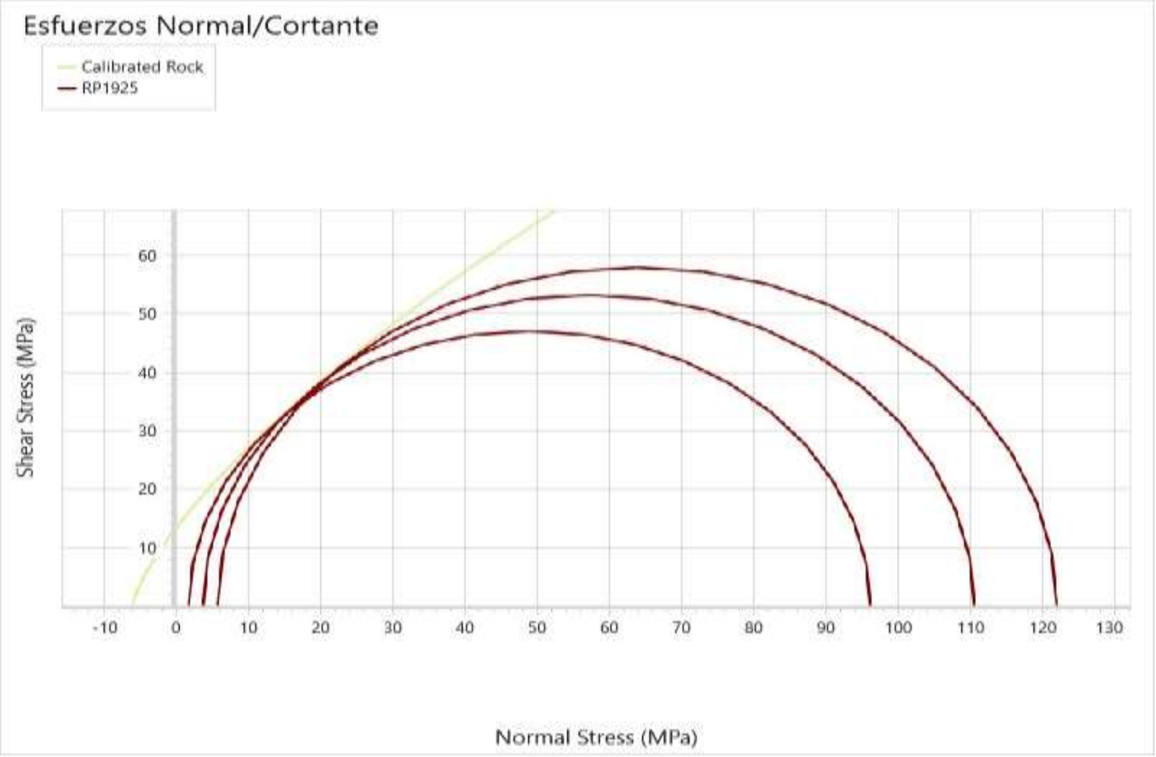
***MUESTRA: TJ2822***



***MUESTRA: BP2331***



***MUESTRA: RP1925***



## ***FOTOS: COMPRESION UNIAXIAL***

***Muestra: RP2800***

***Antes***

***Después***

***Muestra: RP2331***

***Antes***

***Después***

***Muestra: TJ3033***

***Antes***

***Después***

***Muestra: CX2910***


***Antes*** ***Después***

***Muestra: RP1925***


***Antes*** ***Después***

***Muestra: TJ2822***


***Antes*** ***Después***

***Muestra: CX2452***

***Antes*** ***Después***

***Muestra: CX3389***

***Antes*** ***Después***

***Muestra: TJ2027***

***Antes*** ***Después***

***Muestra: RP2705***

***Antes*** ***Después***

## ***FOTOS: COMPRESION TRIAXIAL***

***Muestra: RP2800***

***Antes***

***Después***

***Muestra: RP2705***
***Antes***

***Después***

***Muestra: CX2452***

***Antes***

***Después***

***Muestra: CX3389***

***Antes***

***Después***

***Muestra: CX2910***

***Antes***

*Después*

*Muestra: TJ2822*

*Antes*

*Después*

***Muestra: TJ2027***

***Antes***

***Después***

***Muestra: BP2331***

***Antes***

***Después***

***Muestra: TJ3033***

***Antes***

***Después***

***Muestra: RP1925***

***Antes***

***Después***

## *FOTOS: TRACCION INDIRECTA*

### *Muestra: RP1925*

*Antes*

*Después*

### *Muestra: TJ2822*

*Antes*

*Después*

***Muestra: CX2910***
***Antes***

***Después***

***Muestra: CX3389***

***Antes***

***Después***

*Muestra: CX2452*

*Antes*

*Después*

*Muestra: TJ3033*

*Antes*

*Después*

***Muestra: RP2705***

***Antes***

***Después***

***Muestra: RP2800***

***Antes***

***Después***

# ANEXO 04 – ENSAYOS GENERALES

.

**INFORME GENERAL DE PRINCIPALES ENSAYOS QUE SE REALIZAN EN UN LABORATORIO DE MECANICA DE ROCAS**

## ENSAYO DE PROPIEDADES FISICAS

Los ensayos se realizaron según la norma ASTM D2216-02, dando los siguientes resultados:

| Muestra | Diámetro (cm) | Longitud (cm) | Densidad Seca (g/cm³) | Densidad Húmeda (g/cm³) | Porosidad Aparente (%) | Absorción (%) | Peso Específico Aparente (kN/m³) |
|---|---|---|---|---|---|---|---|
| *M-1* | *6.39* | *2.39* | *2.61* | *2.64* | *3.25* | *1.25* | *25.70* |
| | *6.39* | *2.58* | *2.61* | *2.65* | *3.59* | *1.37* | *25.92* |
| | *6.39* | *2.55* | *2.62* | *2.66* | *3.64* | *1.39* | *25.89* |
| | | ***Promedio*** | ***2.61*** | ***2.65*** | ***3.49*** | ***1.34*** | ***25.84*** |
| *M-2* | *6.38* | *2.48* | *2.80* | *2.82* | *1.84* | *0.66* | *27.56* |
| | *6.38* | *2.26* | *2.79* | *2.80* | *1.80* | *0.65* | *27.42* |
| | *6.38* | *2.33* | *2.80* | *2.82* | *1.89* | *0.68* | *27.54* |
| | | ***Promedio*** | ***2.79*** | ***2.81*** | ***1.84*** | ***0.66*** | ***27.51*** |
| *M-3* | *4.19* | *2.52* | *2.74* | *2.76* | *2.42* | *0.88* | *26.98* |
| | *4.19* | *2.51* | *2.73* | *2.76* | *2.63* | *0.96* | *26.91* |
| | *4.19* | *2.39* | *2.73* | *2.75* | *2.49* | *0.91* | *26.86* |
| | | ***Promedio*** | ***2.73*** | ***2.76*** | ***2.51*** | ***0.92*** | ***26.92*** |
| *M-4* | *5.40* | *2.12* | *2.76* | *2.78* | *2.16* | *0.78* | *27.17* |
| | *5.40* | *2.12* | *2.76* | *2.79* | *2.43* | *0.88* | *27.17* |
| | *5.40* | *2.17* | *2.76* | *2.78* | *2.70* | *0.98* | *27.11* |
| | | ***Promedio*** | ***2.76*** | ***2.79*** | ***2.43*** | ***0.88*** | ***27.15*** |
| *M-5* | *6.39* | *2.26* | *2.76* | *2.78* | *2.52* | *0.92* | *27.21* |
| | *6.39* | *2.28* | *2.75* | *2.77* | *2.13* | *0.78* | *27.12* |
| | *6.39* | *2.16* | *2.75* | *2.77* | *2.41* | *0.88* | *27.08* |
| | | ***Promedio*** | ***2.75*** | ***2.77*** | ***2.36*** | ***0.86*** | ***27.14*** |
| *M-6* | *6.40* | *2.19* | *2.73* | *2.76* | *2.74* | *1.00* | *26.82* |
| | *6.40* | *2.21* | *2.73* | *2.76* | *2.73* | *1.00* | *26.81* |
| | *6.40* | *2.15* | *2.74* | *2.76* | *2.67* | *0.98* | *26.87* |
| | | ***Promedio*** | ***2.73*** | ***2.76*** | ***2.71*** | ***0.99*** | ***26.83*** |
| *M-7* | *5.38* | *2.13* | *2.82* | *2.83* | *1.45* | *0.51* | *27.72* |
| | *5.38* | *2.14* | *2.83* | *2.84* | *1.15* | *0.41* | *27.80* |
| | *5.38* | *2.16* | *2.82* | *2.83* | *1.06* | *0.38* | *27.75* |
| | | ***Promedio*** | ***2.82*** | ***2.84*** | ***1.22*** | ***0.43*** | ***27.76*** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *M-8* | *6.39* | *2.46* | *2.79* | *2.80* | *1.41* | *0.50* | *27.48* |
| | *6.39* | *2.51* | *2.79* | *2.81* | *1.94* | *0.69* | *27.54* |
| | *6.39* | *2.43* | *2.77* | *2.78* | *1.19* | *0.43* | *27.27* |
| | | ***Promedio*** | ***2.78*** | ***2.80*** | ***1.51*** | ***0.54*** | ***27.43*** |

| **Muestra** | **Diámetro (cm)** | **Longitud (cm)** | **Densidad Seca (g/cm³)** | **Densidad Húmeda (g/cm³)** | **Porosidad Aparente (%)** | **Absorción (%)** | **Peso Específico Aparente (kN/m³)** |
|---|---|---|---|---|---|---|---|
| *M-9* | *5.38* | *2.08* | *2.69* | *2.71* | *2.54* | *0.94* | *28.60* |
| | *5.38* | *2.15* | *2.68* | *2.71* | *2.52* | *0.94* | *26.45* |
| | *5.38* | *2.13* | *2.69* | *2.72* | *2.73* | *1.01* | *26.54* |
| | | ***Promedio*** | ***2.69*** | ***2.71*** | ***2.59*** | ***0.97*** | ***27.20*** |
| *M-10* | *4.19* | *2.73* | *2.69* | *2.70* | *1.30* | *0.48* | *26.44* |
| | *4.19* | *2.61* | *2.68* | *2.70* | *1.89* | *0.70* | *26.39* |
| | *4.19* | *2.70* | *2.68* | *2.70* | *1.72* | *0.64* | *26.35* |
| | | ***Promedio*** | ***2.68*** | ***2.70*** | ***1.64*** | ***0.61*** | ***26.39*** |
| *M-11* | *5.38* | *2.28* | *2.70* | *2.71* | *0.68* | *0.25* | *26.53* |
| | *5.38* | *2.38* | *2.70* | *2.70* | *0.65* | *0.24* | *26.52* |
| | *5.38* | *2.39* | *2.70* | *2.70* | *0.52* | *0.19* | *26.50* |
| | | ***Promedio*** | ***2.70*** | ***2.70*** | ***0.61*** | ***0.23*** | ***26.52*** |
| *M-12* | *5.37* | *2.10* | *2.68* | *2.69* | *0.84* | *0.31* | *26.73* |
| | *5.37* | *2.13* | *2.67* | *2.68* | *0.89* | *0.33* | *26.18* |
| | *5.37* | *2.09* | *2.68* | *2.69* | *0.53* | *0.20* | *26.33* |
| | | ***Promedio*** | ***2.68*** | ***2.68*** | ***0.75*** | ***0.28*** | ***26.41*** |
| *M-13* | *5.38* | *2.36* | *2.79* | *2.81* | *2.42* | *0.87* | *27.46* |
| | *5.38* | *2.19* | *2.78* | *2.80* | *2.13* | *0.77* | *27.43* |
| | *5.38* | *2.20* | *2.78* | *2.80* | *2.06* | *0.74* | *27.42* |
| | | ***Promedio*** | ***2.78*** | ***2.80*** | ***2.20*** | ***0.79*** | ***27.44*** |
| *M-14* | *5.39* | *2.34* | *2.75* | *2.76* | *1.09* | *0.40* | *27.20* |
| | *5.39* | *2.28* | *2.74* | *2.76* | *1.11* | *0.41* | *26.96* |
| | *5.39* | *2.25* | *2.75* | *2.76* | *1.11* | *0.40* | *27.00* |
| | | ***Promedio*** | ***2.75*** | ***2.76*** | ***1.10*** | ***0.40*** | ***27.05*** |
| *M-15* | *6.39* | *2.07* | *2.78* | *2.78* | *0.78* | *0.28* | *27.30* |
| | *6.39* | *2.16* | *2.78* | *2.79* | *0.55* | *0.20* | *27.32* |
| | *6.39* | *2.16* | *2.77* | *2.78* | *0.58* | *0.21* | *27.23* |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Promedio** | **2.78** | **2.78** | **0.64** | **0.23** | **27.28** |
| M-16 | 6.40 | 2.14 | 2.71 | 2.72 | 1.16 | 0.43 | 26.63 |
| | 6.40 | 2.15 | 2.72 | 2.73 | 1.11 | 0.41 | 26.57 |
| | 6.40 | 2.15 | 2.72 | 2.73 | 1.08 | 0.40 | 25.71 |
| | | **Promedio** | **2.71** | **2.73** | **1.12** | **0.41** | **26.31** |

| **Muestra** | **Diámetro (cm)** | **Longitud (cm)** | **Densidad Seca (g/cm³)** | **Densidad Húmeda (g/cm³)** | **Porosidad Aparente (%)** | **Absorción (%)** | **Peso Específico Aparente (kN/m³)** |
|---|---|---|---|---|---|---|---|
| M-17 | 5.40 | 2.41 | 2.47 | 2.48 | 1.03 | 0.42 | 24.25 |
| | 5.40 | 2.29 | 2.47 | 2.48 | 1.79 | 0.73 | 24.31 |
| | 5.40 | 2.30 | 2.46 | 2.47 | 1.46 | 0.59 | 24.21 |
| | | **Promedio** | **2.46** | **2.48** | **1.43** | **0.58** | **24.25** |
| M-18 | 5.38 | 2.28 | 2.75 | 2.76 | 1.39 | 0.51 | 26.98 |
| | 5.38 | 2.45 | 2.75 | 2.76 | 1.31 | 0.48 | 27.03 |
| | 5.38 | 2.27 | 2.74 | 2.75 | 1.53 | 0.56 | 26.90 |
| | | **Promedio** | **2.74** | **2.76** | **1.41** | **0.51** | **26.97** |

## ENSAYO DE COMPRESION TRIAXIAL

Los ensayos se realizaron según la norma ASTM 2664-95, dando los siguientes resultados:

| Muestra | Diámetro (cm) | Altura (cm) | Confin. (MPa) | Esfuerzo Rotura (MPa) | Resistencia Compresiva MPa | *mi* | Cohesión *"c"* (MPa) | Ang. de Fricción Interno (°) |
|---|---|---|---|---|---|---|---|---|
| *M-1* | *6.39* | *12.79* | *2* | *117.6* | ***99.16*** | ***17.53*** | ***17.99*** | ***48.71*** |
| | *6.39* | *12.95* | *4* | *132.9* | | | | |
| | *6.39* | *12.81* | *6* | *148.8* | | | | |
| *M-2* | *6.38* | *12.91* | *2* | *102.4* | ***87.93*** | ***13.43*** | ***16.66*** | ***46.06*** |
| | *6.38* | *12.93* | *4* | *115.8* | | | | |
| | *6.38* | *12.88* | *6* | *127.6* | | | | |
| *M-3* | *4.19* | *8.26* | *2* | *74.1* | ***60.89*** | ***12.07*** | ***11.78*** | ***44.96*** |
| | *4.19* | *8.23* | *4* | *85.1* | | | | |
| | *4.19* | *8.21* | *6* | *96.4* | | | | |
| *M-4* | *5.39* | *11.08* | *2* | *110.9* | ***94.17*** | ***15.71*** | ***17.37*** | ***47.64*** |
| | *5.39* | *11.06* | *4* | *125.2* | | | | |
| | *5.39* | *11.13* | *6* | *139.5* | | | | |
| *M-5* | *6.38* | *12.73* | *2* | *106.3* | ***87.33*** | ***18.42*** | ***15.74*** | ***49.18*** |
| | *6.38* | *12.92* | *4* | *122.1* | | | | |
| | *6.38* | *12.82* | *6* | *137.8* | | | | |
| *M-6* | *6.39* | *13.01* | *2* | *115.5* | ***96.25*** | ***18.38*** | ***17.36*** | ***49.16*** |
| | *6.39* | *12.82* | *4* | *130.8* | | | | |
| | *6.39* | *12.80* | *6* | *147.7* | | | | |
| *M-7* | *5.38* | *11.30* | *2* | *114.4* | ***94.61*** | ***19.40*** | ***16.94*** | ***49.67*** |
| | *5.38* | *11.16* | *4* | *131.5* | | | | |
| | *5.38* | *11.27* | *6* | *147.4* | | | | |
| *M-8* | *6.39* | *12.98* | *2* | *163.1* | ***137.10*** | ***26.20*** | ***23.89*** | ***52.40*** |
| | *6.39* | *12.77* | *4* | *186.4* | | | | |
| | *6.39* | *12.94* | *6* | *206.7* | | | | |
| *M-9* | *5.38* | *11.17* | *2* | *104.4* | ***81.68*** | ***23.14*** | ***14.36*** | ***51.29*** |
| | *5.38* | *11.12* | *4* | *122.8* | | | | |
| | *5.38* | *11.10* | *6* | *140.6* | | | | |

| Muestra | Diámetro (cm) | Altura (cm) | Confin. (MPa) | Esfuerzo Rotura (MPa) | Resistencia Compresiva MPa | *mi* | Cohesión *“c”* (MPa) | Ang. de Fricción Interno (°) |
|---|---|---|---|---|---|---|---|---|
| *M-10* | *4.18* | *7.99* | *2* | *112.5* | ***93.30*** | ***18.64*** | ***16.79*** | ***49.30*** |
| | *4.18* | *8.19* | *4* | *128.8* | | | | |
| | *4.18* | *8.29* | *6* | *144.6* | | | | |
| *M-11* | *5.38* | *11.08* | *2* | *95.3* | ***76.79*** | ***18.58*** | ***13.83*** | ***49.27*** |
| | *5.38* | *11.12* | *4* | *112.5* | | | | |
| | *5.38* | *10.92* | *6* | *125.7* | | | | |
| *M-12* | *5.38* | *11.27* | *2* | *44.4* | ***36.31*** | ***6.59*** | ***8.15*** | ***38.20*** |
| | *5.38* | *11.05* | *4* | *51.7* | | | | |
| | *5.38* | *11.00* | *6* | *58.5* | | | | |
| *M-13* | *5.39* | *11.22* | *2* | *53.8* | ***40.15*** | ***13.18*** | ***7.63*** | ***45.88*** |
| | *5.39* | *11.00* | *4* | *64.7* | | | | |
| | *5.39* | *11.09* | *6* | *75.5* | | | | |
| *M-14* | *5.38* | *10.88* | *2* | *124.7* | ***103.47*** | ***20.95*** | ***18.37*** | ***50.39*** |
| | *5.38* | *11.11* | *4* | *143.1* | | | | |
| | *5.38* | *11.04* | *6* | *160.1* | | | | |
| *M-15* | *5.39* | *11.21* | *2* | *166.5* | ***141.41*** | ***24.88*** | ***24.73*** | ***51.94*** |
| | *5.39* | *11.22* | *4* | *188.4* | | | | |
| | *5.39* | *11.20* | *6* | *208.9* | | | | |
| *M-16* | *5.38* | *12.20* | *2* | *169.2* | ***140.81*** | ***28.64*** | ***24.42*** | ***53.17*** |
| | *5.38* | *12.91* | *4* | *193.1* | | | | |
| | *5.38* | *12.86* | *6* | *216.2* | | | | |
| *M-17* | *5.39* | *11.09* | *2* | *46.6* | ***34.50*** | ***11.51*** | ***6.74*** | ***44.47*** |
| | *5.39* | *11.04* | *4* | *56.6* | | | | |
| | *5.39* | *11.21* | *6* | *65.9* | | | | |
| *M-18* | *5.38* | *11.09* | *2* | *103.8* | ***85.04*** | ***18.23*** | ***15.35*** | ***49.09*** |
| | *5.38* | *11.10* | *4* | *119.5* | | | | |
| | *5.38* | *11.01* | *6* | *134.9* | | | | |

## ENSAYO DE CONSTANTES ELASTICAS

Los ensayos se realizaron según la norma ASTM D7012-04, dando los siguientes resultados:

| **Muestra** | **Diámetro (cm)** | **Altura (cm)** | **Resistencia Compresiva MPa** | **Módulo de Young “*E*” (GPa)** | **Relación de Poisson “*v*”** |
|---|---|---|---|---|---|
| M-1 | 6.39 | 12.72 | 95.2 | **12.13** | **0.27** |
| M-2 | 6.38 | 12.81 | 87.8 | **16.02** | **0.25** |
| M-3 | 4.19 | 8.13 | 48.9 | **5.14** | **0.31** |
| M-4 | 5.39 | 11.06 | 36.0 | **5.59** | **0.31** |
| M-5 | 6.39 | 12.89 | 79.8 | **8.70** | **0.28** |
| M-6 | 6.39 | 12.71 | 91.2 | **10.27** | **0.28** |
| M-7 | 5.38 | 11.22 | 107.4 | **9.87** | **0.28** |
| M-8 | 6.34 | 12.82 | 151.5 | **17.09** | **0.24** |
| M-9 | 5.37 | 11.13 | 59.1 | **5.15** | **0.31** |
| M-10 | 4.19 | 8.06 | 61.4 | **6.29** | **0.30** |
| M-11 | 5.39 | 11.17 | 62.5 | **10.38** | **0.28** |
| M-12 | 5.37 | 11.19 | 29.2 | **4.21** | **0.30** |
| M-13 | 5.39 | 11.12 | 32.8 | **5.88** | **0.31** |
| M-14 | 5.38 | 11.2 | 109.5 | **12.31** | **0.26** |
| M-15 | 5.37 | 11.35 | 146.3 | **16.03** | **0.25** |
| M-16 | 6.39 | 12.63 | 140.2 | **15.46** | **0.26** |
| M-17 | 5.37 | 11.26 | 84.9 | **11.51** | **0.27** |
| M-18 | 5.38 | 11.18 | 88.2 | **11.17** | **0.28** |

## ENSAYO DE COMPRESION UNIAXIAL

Los ensayos se realizaron según la norma ASTM D2938-95, dando los siguientes resultados:

| **Muestra** | *Diámetro (cm)* | *Altura (cm)* | *Carga de rotura (kN)* | *Resistencia a la Compresión Uniaxial (kg/cm2)* | *Resistencia a la Compresión Uniaxial (MPa)* |
|---|---|---|---|---|---|
| M-1 | 6.39 | 12.77 | 332.0 | **1056** | **103.5** |
| M-2 | 6.38 | 12.97 | 231.5 | **740** | **72.5** |
| M-3 | 4.19 | 8.13 | 70.9 | **523** | **51.2** |
| M-4 | 5.38 | 11.06 | 187.2 | **843** | **82.6** |
| M-5 | 6.39 | 12.99 | 237.5 | **757** | **74.2** |
| M-6 | 6.39 | 12.92 | 270.9 | **863** | **84.6** |
| M-7 | 5.38 | 11.09 | 225.4 | **1015** | **99.5** |
| M-8 | 6.39 | 12.87 | 375.7 | **1196** | **117.3** |
| M-9 | 5.37 | 11.08 | 155.0 | **701** | **68.7** |
| M-10 | 4.18 | 8.33 | 115.8 | **860** | **84.3** |
| M-11 | 5.38 | 11.05 | 150.6 | **678** | **66.5** |
| M-12 | 5.37 | 11.13 | 69.7 | **315** | **30.9** |
| M-13 | 5.37 | 11.27 | 74.9 | **339** | **33.3** |
| M-14 | 5.38 | 11.04 | 264.8 | **1192** | **116.8** |
| M-15 | 5.37 | 11.05 | 305.8 | **1382** | **135.5** |
| M-16 | 6.39 | 12.90 | 400.1 | **1274** | **124.9** |
| M-17 | 5.38 | 11.21 | 65.4 | **295** | **28.9** |
| M-18 | 5.37 | 11.04 | 220.1 | **995** | **97.5** |

## ENSAYO DE TRACCION INDIRECTA (Brasilero)

Los ensayos se realizaron según la norma ASTM D3967-95, dando los siguientes resultados:

| Muestra | Diámetro (cm) | Altura (cm) | Carga (kN) | Resist. a la tracción (kg/cm²) | Resist. a la tracción (MPa) |
|---|---|---|---|---|---|
| *M-1* | *6.39* | *3.36* | *25.6* | *77* | *7.6* |
| | *6.39* | *3.48* | *26.1* | *76* | *7.5* |
| | *6.39* | *3.40* | *24.0* | *72* | *7.0* |
| | | | ***Promedio*** | *75* | *7.4* |
| *M-2* | *6.38* | *3.24* | *18.3* | *57* | *5.6* |
| | *6.38* | *3.35* | *19.8* | *60* | *5.9* |
| | *6.38* | *3.42* | *18.2* | *54* | *5.3* |
| | | | ***Promedio*** | *59* | *5.8* |
| *M-3* | *5.38* | *3.04* | *12.8* | *51* | *5.0* |
| | *5.38* | *3.00* | *13.8* | *55* | *5.4* |
| | *5.38* | *2.97* | *12.5* | *51* | *5.0* |
| | | | ***Promedio*** | *52* | *5.1* |
| *M-4* | *5.39* | *3.10* | *16.3* | *63* | *6.2* |
| | *5.39* | *3.04* | *17.2* | *68* | *6.7* |
| | *5.39* | *3.07* | *18.1* | *71* | *7.0* |
| | | | ***Promedio*** | *68* | *6.6* |
| *M-5* | *6.40* | *3.07* | *27.4* | *91* | *8.9* |
| | *6.40* | *3.14* | *28.2* | *91* | *8.9* |
| | *6.40* | *3.16* | *28.7* | *92* | *9.0* |
| | | | ***Promedio*** | *91* | *8.9* |
| *M-6* | *6.39* | *3.22* | *24.8* | *78* | *7.7* |
| | *6.39* | *3.31* | *23.6* | *72* | *7.1* |
| | *6.39* | *3.29* | *25.5* | *79* | *7.7* |
| | | | ***Promedio*** | *77* | *7.5* |
| *M-7* | *5.38* | *3.07* | *20.6* | *81* | *8.0* |
| | *5.38* | *3.07* | *21.4* | *84* | *8.2* |
| | *5.38* | *2.99* | *20.1* | *81* | *7.9* |
| | | | ***Promedio*** | *82* | *8.0* |

| | | | | | |
|---|---|---|---|---|---|
| *M-8* | *6.30* | *3.28* | *28.2* | *89* | *8.7* |
| | *6.30* | *3.32* | *27.6* | *86* | *8.4* |
| | *6.30* | *3.38* | *28.1* | *86* | *8.4* |
| | | | **Promedio** | *87* | *8.5* |
| *M-9* | *5.38* | *3.37* | *15.9* | *57* | *5.6* |
| | *5.38* | *3.40* | *15.1* | *54* | *5.3* |
| | *5.38* | *3.30* | *16.3* | *60* | *5.8* |
| | | | **Promedio** | *57* | *5.6* |

| **Muestra** | **Diámetro (cm)** | **Altura (cm)** | **Carga (kN)** | **Resist. a la tracción (kg/cm$^2$)** | **Resist. a la tracción (MPa)** |
|---|---|---|---|---|---|
| *M-10* | *5.37* | *3.25* | *13.4* | *50* | *4.9* |
| | *5.37* | *3.14* | *12.9* | *50* | *4.9* |
| | *5.37* | *3.15* | *12.0* | *46* | *4.5* |
| | | | **Promedio** | *49* | *4.8* |
| *M-11* | *5.38* | *2.94* | *12.3* | *50* | *5.0* |
| | *5.38* | *3.02* | *10.7* | *43* | *4.2* |
| | *5.38* | *3.09* | *12.3* | *48* | *4.7* |
| | | | **Promedio** | *47* | *4.6* |
| *M-12* | *5.38* | *3.08* | *7.3* | *29* | *2.8* |
| | *5.38* | *2.97* | *6.3* | *26* | *2.5* |
| | *5.38* | *3.02* | *6.8* | *27* | *2.7* |
| | | | **Promedio** | *27* | *2.7* |
| *M-13* | *5.39* | *2.99* | *7.4* | *30* | *2.9* |
| | *5.39* | *3.07* | *6.7* | *26* | *2.6* |
| | *5.39* | *3.06* | *6.9* | *27* | *2.6* |
| | | | **Promedio** | *28* | *2.7* |
| *M-14* | *5.38* | *2.93* | *17.5* | *72* | *7.1* |
| | *5.38* | *3.07* | *19.4* | *76* | *7.5* |
| | *5.38* | *3.07* | *18.1* | *71* | *7.0* |
| | | | **Promedio** | *73* | *7.2* |

| | | | | | |
|---|---|---|---|---|---|
| M-15 | 6.39 | 3.26 | 30.3 | 94 | 9.3 |
| | 6.39 | 3.46 | 32.3 | 95 | 9.3 |
| | 6.39 | 3.30 | 31.2 | 96 | 9.4 |
| | | | **Promedio** | 95 | 9.3 |
| M-16 | 6.39 | 3.23 | 33.3 | 105 | 10.3 |
| | 6.39 | 3.13 | 33.1 | 107 | 10.5 |
| | 6.39 | 3.14 | 34.4 | 111 | 10.9 |
| | | | **Promedio** | 108 | 10.6 |
| M-17 | 5.38 | 3.20 | 15.9 | 60 | 5.9 |
| | 5.38 | 3.09 | 16.5 | 64 | 6.3 |
| | 5.38 | 3.17 | 16.9 | 64 | 6.3 |
| | | | **Promedio** | 63 | 6.2 |
| M-18 | 5.38 | 2.8 | 15.6 | 67 | 6.6 |
| | 5.38 | 2.91 | 16.4 | 68 | 6.7 |
| | 5.38 | 3.00 | 17.3 | 70 | 6.8 |
| | | | **Promedio** | 68 | 6.7 |

## ENSAYO DE CORTE DIRECTO (SIMULADO)

Los ensayos se realizaron sobre discontinuidad con caras paralelas a la dirección de corte, según norma ASTM D5607-95, dando los siguientes resultados.

| Muestra | Tipo de discontinuidad | Esfuerzo Normal (MPa) | Esfuerzo de Corte (MPa) | Cohesión (MPa) | Angulo de Fricción (°) |
|---|---|---|---|---|---|
| *M-1* | *Simulado* | *0.78* | *0.52* | ***0.106*** | ***27.84*** |
| | | *1.56* | *0.92* | | |
| | | *2.34* | *1.35* | | |
| | | *3.12* | *1.76* | | |
| | | *3.90* | *2.16* | | |
| *M-2* | *Simulado* | *0.78* | *0.52* | ***0.105*** | ***27.86*** |
| | | *1.56* | *0.93* | | |
| | | *2.35* | *1.35* | | |
| | | *3.13* | *1.75* | | |
| | | *3.91* | *2.18* | | |
| *M-3* | *Simulado* | *1.10* | *0.68* | ***0.103*** | ***28.08*** |
| | | *2.20* | *1.28* | | |
| | | *3.30* | *1.88* | | |
| | | *4.40* | *2.45* | | |
| | | *5.50* | *3.03* | | |
| *M-4* | *Simulado* | *1.10* | *0.69* | ***0.108*** | ***27.99*** |
| | | *2.19* | *1.27* | | |
| | | *3.29* | *1.86* | | |
| | | *4.38* | *2.45* | | |
| | | *5.48* | *3.01* | | |
| *M-5* | *Simulado* | *0.78* | *0.52* | ***0.103*** | ***28.01*** |
| | | *1.55* | *0.93* | | |
| | | *2.33* | *1.34* | | |
| | | *3.11* | *1.75* | | |
| | | *3.89* | *2.18* | | |

| | | | | | |
|---|---|---|---|---|---|
| *M-6* | *Simulado* | *0.78* | *0.53* | ***0.112*** | ***28.07*** |
| | | *1.56* | *0.94* | | |
| | | *2.34* | *1.36* | | |
| | | *3.12* | *1.78* | | |
| | | *3.90* | *2.19* | | |
| *M-7* | *Simulado* | *1.10* | *0.69* | ***0.100*** | ***27.99*** |
| | | *2.19* | *1.26* | | |
| | | *3.29* | *1.85* | | |
| | | *4.38* | *2.42* | | |
| | | *5.48* | *3.02* | | |

| **Muestra** | **Tipo de discontinuidad** | **Esfuerzo Normal (MPa)** | **Esfuerzo de Corte (MPa)** | **Cohesión (MPa)** | **Angulo de Fricción (°)** |
|---|---|---|---|---|---|
| *M-8* | *Simulado* | *0.78* | *0.51* | ***0.097*** | ***27.78*** |
| | | *1.56* | *0.92* | | |
| | | *2.34* | *1.33* | | |
| | | *3.12* | *1.73* | | |
| | | *3.90* | *2.16* | | |
| *M-9* | *Simulado* | *1.10* | *0.68* | ***0.102*** | ***27.88*** |
| | | *2.20* | *1.27* | | |
| | | *3.30* | *1.85* | | |
| | | *4.40* | *2.43* | | |
| | | *5.50* | *3.01* | | |
| *M-10* | *Simulado* | *1.10* | *0.69* | ***0.103*** | ***28.08*** |
| | | *2.20* | *1.28* | | |
| | | *3.30* | *1.86* | | |
| | | *4.40* | *2.45* | | |
| | | *5.50* | *3.04* | | |
| *M-11* | *Simulado* | *1.10* | *0.69* | ***0.100*** | ***27.96*** |
| | | *2.20* | *1.27* | | |
| | | *3.30* | *1.84* | | |
| | | *4.40* | *2.43* | | |
| | | *5.50* | *3.03* | | |
| *M-12* | *Simulado* | *1.10* | *0.71* | ***0.108*** | ***28.12*** |
| | | *2.20* | *1.27* | | |
| | | *3.30* | *1.87* | | |
| | | *4.40* | *2.45* | | |
| | | *5.50* | *3.06* | | |
| *M-13* | *Simulado* | *1.10* | *0.69* | ***0.103*** | ***27.95*** |
| | | *2.19* | *1.26* | | |
| | | *3.29* | *1.85* | | |
| | | *4.38* | *2.43* | | |
| | | *5.48* | *3.01* | | |
| *M-14* | *Simulado* | *1.10* | *0.69* | ***0.106*** | ***27.96*** |
| | | *2.20* | *1.28* | | |

| | | | | | |
|---|---|---|---|---|---|
| | | *3.30* | *1.85* | | |
| | | *4.40* | *2.44* | | |
| | | *5.50* | *3.03* | | |

| **Muestra** | **Tipo de discontinuidad** | **Esfuerzo Normal (MPa)** | **Esfuerzo de Corte (MPa)** | **Cohesión (MPa)** | **Angulo de Fricción (°)** |
|---|---|---|---|---|---|
| *M-15* | *Simulado* | *0.78* | *0.52* | ***0.107*** | ***27.78*** |
| | | *1.56* | *0.92* | | |
| | | *2.34* | *1.36* | | |
| | | *3.12* | *1.73* | | |
| | | *3.90* | *2.17* | | |
| *M-16* | *Simulado* | *0.78* | *0.51* | ***0.097*** | ***28.01*** |
| | | *1.56* | *0.93* | | |
| | | *2.34* | *1.34* | | |
| | | *3.12* | *1.76* | | |
| | | *3.90* | *2.17* | | |
| *M-17* | *Simulado* | *1.10* | *0.69* | ***0.100*** | ***28.07*** |
| | | *2.19* | *1.27* | | |
| | | *3.29* | *1.85* | | |
| | | *4.38* | *2.43* | | |
| | | *5.48* | *3.03* | | |
| *M-18* | *Simulado* | *1.10* | *0.68* | ***0.101*** | ***28.00*** |
| | | *2.20* | *1.28* | | |
| | | *3.30* | *1.85* | | |
| | | *4.40* | *2.45* | | |
| | | *5.50* | *3.02* | | |

## ENSAYO DE CARGA PUNTUAL

Los ensayos se realizaron según la norma ASTM D5731-02, dando los siguientes resultados:

| Muestra | Diámetro equivalente “De” (mm) | Carga de rotura (kN) | Indice de carga puntual corregido “$I_{s(50)}$” (MPa) | Resistencia a la Compresión Simple (MPa) |
|---|---|---|---|---|
| *M-1* | *41.0* | *8.9* | *5.28* | *111.7* |
| | *42.6* | *9.7* | *5.31* | *114.0* |
| | *40.7* | *8.6* | *5.21* | *110.1* |
| | *42.6* | *9.3* | *5.10* | *109.4* |
| | *42.9* | *9.9* | *5.35* | *115.1* |
| | | ***Promedio*** | ***5.25*** | ***112.1*** |
| *M-2* | *39.9* | *9.5* | *5.99* | *125.8* |
| | *36.8* | *8.0* | *5.91* | *120.8* |
| | *38.3* | *9.1* | *6.22* | *128.8* |
| | *37.8* | *8.8* | *6.17* | *127.2* |
| | *39.6* | *9.6* | *6.13* | *128.3* |
| | | ***Promedio*** | ***6.09*** | ***126.2*** |
| *M-3* | *43.6* | *7.3* | *3.83* | *82.8* |
| | *42.6* | *6.7* | *3.70* | *79.4* |
| | *43.6* | *7.3* | *3.81* | *82.4* |
| | *43.2* | *7.2* | *3.87* | *83.3* |
| | *42.6* | *7.1* | *3.92* | *84.0* |
| | | ***Promedio*** | ***3.82*** | ***82.4*** |
| *M-4* | *43.1* | *8.5* | *4.56* | *98.3* |
| | *43.4* | *8.2* | *4.34* | *93.8* |
| | *42.0* | *8.2* | *4.64* | *99.1* |
| | *41.6* | *8.0* | *4.62* | *98.2* |
| | *41.5* | *8.1* | *4.68* | *99.4* |
| | | ***Promedio*** | ***4.57*** | ***97.8*** |
| *M-5* | *45.3* | *7.6* | *3.69* | *80.9* |
| | *43.6* | *7.3* | *3.85* | *83.3* |
| | *43.8* | *7.1* | *3.70* | *80.2* |
| | *45.7* | *8.6* | *4.12* | *90.7* |
| | *44.9* | *8.0* | *3.94* | *86.0* |
| | | ***Promedio*** | ***3.86*** | ***84.2*** |

| | | | | |
|---|---|---|---|---|
| *M-6* | *40.0* | *8.3* | *5.17* | *108.5* |
| | *42.0* | *9.1* | *5.19* | *110.7* |
| | *40.8* | *9.0* | *5.38* | *113.7* |
| | *41.6* | *8.2* | *4.75* | *101.1* |
| | *40.9* | *8.0* | *4.76* | *100.6* |
| | | ***Promedio*** | ***5.05*** | ***106.9*** |

| **Muestra** | **Diámetro equivalente “De” (mm)** | **Carga de rotura (kN)** | **Indice de carga puntual corregido “$I_{s(50)}$” (MPa)** | **Resistencia a la Compresión Simple (MPa)** |
|---|---|---|---|---|
| *M-7* | *43.3* | *10.9* | *5.79* | *124.9* |
| | *41.3* | *10.4* | *6.11* | *129.6* |
| | *42.8* | *11.2* | *6.09* | *130.8* |
| | *41.5* | *10.7* | *6.20* | *131.8* |
| | *41.0* | *9.6* | *5.73* | *121.4* |
| | | ***Promedio*** | ***5.98*** | ***127.7*** |
| *M-8* | *39.2* | *12.0* | *7.76* | *162.0* |
| | *40.7* | *12.5* | *7.50* | *158.4* |
| | *40.9* | *13.0* | *7.78* | *164.6* |
| | *41.3* | *13.3* | *7.78* | *165.0* |
| | *43.2* | *14.0* | *7.52* | *162.1* |
| | | ***Promedio*** | ***7.67*** | ***162.4*** |
| *M-9* | *42.1* | *7.5* | *4.20* | *89.8* |
| | *40.0* | *6.8* | *4.25* | *89.3* |
| | *41.7* | *7.9* | *4.54* | *96.7* |
| | *39.9* | *7.2* | *4.53* | *95.0* |
| | *41.6* | *8.1* | *4.67* | *99.4* |
| | | ***Promedio*** | ***4.44*** | ***94.0*** |
| *M-10* | *47.2* | *7.7* | *3.44* | *76.5* |
| | *48.1* | *7.5* | *3.25* | *72.9* |
| | *46.0* | *7.6* | *3.57* | *78.8* |
| | *45.8* | *7.0* | *3.32* | *73.2* |
| | *45.6* | *6.2* | *2.99* | *65.6* |
| | | ***Promedio*** | ***3.31*** | ***73.4*** |

| | | | | |
|---|---|---|---|---|
| M-11 | 37.4 | 4.7 | 3.33 | 68.4 |
| | 41.1 | 4.9 | 2.92 | 61.8 |
| | 42.1 | 5.7 | 3.21 | 68.5 |
| | 42.2 | 5.6 | 3.13 | 66.9 |
| | 39.7 | 5.2 | 3.27 | 68.6 |
| | | **Promedio** | **3.17** | **66.8** |
| M-12 | 42.1 | 2.9 | 1.61 | 34.4 |
| | 43.4 | 2.5 | 1.30 | 28.1 |
| | 44.6 | 2.9 | 1.47 | 32.0 |
| | 44.5 | 2.7 | 1.37 | 29.9 |
| | 42.8 | 2.8 | 1.50 | 32.3 |
| | | **Promedio** | **1.45** | **31.3** |

| **Muestra** | **Diámetro equivalente “De” (mm)** | **Carga de rotura (kN)** | **Indice de carga puntual corregido “$I_{s(50)}$” (MPa)** | **Resistencia a la Compresión Simple (MPa)** |
|---|---|---|---|---|
| M-13 | 44.9 | 3.9 | 1.92 | 42.0 |
| | 44.9 | 4.2 | 2.09 | 45.7 |
| | 44.7 | 4.3 | 2.13 | 46.4 |
| | 43.9 | 4.8 | 2.47 | 53.6 |
| | 44.7 | 4.3 | 2.17 | 47.3 |
| | | **Promedio** | **2.16** | **47.0** |
| M-14 | 39.5 | 10.6 | 6.75 | 141.2 |
| | 38.1 | 9.8 | 6.75 | 139.5 |
| | 39.5 | 9.8 | 6.27 | 131.1 |
| | 39.0 | 9.7 | 6.38 | 132.8 |
| | 40.9 | 10.5 | 6.25 | 132.2 |
| | | **Promedio** | **6.48** | **135.3** |
| M-15 | 42.7 | 15.4 | 8.45 | 181.5 |
| | 42.7 | 14.8 | 8.14 | 174.7 |
| | 43.2 | 15.4 | 8.25 | 177.8 |
| | 39.5 | 12.7 | 8.14 | 170.3 |
| | 41.2 | 13.8 | 8.13 | 172.5 |
| | | **Promedio** | **8.22** | **175.4** |

| | | | | |
|---|---|---|---|---|
| *M-16* | *37.9* | *9.6* | *6.66* | *137.5* |
| | *41.3* | *10.6* | *6.18* | *131.3* |
| | *39.9* | *9.8* | *6.19* | *129.8* |
| | *42.9* | *11.5* | *6.22* | *133.9* |
| | *44.3* | *12.5* | *6.38* | *138.9* |
| | | ***Promedio*** | ***6.33*** | ***134.3*** |
| *M-17* | *40.4* | *3.4* | *2.09* | *44.1* |
| | *40.1* | *3.0* | *1.84* | *38.6* |
| | *41.1* | *3.2* | *1.89* | *40.1* |
| | *46.2* | *3.9* | *1.80* | *39.9* |
| | *41.4* | *3.1* | *1.78* | *37.9* |
| | | ***Promedio*** | ***1.88*** | ***40.1*** |
| *M-18* | *41.0* | *10.1* | *6.01* | *127.2* |
| | *44.2* | *10.8* | *5.53* | *120.1* |
| | *41.3* | *9.9* | *5.82* | *123.5* |
| | *42.5* | *10.7* | *5.92* | *127.0* |
| | *42.9* | *10.5* | *5.68* | *122.3* |
| | | ***Promedio*** | ***5.79*** | ***124.0*** |

## ENSAYO DE CORTE DIRECTO (NATURAL)

Los ensayos se realizaron sobre discontinuidad con caras paralelas a la dirección de corte, según norma ASTM D5607-95, dando los siguientes resultados.

| **Muestra - Zona** | **Estructura** | **Tipo de discontinuidad** | **Esfuerzo Normal (MPa)** | **Esfuerzo de Corte (MPa)** | **Cohesión (MPa)** | **Angulo de Fricción (°)** |
|---|---|---|---|---|---|---|
| *M-1 CUERPOS* | *CASAPALCA* | *Natural* | *0.96* | *0.73* | ***0.105*** | ***32.86*** |
| | | | *1.91* | *1.34* | | |
| | | | *2.87* | *1.94* | | |
| | | | *3.82* | *2.59* | | |
| | | | *4.78* | *3.19* | | |
| *M-1 VETAS* | *XIMENA* | *Natural* | *0.98* | *0.78* | ***0.099*** | ***34.55*** |
| | | | *1.96* | *1.44* | | |
| | | | *2.94* | *2.12* | | |
| | | | *3.92* | *2.81* | | |
| | | | *4.90* | *3.47* | | |
| *M-2 CUERPOS* | *CASAPALCA* | *Natural* | *0.90* | *0.72* | ***0.100*** | ***34.74*** |
| | | | *1.81* | *1.35* | | |
| | | | *2.71* | *2.00* | | |
| | | | *3.61* | *2.60* | | |
| | | | *4.52* | *3.23* | | |
| *M-2 VETAS* | *XIMENA* | *Natural* | *0.69* | *0.58* | ***0.101*** | ***34.88*** |
| | | | *1.38* | *1.07* | | |
| | | | *2.07* | *1.54* | | |
| | | | *2.76* | *2.02* | | |
| | | | *3.45* | *2.51* | | |
| *M-3 CUERPOS* | *CASAPALCA* | *Natural* | *0.70* | *0.60* | ***0.102*** | ***35.34*** |
| | | | *1.39* | *1.10* | | |
| | | | *2.09* | *1.57* | | |
| | | | *2.78* | *2.07* | | |
| | | | *3.48* | *2.58* | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| *M-3 VETAS* | *XIMENA* | *Natural* | *0.62* | *0.51* | ***0.090*** | ***34.86*** |
| | | | *1.24* | *0.96* | | |
| | | | *1.86* | *1.40* | | |
| | | | *2.48* | *1.82* | | |
| | | | *3.10* | *2.24* | | |
| *M-4 CUERPOS* | *MS* | *Natural* | *0.81* | *0.65* | ***0.100*** | ***33.32*** |
| | | | *1.63* | *1.15* | | |
| | | | *2.44* | *1.70* | | |
| | | | *3.25* | *2.25* | | |
| | | | *4.06* | *2.77* | | |

| **Muestra - Zona** | **Estructura** | **Tipo de discontinuidad** | **Esfuerzo Normal (MPa)** | **Esfuerzo de Corte (MPa)** | **Cohesión (MPa)** | **Angulo de Fricción (°)** |
|---|---|---|---|---|---|---|
| *M-4 VETAS* | *XIMENA* | *Natural* | *0.94* | *0.71* | ***0.105*** | ***32.59*** |
| | | | *1.88* | *1.31* | | |
| | | | *2.82* | *1.90* | | |
| | | | *3.76* | *2.50* | | |
| | | | *4.70* | *3.12* | | |
| *M-5 CUERPOS* | *MS* | *Natural* | *0.85* | *0.68* | ***0.104*** | ***34.15*** |
| | | | *1.71* | *1.26* | | |
| | | | *2.56* | *1.85* | | |
| | | | *3.42* | *2.42* | | |
| | | | *4.27* | *3.00* | | |
| *M-5 VETAS* | *ESPERANZA* | *Natural* | *0.80* | *0.61* | ***0.100*** | ***32.53*** |
| | | | *1.59* | *1.11* | | |
| | | | *2.39* | *1.64* | | |
| | | | *3.19* | *2.12* | | |
| | | | *3.99* | *2.65* | | |
| *M-6 CUERPOS* | *MS* | *Natural* | *0.84* | *0.66* | ***0.103*** | ***33.53*** |
| | | | *1.69* | *1.23* | | |
| | | | *2.53* | *1.77* | | |
| | | | *3.38* | *2.35* | | |
| | | | *4.22* | *2.90* | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| *M-6 VETAS* | *ESPERANZA* | *Natural* | *0.72* | *0.59* | ***0.099*** | ***34.18*** |
| | | | *1.44* | *1.08* | | |
| | | | *2.16* | *1.57* | | |
| | | | *2.88* | *2.03* | | |
| | | | *3.60* | *2.56* | | |
| *M-7 CUERPOS* | *ESPERANZA* | *Natural* | *0.82* | *0.65* | ***0.096*** | ***33.97*** |
| | | | *1.65* | *1.20* | | |
| | | | *2.47* | *1.77* | | |
| | | | *3.29* | *2.32* | | |
| | | | *4.11* | *2.86* | | |
| *M-7 VETAS* | *ESPERANZA* | *Natural* | *0.85* | *0.64* | ***0.098*** | ***32.45*** |
| | | | *1.69* | *1.17* | | |
| | | | *2.54* | *1.72* | | |
| | | | *3.39* | *2.25* | | |
| | | | *4.23* | *2.79* | | |

| **Muestra - Zona** | **Estructura** | **Tipo de discontinuidad** | **Esfuerzo Normal (MPa)** | **Esfuerzo de Corte (MPa)** | **Cohesión (MPa)** | **Angulo de Fricción (°)** |
|---|---|---|---|---|---|---|
| *M-8 CUERPOS* | *ESPERANZA* | *Natural* | *1.24* | *0.87* | ***0.099*** | ***32.06*** |
| | | | *2.48* | *1.65* | | |
| | | | *3.71* | *2.43* | | |
| | | | *4.95* | *3.22* | | |
| | | | *6.19* | *3.96* | | |
| *M-9 CUERPOS* | *ESPERANZA* | *Natural* | *0.93* | *0.73* | ***0.101*** | ***33.97*** |
| | | | *1.87* | *1.38* | | |
| | | | *2.80* | *1.96* | | |
| | | | *3.74* | *2.62* | | |
| | | | *4.67* | *3.26* | | |
| *M-10 CUERPOS* | *PIQUE CIRCULAR* | *Natural* | *0.49* | *0.43* | ***0.099*** | ***33.60*** |
| | | | *0.97* | *0.74* | | |
| | | | *1.46* | *1.07* | | |
| | | | *1.95* | *1.39* | | |
| | | | *2.43* | *1.72* | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| *M-11 CUERPOS* | *RAMPA 565* | Natural | *1.04* | *0.76* | ***0.097*** | ***32.43*** |
| | | | *2.08* | *1.42* | | |
| | | | *3.12* | *2.07* | | |
| | | | *4.16* | *2.75* | | |
| | | | *5.20* | *3.40* | | |

## ENSAYO DE VELOCIDAD DE ONDAS (Vp - Vs)

Los ensayos se realizaron según la norma ASTM D 2845, dando los siguientes resultados:

| **Muestra** | *Longitud (cm)* | ***Altura* (cm)** | ***Vp* (m/seg.)** | ***Vs* (m/seg.)** |
|---|---|---|---|---|
| *M-1* | *6.39* | *12.77* | **4942.0** | **3879.7** |
| *M-2* | *6.38* | *12.97* | **4507.0** | **3583.7** |
| *M-3* | *4.19* | *8.13* | **4392.0** | **1304.0** |
| *M-4* | *5.39* | *11.06* | **4005.0** | **2963.0** |
| *M-5* | *6.39* | *12.99* | **5759.0** | **4354.8** |
| *M-6* | *6.39* | *12.92* | **5526.0** | **4040.7** |
| *M-7* | *5.38* | *11.09* | **4891.0** | **3323.0** |
| *M-8* | *6.34* | *12.87* | **6275.0** | **4830.7** |
| *M-9* | *5.37* | *11.08* | **4970.0** | **3877.0** |
| *M-10* | *4.19* | *8.33* | **3452.0** | **1564.0** |
| *M-11* | *5.39* | *11.05* | **5178.0** | **3793.0** |
| *M-12* | *5.37* | *11.13* | **4856.0** | **3327.0** |
| *M-13* | *5.39* | *11.27* | **5441.0** | **4508.7** |
| *M-14* | *5.38* | *11.04* | **4205.0** | **3971.7** |
| *M-15* | *5.37* | *11.05* | **5827.0** | **5196.3** |
| *M-16* | *6.39* | *12.90* | **5526.0** | **4010.7** |
| *M-17* | *5.37* | *11.21* | **4050.0** | **2640.0** |
| *M-18* | *5.38* | *11.04* | **3304.0** | **2563.7** |

# ANEXO 05 - NORMAS ASTM

## NORMAS ASTM ASTM 2664-95, D7012-14 y D3967-08

**Designation: D 2664 – 95a**

AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428
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# Standard Test Method for Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements[1]

This standard is issued under the fixed designation D 2664; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers the determination of the strength of cylindrical rock core specimens in an undrained state under triaxial compression loading. The test provides data useful in determining the strength and elastic properties of rock, namely: shear strengths at various lateral pressures, angle of internal friction, (angle of shearing resistance), cohesion intercept, and Young's modulus. It should be observed that this method makes no provision for pore pressure measurements. Thus the strength values determined are in terms of total stress, that is, not corrected for pore pressures.

1.2 The values stated in inch-pound units are to be regarded as the standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*

D 4543 Practice for Preparing Rock Core Specimens and Determining Dimensional and Shape Tolerances[2]
E 4 Practices for Force Verification of Testing Machines[3]
E 122 Practice for Choice of Sample Size to Estimate a Measure of Quality for a Lot or Process[4]

## 3. Significance and Use

3.1 Rock is known to behave as a function of the confining pressure. The triaxial compression test is commonly used to simulate the stress conditions under which most underground rock masses exist.

## 4. Apparatus

4.1 *Loading Device*—A suitable device for applying and measuring axial load to the specimen. It shall be of sufficient capacity to apply load at a rate conforming to the requirements specified in 7.2. It shall be verified at suitable time intervals in accordance with the procedures given in Practices E 4 and comply with the requirements prescribed in the method.

4.2 *Pressure-Maintaining Device*—A hydraulic pump, pressure intensifier, or other system of sufficient capacity to maintain constant the desired lateral pressure, $\sigma_3$.

NOTE 1—A pressure intensifier as described by Leonard Obert in U.S. Bureau of Mines Report of Investigations No. 6332, "An Inexpensive Triaxial Apparatus for Testing Mine Rock," has been found to fulfill the above requirements.

4.3 *Triaxial Compression Chamber*[5]—An apparatus in which the test specimen may be enclosed in an impermeable flexible membrane; placed between two hundred platens, one of which shall be spherically seated; subjected to a constant lateral fluid pressure; and then loaded axially to failure. The platens shall be made of tool steel hardened to a minimum of Rockwell 58 HRC, the bearing faces of which shall not depart from plane surfaces by more than 0.0005 in. (0.0127 mm) when the platens are new and which shall be maintained within a permissible variation of 0.001 in. (0.025 mm). In addition to the platens and membrane, the apparatus shall consist of a high-pressure cylinder with overflow valve, a base, suitable entry ports for filling the cylinder with hydraulic fluid and applying the lateral pressure, and hoses, gages, and valves as needed.

4.4 *Deformation and Strain-Measuring Devices*—High-grade dial micrometers or other measuring devices graduated to read in 0.0001-in. (0.0025-mm) units, and accurate within 0.0001 in. (0.0025 mm) in any 0.0010-in. (0.025-mm) range, and within 0.0002 in. (0.005 mm) in any 0.0100-in. (0.25-mm) range shall be provided for measuring axial deformation due to loading. These may consist of micrometer screws, dial micrometers, or linear variable differential transformers securely attached to the high pressure cylinder.

4.4.1 Electrical resistance strain gages applied directly to the rock specimen in the axial direction may also be used. In addition, the use of circumferentially applied strain gages will permit the observation of data necessary in the calculation of

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

Current edition approved Dec. 10, 1995. Published April 1996. Originally published as D 2664 – 67. Last previous edition D 2664 – 86 (1995).

[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vols 03.01, 14.02.

[4] *Annual Book of ASTM Standards*, Vol 14.02.

[5] Assembly and detail drawings of an apparatus that meets these requirements and which is designed to accommodate 2⅛-in. (53.975-mm) diameter specimens and operate at a lateral fluid pressure of 10 000 psi (689 MPa) are available from Headquarters. Request Adjunct No. 12-426640-00.

Poisson's ratio. In this case two axial (vertical) gages should be mounted on opposite sides of the specimen at mid-height and two circumferential (horizontal) gages similarly located around the circumference, but in the direction perpendicular to the axial gages.

4.5 *Flexible Membrane*—A flexible membrane of suitable material to exclude the confining fluid from the specimen, and that shall not significantly extrude into abrupt surface pores. It should be sufficiently long to extend well onto the platens and when slightly stretched be of the same diameter as the rock specimen.

NOTE 2—Neoprene rubber tubing of 1/16-in. (1.588-mm) wall thickness and of 40 to 60 Durometer hardness, Shore Type A or various sizes of bicycle inner tubing, have been found generally suitable for this purpose.

## 5. Sampling

5.1 The specimen shall be selected from the cores to represent a true average of the type of rock under consideration. This can be achieved by visual observations of mineral constituents, grain sizes and shapes, partings and defects such as pores and fissures.

## 6. Test Specimens

6.1 *Preparation*—The test specimens shall be prepared in accordance with Practice D 4543.

6.2 Moisture condition of the specimen at the time of test can have a significant effect upon the indicated strength of the rock. Good practice generally dictates that laboratory tests be made upon specimens representative of field conditions. Thus it follows that the field moisture condition of the specimen should be preserved until the time of test. On the other hand, there may be reasons for testing specimens at other moisture contents, including zero. In any case the moisture content of the test specimen should be tailored to the problem at hand and reported in accordance with 9.1.6.

## 7. Procedure

7.1 Place the lower platen on the base. Wipe clean the bearing faces of the upper and lower platens and of the test specimen, and place the test specimen on the lower platen. Place the upper platen on the specimen and align properly. Fit the flexible membrane over the specimen and platen and install rubber or neoprene O-rings to seal the specimen from the confining fluid. Place the cylinder over the specimen, ensuring proper seal with the base, and connect the hydraulic pressure lines. Position the deformation measuring device and fill the chamber with hydraulic fluid. Apply a slight axial load, approximately 25 lbf (110 N), to the triaxial compression chamber by means of the loading device in order to properly seat the bearing parts of the apparatus. Take an initial reading on the deformation device. Slowly raise the lateral fluid pressure to the predetermined test level and at the same time apply sufficient axial load to prevent the deformation measuring device from deviating from the initial reading. When the predetermined test level of fluid pressure is reached, note and record the axial load registered by the loading device. Consider this load to be the zero or starting load for the test.

7.2 Apply the axial load continuously and without shock until the load becomes constant, or reduces, or a predetermined amount of strain is achieved. Apply the load in such a manner as to produce a strain rate as constant as feasible throughout the test. Do not permit the strain rate at any given time to deviate by more than 10 % from that selected. The strain rate selected should be that which will produce failure of a similar test specimen in unconfined compression, in a test time of between 2 and 15 min. The selected strain rate for a given rock type shall be adhered to for all tests in a given series of investigation (Note 3). Maintain constant the predetermined confining pressure throughout the test and observe and record readings of deformation as required.

NOTE 3—Results of tests by other investigators have shown that strain rates within this range will provide strength values that are reasonably free from rapid loading effects and reproducible within acceptable tolerances.

7.3 To make sure that no testing fluid has penetrated into the specimen, the specimen membrane shall be carefully checked for fissures or punctures at the completion of each triaxial test. If in question, weigh the specimen before and after the test.

## 8. Calculation

8.1 Make the following calculations and graphical plots:

8.1.1 Construct a stress difference versus axial strain curve (Note 5). Stress difference is defined as the maximum principal axial stress,$\sigma_1$, minus the lateral pressure, $\sigma_3$. Indicate the value of the lateral pressure, $\sigma_3$, on the curve.

NOTE 4—If the specimen diameter is not the same as the piston diameter through the chamber, a correction must be applied to the measured load to account for differences in area between the specimen and the loading piston where it passes through the seals into the chamber.

NOTE 5—If the total deformation is recorded during the test, suitable calibration for apparatus deformation must be made. This may be accomplished by inserting into the apparatus a steel cylinder having known elastic properties and observing differences in deformation between the assembly and steel cylinder throughout the loading range. The apparatus deformation is then subtracted from the total deformation at each increment of load in order to arrive at specimen deformation from which the axial strain of the specimen is computed.

8.1.2 Construct the Mohr stress circles on an arithmetic plot with shear stresses as ordinates and normal stresses as abscissas. Make at least three triaxial compression tests, each at a different confining pressure, on the same material to define the envelope to the Mohr stress circles.

NOTE 6—Because of the heterogeneous nature of rock and the scatter in results often encountered, it is considered good practice to make at least three tests of essentially identical specimens at each confining pressure or single tests at nine different confining pressures covering the range investigated. Individual stress circles shall be plotted and considered in drawing the envelope.

8.1.3 Draw a "best-fit," smooth curve (the Mohr envelope) approximately tangent to the Mohr circles as in Fig. 1. The figure shall also include a brief note indicating whether a pronounced failure plane was or was not developed during the test and the inclination of this plane with reference to the plane of major principal stress.

NOTE 7—If the envelope is a straight line, the angle the line makes with the horizontal shall be reported as the angle of interval friction, $\phi$ (or the slope of the line as tan $\phi$ depending upon preference) and the intercept of this line at the vertical axis reported as the cohesion intercept, *C*. If the envelope is not a straight line, values of $\phi$ (or tan $\phi$) should be determined

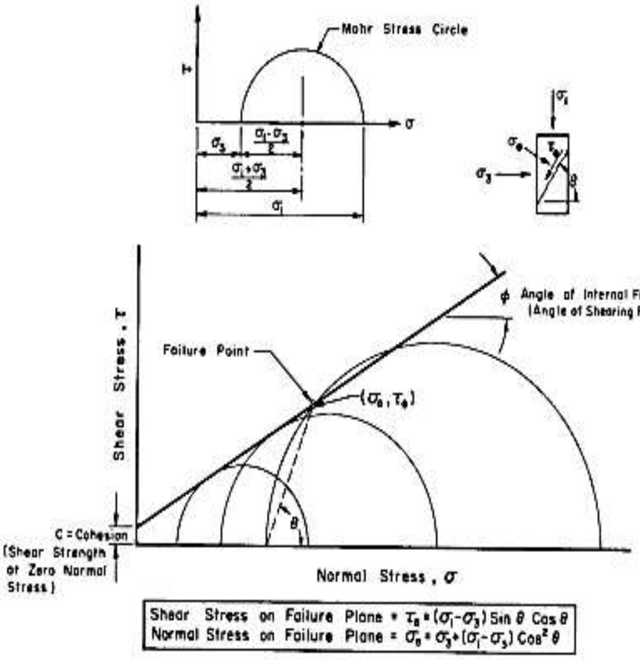


FIG. 1 Typical Mohr Stress Circles

by constructing a tangent to the Mohr circle for each confining stress at the point of contact with the envelope and the corresponding cohesion intercept noted.

## 9. Report

9.1 The report shall include as much of the following as possible:

9.1.1 Sources of the specimen including project name and location, and if known, storage environment. The location is frequently specified in terms of the borehole number and depth of specimen from collar of hole.

9.1.2 Physical description of the specimen including rock type; location and orientation of apparent weakness planes, bedding planes, and schistosity; large inclusions or inhomogeneities, if any.

9.1.3 Dates of sampling and testing.

9.1.4 Specimen diameter and length, conformance with dimensional requirements.

9.1.5 Rate of loading or deformation or strain rate.

9.1.6 General indication of moisture condition of the specimen at time of test such as: as-received, saturated, laboratory air-dry, or oven dry. It is recommended that the moisture condition be more precisely determined when possible and reported as either water content or degree of saturation.

9.1.7 Type and location of failure. A sketch of the fractured specimen is recommended.

NOTE 8—If it is a ductile failure and $\sigma_1 - \sigma_3$, is still increasing when the test is terminated, the maximum strain at which $\sigma_1 - \sigma_3$ is obtained shall be clearly stated.

## 10. Precision and Bias

10.1 An interlaboratory study was conducted in which six laboratories each tested five specimens of three different rocks, three confining pressure and four replications. The specimens were prepared by a single laboratory from a common set of samples and randomly distributed to the testing laboratories for testing. The study was carried out in accordance with Practice E 691. Details of the study are given in ISR Research Report "Interlaboratory Testing Program for Rock Properties (ITP/RP) Round Two," 1994. Tables 1-3 give the repeatability (within a laboratory) and reproducibility (between laboratories) for the method at confining pressure of 10, 25 and 40 MPa.

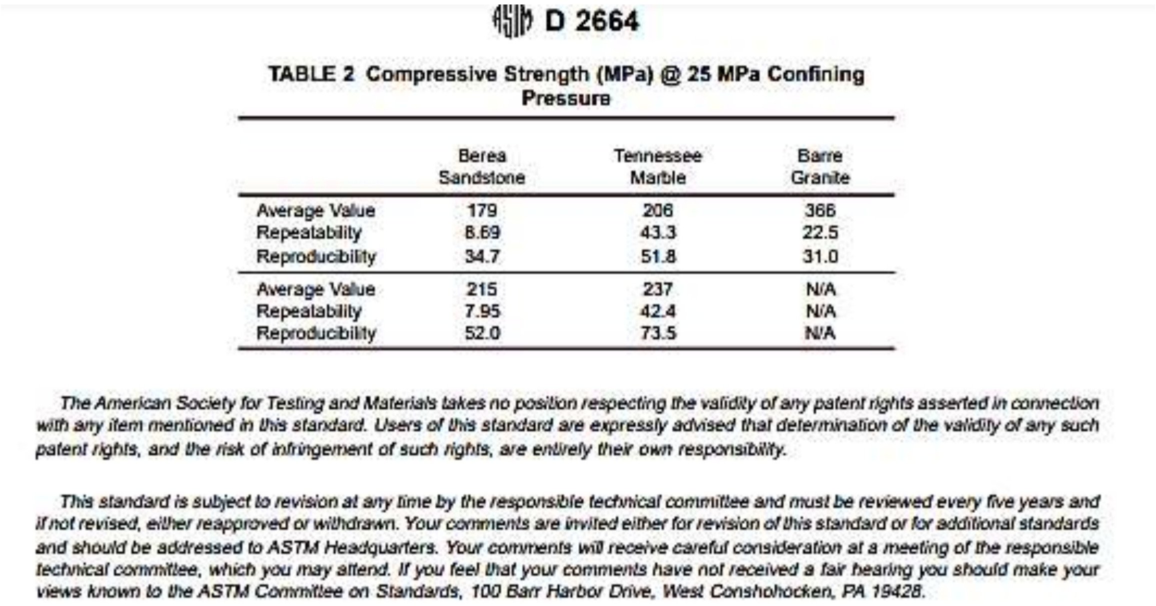
10.1.1 The probability is approximately 95 % that two test results obtained in the same laboratory on the same material will not differ by more than the repeatability limit. Likewise, the probability is approximately 95 % that two test results obtained in different laboratories on the same material will not differ by more than the reproducibility limit.

## 11. Keywords

11.1 compression strength; compression testing; loading tests; rock; triaxial compression

TABLE 1 Compressive Strength (MPa) @ 10 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 127 | 173 | 282 |
| Repeatability | 5.29 | 32.2 | 13.5 |
| Reproducibility | 22.5 | 38.3 | 25.7 |



D 2664

TABLE 2 Compressive Strength (MPa) @ 25 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 179 | 206 | 366 |
| Repeatability | 8.69 | 43.3 | 22.5 |
| Reproducibility | 34.7 | 51.8 | 31.0 |
| Average Value | 215 | 237 | N/A |
| Repeatability | 7.95 | 42.4 | N/A |
| Reproducibility | 52.0 | 73.5 | N/A |

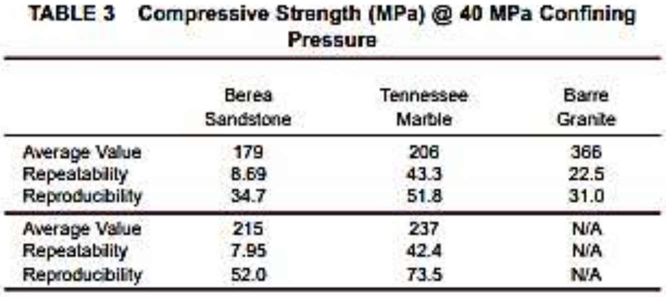


TABLE 3 Compressive Strength (MPa) @ 40 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 179 | 206 | 366 |
| Repeatability | 8.69 | 43.3 | 22.5 |
| Reproducibility | 34.7 | 51.8 | 31.0 |
| Average Value | 215 | 237 | N/A |
| Repeatability | 7.95 | 42.4 | N/A |
| Reproducibility | 52.0 | 73.5 | N/A |

Designation: D7012 – $14^{\varepsilon 1}$

# Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures[1]

This standard is issued under the fixed designation D7012; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

$\varepsilon^1$ NOTE—Editorially corrected legend for Eq 3 in August 2017.

## 1. Scope

1.1 These four test methods cover the determination of the strength of intact rock core specimens in uniaxial and triaxial compression. Methods A and B determine the triaxial compressive strength at different pressures and Methods C and D determine the unconfined, uniaxial strength.

1.2 Methods A and B can be used to determine the angle of internal friction, angle of shearing resistance, and cohesion intercept.

1.3 Methods B and D specify the apparatus, instrumentation, and procedures for determining the stress-axial strain and the stress-lateral strain curves, as well as Young's modulus, *E*, and Poisson's ratio, *υ*. These methods make no provision for pore pressure measurements and specimens are undrained (platens are not vented). Thus, the strength values determined are in terms of total stress and are not corrected for pore pressures. These test methods do not include the procedures necessary to obtain a stress-strain curve beyond the ultimate strength.

1.4 Option A allows for testing at different temperatures and can be applied to any of the test methods, if requested.

1.5 This standard replaces and combines the following Standard Test Methods: D2664 Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements; D5407 Elastic Moduli of Undrained Rock Core Specimens in Triaxial Compression Without Pore Pressure Measurements; D2938 Unconfined Compressive Strength of Intact Rock Core Specimens; and D3148 Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression. The original four standards are now referred to as Methods in this standard.

1.5.1 *Method A:* Triaxial Compressive Strength of Undrained Rock Core Specimens Without Pore Pressure Measurements.

1.5.1.1 Method A is used for obtaining strength determinations. Strain is not typically measured; therefore a stress-strain curve is not produced.

1.5.2 *Method B:* Elastic Moduli of Undrained Rock Core Specimens in Triaxial Compression Without Pore Pressure Measurements.

1.5.3 *Method C:* Uniaxial Compressive Strength of Intact Rock Core Specimens.

1.5.3.1 Method C is used for obtaining strength determinations. Strain is not typically measured; therefore a stress-strain curve is not produced.

1.5.4 *Method D:* Elastic Moduli of Intact Rock Core Specimens in Uniaxial Compression.

1.5.5 *Option A: Temperature Variation*—Applies to any of the methods and allows for testing at temperatures above or below room temperature.

1.6 For an isotropic material in Test Methods B and D, the relation between the shear and bulk moduli and Young's modulus and Poisson's ratio are:

$$G = \frac{E}{2(1+\upsilon)} \tag{1}$$

$$K = \frac{E}{3(1-2\upsilon)} \tag{2}$$

where:

$G$ = shear modulus,
$K$ = bulk modulus,
$E$ = Young's modulus, and
$\upsilon$ = Poisson's ratio.

1.6.1 The engineering applicability of these equations decreases with increasing anisotropy of the rock. It is desirable to conduct tests in the plane of foliation, cleavage or bedding and at right angles to it to determine the degree of anisotropy. It is noted that equations developed for isotropic materials may give

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[1] These test methods are under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

Current edition approved May 1, 2014. Published June 2014. Originally approved in 2004. Last previous edition approved in 2013 as D7012 – 13. DOI: 10.1520/D7012-14E01.

only approximate calculated results if the difference in elastic moduli in two orthogonal directions is greater than 10 % for a given stress level.

NOTE 1—Elastic moduli measured by sonic methods (Test Method D2845) may often be employed as a preliminary measure of anisotropy.

1.7 Test Methods B and D for determining the elastic constants do not apply to rocks that undergo significant inelastic strains during the test, such as potash and salt. The elastic moduli for such rocks should be determined from unload-reload cycles that are not covered by these test methods.

1.8 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.9 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.9.1 The procedures used to specify how data are collected/recorded or calculated, in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analytical methods for engineering design.

1.10 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.11 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D2845 Test Method for Laboratory Determination of Pulse Velocities and Ultrasonic Elastic Constants of Rock (Withdrawn 2017)[3]

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4543 Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances (Withdrawn 2017)[3]

D6026 Practice for Using Significant Digits in Geotechnical Data

E4 Practices for Force Verification of Testing Machines

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

2.2 *ASTM Adjunct:*[4]

Triaxial Compression Chamber Drawings (3)

## 3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms in this standard, refer to Terminology D653.

## 4. Summary of Test Method

4.1 A rock core specimen is cut to length and the ends are machined flat. The specimen is placed in a loading frame and if necessary, placed in a loading chamber and subjected to confining pressure. For a specimen tested at a different temperature, the test specimen is heated or cooled to the desired test temperature prior to the start of the test. The axial load on the specimen is then increased and measured continuously. Deformation measurements are not obtained for Methods A and C, and are measured as a function of load until peak load and failure are obtained for Methods B and D.

## 5. Significance and Use

5.1 The parameters obtained from Methods A and B are in terms of undrained total stress. However, there are some cases where either the rock type or the loading condition of the problem under consideration will require the effective stress or drained parameters be determined.

5.2 Method C, uniaxial compressive strength of rock is used in many design formulas and is sometimes used as an index property to select the appropriate excavation technique. Deformation and strength of rock are known to be functions of confining pressure. Method A, triaxial compression test, is commonly used to simulate the stress conditions under which most underground rock masses exist. The elastic constants (Methods B and D) are used to calculate the stress and deformation in rock structures.

5.3 The deformation and strength properties of rock cores measured in the laboratory usually do not accurately reflect large-scale *in situ* properties because the latter are strongly influenced by joints, faults, inhomogeneity, weakness planes, and other factors. Therefore, laboratory values for intact specimens must be employed with proper judgment in engineering applications.

NOTE 2—The quality of the result produced by this standard is

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Assembly and detail drawings of an apparatus that meets these requirements and which is designed to accommodate 54-mm diameter specimens and operate at a confining fluid pressure of 68.9 MPa are available from ASTM International Headquarters. Order Adjunct No. ADJD7012. Original adjunct produced in 1982.

properly lubricated to allow free movement. The movable portion of the platen shall be held closely in the spherical seat, but the design shall be such that the bearing face can be rotated and tilted through small angles in any direction. If a spherical seat is not used, the bearing surfaces shall be parallel to 0.0005 mm/mm of platen diameter. The platen diameter shall be at least as great as that of the specimen and have a thickness-to-diameter ratio of at least 1:2.

6.3 *Deformation Devices:*

6.3.1 *Methods B and D:*

6.3.1.1 *Strain/Deformation Measuring Devices*—Deformations or strains may be determined from data obtained by electrical resistance strain gages, compressometers, linear variable differential transformers (LVDTs), or other suitable means. The strain/deformation measuring system shall measure the strain with a resolution of at least $25 \times 10^{-6}$ strain and an accuracy within 2 % of the value of readings above $250 \times 10^{-6}$ strain and accuracy and resolution within $5 \times 10^{-6}$ for readings lower than $250 \times 10^{-6}$ strain, including errors introduced by excitation and readout equipment. The system shall be free from non-characterized long-term instability (drift) that results in an apparent strain of $10^{-8}$/s or greater.

NOTE 5—The user is cautioned about the influence of pressure and temperature on the output of strain and deformation sensors located within the confining pressure apparatus.

6.3.1.2 *Determination of Axial Strain*—The design of the measuring device shall be such that the average of at least two axial strain measurements can be determined. Measuring positions shall be equally spaced around the circumference of the specimen, close to midheight. The gauge length over which the axial strains are determined shall be at least ten grain diameters in magnitude.

6.3.1.3. *Determination of Lateral Strain*—The lateral deformations or strains may be measured by any of the methods mentioned in 6.3.1.1. Either circumferential or diametric deformations or strains may be measured. A single transducer that wraps around the specimen can be used to measure the change in circumference. At least two diametric deformation sensors shall be used if diametric deformations are measured. These sensors shall be equally spaced around the circumference of the specimen, close to midheight. The average deformation or strain from the diametric sensors shall be recorded.

NOTE 6—The use of strain gauge adhesives requiring cure temperatures above 65°C is not allowed unless it is known that microfractures do not develop and mineralogical changes do not occur at the cure temperature.

6.4 *Timing Devices*—A clock, stopwatch, digital timer, or alike readable to 1 minute.

## 7. Safety Precautions

7.1 Danger exists near confining pressure testing equipment because of the high pressures and loads developed within the system. Test systems must be designed and constructed with adequate safety factors, assembled with properly rated fittings, and provided with protective shields to protect people in the area from unexpected system failure. The use of a gas as the confining pressure fluid introduces potential for extreme violence in the event of a system failure.

7.2 Many rock types fail in a violent manner when loaded to failure in compression. A protective shield shall be placed around the uniaxial test specimen to prevent injury from flying rock fragments.

7.3 Elevated temperatures increase the risks of electrical shorts and fire. The flash point of the confining pressure fluid shall be above the operating temperatures during the test.

## 8. Test Specimens

8.1 *Specimen Selection*—The specimens for each sample shall be selected from cores representing a valid average of the type of rock under consideration. This sample selection can be achieved by visual observations of mineral constituents, grain sizes and shape, partings and defects such as pores and fissures, or by other methods such as ultrasonic velocity measurements. The diameter of rock test specimens shall be at least ten times the diameter of the largest mineral grain. For weak rock types, which behave more like soil, for example, weakly cemented sandstone, the specimen diameter shall be at least six times the maximum particle diameter. The specified minimum specimen diameter of approximately 47-mm satisfy this criterion in the majority of cases. When cores of diameter smaller than the specified minimum must be tested because of the unavailability of larger diameter core, as is often the case in the mining industry, suitable notation of this fact shall be made in the report.

8.1.1 Desirable specimen length to diameter ratios are between 2.0:1 and 2.5:1. Specimen length to diameter ratios of less than 2.0:1 are unacceptable. If it is necessary to test specimens not meeting the length to diameter ratio requirements due to lack of available specimens, the report shall contain a note stating the non-conformance with this standard including a statement explaining that the results may differ from results obtained from a test specimen that meets the requirements. Laboratory specimen length to diameter ratios must be employed with proper judgment in engineering applications.

8.1.2 The number of specimens necessary to obtain a specific level of statistical results may be determined using Test Method E122. However, it may not be economically possible to achieve a specific confidence level and professional judgment may be necessary.

8.2 *Preparation*—Test specimens shall be prepared in accordance with Practice D4543.

8.2.1 Test results for specimens not meeting the requirements of Practice D4543 shall contain a note describing the non-conformance and a statement explaining that the results reported may differ from results obtained from a test specimen that meets the requirements of Practice D4543.

8.3 Moisture condition of the specimen at the time of test can have a significant effect upon the deformation of the rock. Good practice generally dictates that laboratory tests shall be made upon specimens representative of field conditions. Thus, it follows that the field moisture condition of the specimen shall be preserved until the time of test. On the other hand, there may be reasons for testing specimens at other moisture contents, including zero. In any case, the moisture content of dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing. Users of this standard are cautioned that compliance with Practice D3740 does not in itself ensure reliable results. Reliable results depend on many factors; Practice D3740 provides a means for evaluating some of those factors.

## 6. Apparatus

6.1 *Compression Apparatus:*

6.1.1 *Methods A to D:*

6.1.1.1 *Loading Device*—The loading device shall be of sufficient capacity to apply load at a rate conforming to the requirements specified in 9.4.1. It shall be verified at suitable time intervals in accordance with the procedures given in Practices E4 and comply with the requirements prescribed in the method. The loading device may be equipped with a displacement transducer that can be used to advance the loading ram at a specified rate.

NOTE 3—For Methods A and B, if the load-measuring device is located outside the confining compression apparatus, calibrations to determine the seal friction need to be made to make sure the loads measured meet the accuracy specified in Practices E4.

6.2 *Confining System:*[4]

6.2.1 *Methods A and B:*

6.2.1.1 *Confining Apparatus*[5]—The confining pressure apparatus shall consist of a chamber in which the test specimen may be subjected to a constant lateral fluid pressure and the required axial load. The apparatus shall have safety valves, suitable entry ports for filling the chamber, and associated hoses, gages, and valves as needed.

6.2.1.2 *Flexible Membrane*—This membrane encloses the rock specimen and extends over the platens to prevent penetration by the confining fluid. A sleeve of natural or synthetic rubber or plastic is satisfactory for room temperature tests; however, metal or high-temperature rubber (viton) jackets are usually necessary for elevated temperature tests. The membrane shall be inert relative to the confining fluid and shall cover small pores in the specimen without rupturing when confining pressure is applied. Plastic or silicone rubber coatings may be applied directly to the specimen provided these materials do not penetrate and strengthen or weaken the specimen. Care must be taken to form an effective seal where the platen and specimen meet. Membranes formed by coatings shall be subject to the same performance requirements as elastic sleeve membranes.

6.2.1.3 *Pressure-Maintaining Device*—A hydraulic pump, pressure intensifier, or other system having sufficient capacity to maintain the desired lateral pressure to within ±1 % throughout the test. The confining pressure shall be measured with a hydraulic pressure gauge or electronic transducer having an accuracy of at least ±1 % of the confining pressure, including errors due to readout equipment, and a resolution of at least 0.5 % of the confining pressure.

6.2.1.4 *Confining-Pressure Fluids*—Hydraulic fluids compatible with the pressure-maintaining device and flexible membranes shall be used. For tests using Option A, the fluid must remain stable at the temperature and pressure levels designated for the test.

6.2.2 *Option A:*

6.2.2.1 *Temperature Enclosure*—The temperature enclosure shall be either an internal system that fits inside the loading apparatus or the confining pressure apparatus, an external system enclosing the entire confining pressure apparatus, or an external system encompassing the complete test apparatus. For high or low temperatures, a system of heaters or coolers, respectively, insulation, and temperature-measuring devices are normally necessary to maintain the specified temperature. Temperature shall be measured at three locations, with one sensor near the top, one at mid-height, and one near the bottom of the specimen. The "average" specimen temperature, based on the mid-height sensor, shall be maintained to within ±1°C of the specified test temperature. The maximum temperature difference between the mid-height sensor and either end sensor shall not exceed 3°C.

NOTE 4—An alternative to measuring the temperature at three locations along the specimen during the test is to determine the temperature distribution in a specimen that has temperature sensors located in drill holes at a minimum of six positions: along both the centerline and specimen periphery at mid-height and each end of the specimen. The specimen may originate from the same batch as the test specimens and conform to the same dimensional tolerances and to the same degree of intactness. The temperature controller set point may be adjusted to obtain steady-state temperatures in the specimen that meet the temperature requirements at each test temperature. The centerline temperature at mid-height may be within ±1°C of the specified test temperature and all other specimen temperatures may not deviate from this temperature by more than 3°C. The relationship between controller set point and specimen temperature can be used to determine the specimen temperature during testing provided that the output of the temperature feedback sensor or other fixed-location temperature sensor in the triaxial apparatus is maintained constant within ±1°C of the specified test temperature. The relationship between temperature controller set point and steady-state specimen temperature may be verified periodically. The specimen is used solely to determine the temperature distribution in a specimen in the triaxial apparatus. It is not to be used to determine compressive strength or elastic constants.

6.2.2.2 *Temperature Measuring Device*—Special limits-of-error thermocouples or platinum resistance thermometers (RTDs) having accuracies of at least ±1°C with a resolution of 0.1°C shall be used.

6.2.3 *Bearing Surfaces:*

6.2.3.1 *Methods A to D:*

*(1) Platens*—Two steel platens are used to transmit the axial load to the ends of the specimen. They shall be made of tool-hardened steel to a minimum Rockwell Hardness of 58 on the "C" scale. One of the platens shall be spherically seated and the other shall be a plain rigid platen. The bearing faces shall not depart from a plane by more than 0.015 mm when the platens are new and shall be maintained within a permissible variation of 0.025 mm. The diameter of the spherical seat shall be at least as large as that of the test specimen, but shall not exceed twice the diameter of the test specimen. The center of the sphere in the spherical seat shall coincide with that of the bearing face of the specimen. The spherical seat shall be

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[4] Assembly and detail drawings of an apparatus that meets these requirements and which is designed to accommodate 21/8-in. (53.975-mm) diameter specimens and operate at a confining fluid pressure of 68.9 MPa are available from ASTM International Headquarters. Order Adjunct No. ADJD7012. Original adjunct produced in 1982.

the test specimen shall be tailored to the problem at hand and determined according to the procedures given in Method D2216. If moisture condition is to be maintained and the temperature enclosure is not equipped with humidity control, the specimen shall be sealed using a flexible membrane or by applying a plastic or silicone rubber coating to the specimen sides. If the specimen is to be saturated, porous sandstones may present little or no difficulty. For siltstone, saturation may take longer. For tight rocks such as intact granite, saturation by water may be impractical.

## 9. Procedure

9.1 *Seating:*

9.1.1 *Methods A to D:*

9.1.1.1 The spherical seat shall rotate freely in its socket before each test.

9.1.1.2 The lower platen shall be placed on the base or actuator rod of the loading device. The bearing faces of the upper and lower platens and of the test specimen shall be wiped clean, and the test specimen shall be placed on the lower platen. The upper platen shall be placed on the specimen and aligned properly.

9.2 *Confining Stress:*

9.2.1 *Methods A and B:*

9.2.1.1 The membrane shall be fitted over the specimen and platens to seal the specimen from the confining fluid. The specimen shall be placed in the test chamber, ensuring proper seal with the base, and connection to the confining pressure lines. A small axial load, <1 % of anticipated ultimate strength, may be applied to the confining compression chamber by means of the loading device to properly seat the bearing parts of the apparatus.

9.2.1.2 The chamber shall be filled with confining fluid and the confining stress shall be raised uniformly to the specified level within 5 min. The lateral and axial components of the confining stress shall not be allowed to differ by more than 5 percent of the instantaneous pressure at any time.

9.2.1.3 The predetermined confining pressure shall be maintained approximately throughout the test.

9.2.1.4 To make sure that no confining fluid has penetrated into the specimen, the specimen membrane shall be carefully checked for fissures or punctures and the specimen shall be examined with a hand lens at the completion of each confining test.

9.3 *Option A:*

9.3.1 Install the elevated-temperature enclosure for the apparatus used. The temperature shall be raised at a rate not exceeding 2°C/min until the required temperature is reached (Note 7). The test specimen shall be considered to have reached pressure and temperature equilibrium when all deformation transducer outputs are stable for at least three readings taken at equal intervals over a period of no less than 30 min (3 min for tests performed at room temperature). Stability is defined as a constant reading showing only the effects of normal instrument and heater unit fluctuations. Record the initial deformation readings, which are to be taken as zeroes for the test.

Note 7—It has been observed that for some rock types microcracking will occur for heating rates above 1°C/min. The operator is cautioned to select a heating rate such that microcracking does not significantly affect the test result.

9.4 *Applying Load:*

9.4.1 *Methods A to D:*

9.4.1.1 The axial load shall be applied continuously and without shock until the load becomes constant, is reduced, or a predetermined amount of strain is achieved. The load shall be applied in such a manner as to produce either a stress rate between 0.5 and 1.0 MPa/s or a strain rate as constant as feasible throughout the test. The stress rate or strain rate shall not be permitted at any given time to deviate by more than 10 % from that selected. The stress rate or strain rate selected shall be that which will produce failure of a cohort test specimen in compression, in a test time between 2 and 15 min. The selected stress rate or strain rate for a given rock type shall be adhered to for all tests in a given series of investigation (Note 8). Readings of deformation shall be observed and recorded at a minimum of ten load levels that are evenly spaced over the load range. Continuous data recording shall be permitted provided that the recording system meets the precision and accuracy requirements of 12.1.1. The maximum load sustained by the specimen shall be recorded. Load readings in kilonewtons shall be recorded to 2 decimal places. Stress readings in megapascals shall be recorded to 1 decimal place.

Note 8—Results of tests by other investigators have shown that strain rates within this range will provide strength values that are reasonably free from rapid loading effects and reproducible within acceptable tolerances. Lower strain rates may be permissible, if required by the investigation. The drift of the strain measuring system (see 6.3) may be constrained more stringently, corresponding to the longer duration of the test.

Note 9—Loading a high-strength specimen in load control to failure in a loading frame will often result in violent failure, which will tend to damage the strain/deformation measuring devices and be hazardous to the operator.

## 10. Calculations

10.1 For Methods C and D, the uniaxial compressive strength $\sigma_u$, of the test specimen shall be calculated as follows:

$$\sigma_u = \frac{P}{A} \tag{3}$$

where:

$\sigma_u$ = uniaxial compressive strength (MPa),
$P$ = failure load (N),
$A$ = cross-sectional area (mm$^2$).

10.2 For Methods A and B, the triaxial compressive strength, $\sigma$, of the test specimen shall be calculated as follows:

$$\sigma = \sigma_1 - \sigma_3 \tag{4}$$

where:

$\sigma$ = differential failure stress (MPa),
$\sigma_1$ = total failure stress (MPa), and
$\sigma_3$ = confining stress (MPa).

Note 10—Tensile stresses and strains are normally recorded as being positive. A consistent application of a compression-positive sign convention may be employed if desired. The sign convention adopted needs to be stated explicitly in the report. The formulas given are for engineering stresses and strains. True stresses and strains may be used, provided that the specimen diameter at the time of peak load is known.

Note 11—If the specimen diameter is not the same as the piston diameter through the triaxial apparatus, a correction may be applied to the measured load to account for the confining pressure acting on the difference in area between the specimen and the loading piston where it passes through the seals into the apparatus. The engineer must be knowledgeable in the differences in confinement test systems such as a Hoek cell, through piston chamber, integral load cell and external load cell.

10.3 *Methods B and D:*

10.3.1 Axial strain, $\varepsilon_a$ and lateral strain, $\varepsilon_l$, shall be obtained directly from strain-indicating equipment or shall be calculated from deformation readings, depending on the type of apparatus or instrumentation employed. Strain readings shall be recorded to six decimal places.

10.3.2 Axial strain, $\varepsilon_a$ shall be calculated as follows:

$$\varepsilon_a = \frac{\Delta L}{L} \tag{5}$$

where:

$\varepsilon_a$ = axial strain (mm),
$L$ = original undeformed axial gauge length (mm), and
$\Delta L$ = change in measured axial gauge length (mm).

NOTE 12—If the deformation recorded during the test includes deformation of the apparatus, suitable calibration for apparatus deformation shall be made. This may be accomplished by inserting into the apparatus a steel cylinder having known elastic properties and observing differences in deformation between the assembly and steel cylinder throughout the loading range. The apparatus deformation is then subtracted from the total deformation at each increment of load to arrive at specimen deformation from which the axial strain of the specimen is computed. The accuracy of this correction should be verified by measuring the elastic deformation of a cylinder of material having known elastic properties (other than steel) and comparing the measured and computed deformations.

10.3.3 Lateral strain, $\varepsilon_l$, shall be calculated as follows:

$$\varepsilon_l = \frac{\Delta D}{D} \tag{6}$$

where:

$\varepsilon_l$ = lateral strain (mm),
$D$ = original undeformed diameter (mm), and
$\Delta D$ = change in diameter (mm); where positive is an increase in diameter and negative is a decrease in diameter.

NOTE 13—Many circumferential transducers measure change in chord length and not change in arc length (circumference). The geometrically nonlinear relationship between change in chord length and change in diameter must be used to obtain accurate values of lateral strain.

10.3.4 The stress-versus-strain curves shall be plotted for the axial and lateral directions, see Fig. 1. The complete curve gives the best description of the deformation behavior of rocks having nonlinear stress-strain relationships at low- and high-stress levels.

10.3.5 The value of Young's modulus, $E$, shall be calculated using any of several methods employed in engineering practice. The most common methods, described in Fig. 2, are as follows:

10.3.5.1 Tangent modulus at a stress level that is some fixed percentage, usually 50 % of the maximum strength.

10.3.5.2 Average slope of the straight-line portion of the stress-strain curve. The average slope shall be calculated either by dividing the change in stress by the change in strain or by making a linear least squares fit to the stress-strain data in the straight-line portion of the curve.

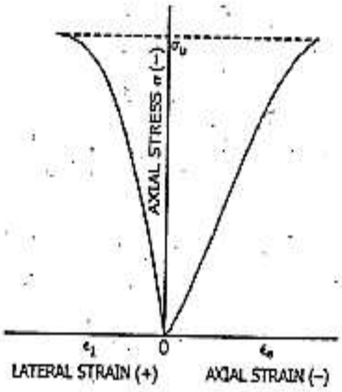


FIG. 1 Format for Graphical Presentation of Data

10.3.5.3 Secant modulus, usually from zero stress to some fixed percentage of maximum strength.

10.3.6 The value of Poisson's ratio, $\upsilon$, is greatly affected by nonlinearity at low-stress levels in the axial and lateral stress-strain curves. It is desirable that Poisson's ratio shall be calculated from the following equation:

$$\upsilon = -\frac{\text{slope of axial curve}}{\text{slope of lateral curve}} \tag{7}$$

$$= -\frac{E}{\text{slope of lateral curve}}$$

where:

$\upsilon$ = Poisson's ratio
$E$ = Young's modulus

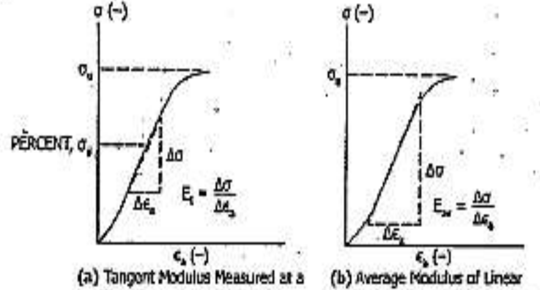
where the slope of the lateral curve is determined in the same manner as was done in 10.3.6 for Young's modulus, $E$.

NOTE 14—The denominator in Eq 7 will usually have a negative value if the sign convention is applied properly.

10.4 *Method A:*

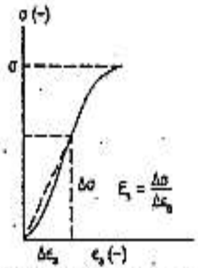
10.4.1 The Mohr stress circles shall be constructed on an arithmetic plot with shear stress as the ordinate and normal stress as the abscissa using the same scale. At least three triaxial compression tests should be conducted, each at a different confining pressure, on the same material to define the envelope to the Mohr stress circles. Because of the heterogeneity of rock and the scatter in results often encountered, good practice requires making at least three tests on essentially identical specimens at each confining pressure or single tests at nine different confining pressures covering the range investigated. Individual stress circles shall be plotted and used in drawing the envelope.

10.4.2 A "best-fit," smooth curve or straight line (Mohr envelope) shall be drawn approximately tangent to the Mohr circles, as shown in Fig. 3. The figure shall also include a brief note indicating whether a pronounced failure plane was or was not developed during the test and the inclination of this plane with reference to the plane of major principal stress. If the envelope is a straight line, the angle the line makes with the horizontal shall be reported as the angle of internal friction, φ, or the slope of the line as tan φ depending upon preference. The intercept of this line at the vertical axis is reported as the



(a) Tangent Modulus Measured at a Fixed Percentage of Ultimate Strength

(b) Average Modulus of Linear Portion of Axial Stress-Strain Curve



(c) Secant Modulus Measured up to a Fixed Percentage of Ultimate Strength

FIG. 2 Methods for Calculating Young's Modulus from Axial Stress-Axial Strain Curve

apparent cohesion intercept, *c*. If the envelope is not a straight line, values of φ or tan φ shall be determined by constructing a tangent to the Mohr circle for each confining pressure at the point of contact with the envelope and the corresponding cohesion intercept noted.

## 11. Report: Test Data Sheet(s)/Form(s)

11.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s) as given below, is covered in 1.9 and Practice D6026.

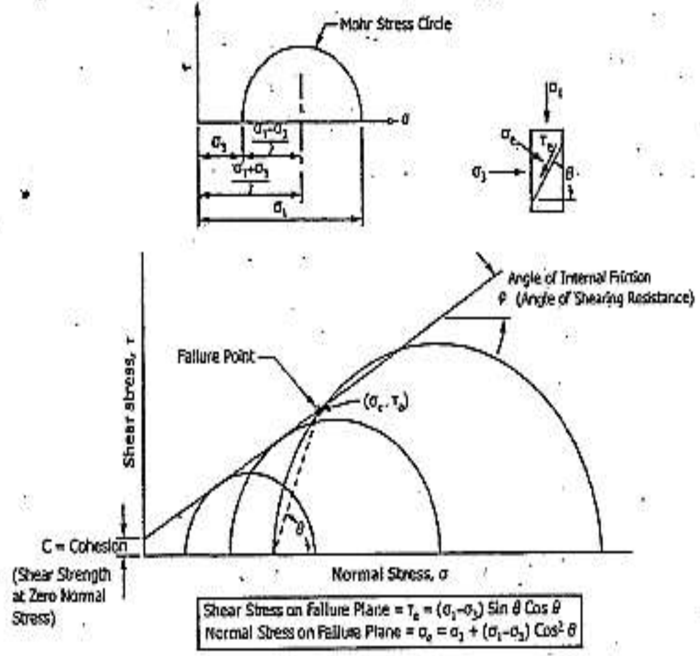


FIG. 3 Typical Mohr Stress Circles

11.2 Record as a minimum the following general information (data):

11.2.1 *Methods A–D:*

11.2.1.1 Source of sample including project name and location. Often the location is specified in terms of the drill hole number, angle and depth of specimen from the collar of the hole,

11.2.1.2 Name or initials of the person(s) who performed the test and the date(s) performed,

11.2.1.3 Lithologic description of the test specimen, formation name, and load direction with respect to lithology,

11.2.1.4 Moisture condition of specimen at the start of shear,

11.2.1.5 Specimen diameter and height, conformance with dimensional requirements,

11.2.1.6 Description of physical appearance of specimen after test, including visible end effects such as cracking, spalling, or shearing at the platen-specimen interfaces,

11.2.1.7 A sketch or photograph of the fractured specimen is recommended,

11.2.1.8 The actual equipment, procedures and the reasons for any variations shall be presented in detail,

11.2.1.9 Temperature at which test was performed if other than room temperature, to the nearest 0.5°C,

11.2.1.10 Any non-conformances with D4543 and the length to diameter ratios, include the explanation statements as describe in 8.1.2 and 8.2.1,

11.2.1.11 Time to failure,

11.2.1.12 Loading, stress, or strain rate as applicable based on method performed.

11.3 Record as a minimum the following test specimen data:

11.3.1 *Methods B and D:*

11.3.1.1 Plot of the stress-versus-strain curves (see Fig. 1),

11.3.1.2 Young's modulus, *E*, method of determination as given in Fig. 2, and at which stress level or levels determined, and

11.3.1.3 Poisson's ratio, υ, method of determination in 10.3.6, and at what stress level or levels determined.

11.3.1.4 Rate of loading or deformation rate.

11.3.2 *Method A:*

11.3.2.1 Confining stress level at which a triaxial test was performed,

11.3.2.2 Plot of the Mohr stress circles (see Fig. 3), and

11.3.2.3 Triaxial compressive strength as determined in 10.1 to the nearest MPa.

11.3.3 *Method C:*

11.3.3.1 Uniaxial compressive strength as determined in 10.1 to the nearest MPa.

NOTE 15—If failure is ductile, with the load on the specimen still increasing when the test is terminated, the strain at which the compressive strength was calculated may be reported.

TABLE 1 Compressive Strength (MPa) at 0 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 62.0 | 142.0 | 217.0 |
| Repeatability | 15.8 | 20.4 | 15.7 |
| Reproducibility | 22.4 | 38.0 | 27.7 |

TABLE 2 Compressive Strength (MPa) at 10 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 127.0 | 173.0 | 262.0 |
| Repeatability | 5.29 | 32.2 | 13.5 |
| Reproducibility | 22.5 | 38.3 | 25.7 |

TABLE 3 Compressive Strength (MPa) at 25 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 179.0 | 206.0 | 366.0 |
| Repeatability | 8.69 | 43.3 | 22.5 |
| Reproducibility | 34.7 | 51.8 | 31.0 |

TABLE 4 Compressive Strength (MPa) at 40 MPa Confining Pressure

| | Berea Sandstone | Tennessee Marble | Barre Granite |
|---|---|---|---|
| Average Value | 215.0 | 237.0 | N/A |
| Repeatability | 7.85 | 42.4 | N/A |
| Reproducibility | 62.0 | 73.5 | N/A |

TABLE 5 Young's Modulus (GPa) at 0 MPa Confining Pressure

| | Berea Sandstone | | Tennessee Marble | | Barre Granite | |
|---|---|---|---|---|---|---|
| | 25 % | 50 % | 25 % | 50% | 25 % | 50 % |
| Average Value | 12.4 | 16.7 | 76.3 | 74.2 | 48.9 | 54.2 |
| Repeatability | 3.37 | 4.15 | 14.8 | 10.1 | 6.12 | 8.75 |
| Reproducibility | 4.17 | 5.18 | 17.2 | 12.3 | 6.45 | 7.77 |

## 12. Precision and Bias

12.1 The data in Tables 1-5 are the products of the Interlaboratory Testing Program. Table 1 is the product of the work of seven laboratories with five replications. Table 5 is the product of the work of eight laboratories with five replications. Round 1 involved four rock types, but only the data from three were displayed here that were rock types used in all the series of tests. The remaining tables (Tables 6-10) are the products of Round 2 in which six laboratories each tested five specimens of three different rocks, three confining pressures and four replications. Details of the study are referenced in Section 2.2. The tables give the repeatability (within a laboratory) and reproducibility (between laboratories) for the compressive and confined methods and values for Young's Modulus and Poisson's ratio calculated for the intervals from 25 to 50 % and 40 to 60 % of the maximum differential stress at confining

TABLE 6 Young's Modulus (GPa) at 25 MPa Confining Pressure

| | Berea Sandstone | | Tennessee Marble | | Barre Granite | |
|---|---|---|---|---|---|---|
| | 25-50 % | 40-60 % | 25-50 % | 40-60 % | 25-50 % | 40-60 % |
| Average Value | 23.5 | 22.5 | 71.1 | 65.2 | 60.4 | 59.8 |
| Repeatability | 0.90 | 1.28 | 11.4 | 9.15 | 2.53 | 2.49 |
| Reproducibility | 3.34 | 3.47 | 13.9 | 11.6 | 6.80 | 6.12 |

pressures of 10, 25, and 40 MPa and 25 % and 50 % for the compressive test case. Additional Reference Material found in ASTM Geotechnical Journal.[6,7]

TABLE 7 Young's Modulus (GPa) at 40 MPa Confining Pressure

| | Berea Sandstone | | Tennessee Marble | | Barre Granite | |
|---|---|---|---|---|---|---|
| | 25-50 % | 40-60 % | 25-50 % | 40-60 % | 25-50 % | 40-60 % |
| Average Value | 24.2 | 22.8 | 70.0 | 63.4 | 61.9 | 60.5 |
| Repeatability | 1.09 | 0.79 | 9.60 | 9.57 | 2.27 | 2.49 |
| Reproducibility | 3.82 | 3.57 | 9.69 | 9.57 | 5.95 | 5.34 |

TABLE 8 Poisson's Ratio at 10 MPa Confining Pressure

| | Berea Sandstone | | Tennessee Marble | | Barre Granite | |
|---|---|---|---|---|---|---|
| | 25-50 % | 40-60 % | 25-50 % | 40-60 % | 25-50 % | 40-60 % |
| Average Value | 0.20 | 0.34 | 0.30 | 0.33 | 0.26 | 0.30 |
| Repeatability | 0.03 | 0.04 | 0.03 | 0.07 | 0.03 | 0.03 |
| Reproducibility | 0.05 | 0.05 | 0.06 | 0.09 | 0.04 | 0.04 |

TABLE 9 Poisson's Ratio at 25 MPa Confining Pressure

| | Berea Sandstone | | Tennessee Marble | | Barre Granite | |
|---|---|---|---|---|---|---|
| | 25-50 % | 40-60 % | 25-50 % | 40-60 % | 25-50 % | 40-60 % |
| Average Value | 0.23 | 0.27 | 0.31 | 0.34 | 0.28 | 0.33 |
| Repeatability | 0.02 | 0.02 | 0.05 | 0.05 | 0.03 | 0.03 |
| Reproducibility | 0.04 | 0.04 | 0.08 | 0.05 | 0.04 | 0.05 |

TABLE 10 Poisson's Ratio at 40 MPa Confining Pressure

| | Berea Sandstone | | Tennessee Marble | | Barre Granite | |
|---|---|---|---|---|---|---|
| | 25-50 % | 40-60 % | 25-50 % | 40-60 % | 25-50 % | 40-60 % |
| Average Value | 0.20 | 0.24 | 0.32 | 0.34 | 0.29 | 0.33 |
| Repeatability | 0.01 | 0.02 | 0.04 | 0.05 | 0.03 | 0.04 |
| Reproducibility | 0.03 | 0.03 | 0.04 | 0.05 | 0.05 | 0.06 |

12.1.1 The probability is approximately 95 % that two test results obtained in the same laboratory on the same material will not differ by more than the repeatability limit *r*. Likewise, the probability is approximately 95 % that two test results obtained in different laboratories on the same material will not differ by more than the reproducibility limit *R*. The precision statistics are calculated from:

$$r = 2\left(\sqrt{2}\right)s_r \tag{8}$$

where:

$r$ = repeatability limit, and
$s_r$ = repeatability standard deviation.

$$R = 2\left(\sqrt{2}\right)s_R \tag{9}$$

where:

$R$ = reproducibility limit, and
$s_R$ = reproducibility standard deviation.

12.2 *Bias*—Bias cannot be determined since there is no standard value of each of the elastic constants that can be used to compare with values determined using this test method.

## 13. Keywords

13.1 bulk modulus; compression testing; compressive strength; confined compression; elastic moduli; loading tests; modulus of elasticity; Mohr stress circle; Poisson's ratio; repeatability; reproducibility; rock; shear modulus; triaxial compression; uniaxial compression; Young's modulus

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[6] Pincus, H. J., "Interlaboratory Testing Program for Properties: Round One-Longitudinal and Transverse Pulse Velocities, Unconfined Compressive Strength, Uniaxial Modulus, and Splitting Tensile Strength," *ASTM Geotechnical Journal*, Vol 16, No. 1, March 1993, pp. 138–163; and Addendum Vol 17, No. 2, June 1993, and 256–258.

[7] Pincus, H. J., "Interlaboratory Testing Program for Rock Properties: Round Two- Confined Compression: Young's Modulus, Poisson's Ratio, and Ultimate Strength," *ASTM Geotechnical Testing Journal*, Vol 19. No. 3, September 1996, pp. 321–336.

Designation: D3967 – 16

# Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens[1]

## 1. Scope*

1.1 This test method covers testing apparatus, specimen preparation, and testing procedures for determining the splitting tensile strength of rock by diametral line compression of disk shape specimens.

NOTE 1—The tensile strength of rock determined by tests other than the straight pull test is designated as the "indirect" tensile strength and, specifically, the value obtained in Section 9 of this test is termed the "splitting" tensile strength.

1.2 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to inch-pound units, which are provided for information only and are not considered standard. Reporting of test results in units other than SI shall not be regarded as nonconformance with this test method.

1.3 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.3.1 The procedures used to specify how data are collected/recorded or calculated, in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D6026 Practice for Using Significant Digits in Geotechnical Data

E4 Practices for Force Verification of Testing Machines

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E2586 Practice for Calculating and Using Basic Statistics

## 3. Terminology

3.1 *Definitions:*

3.1.1 For common definitions of terms in this standard, refer to Terminology D653.

## 4. Summary of Test Method

4.1 Samples are selected from rock cores or cored from platen samples for testing as described. A section of rock core sample is cut perpendicular to the core axis to produce disk shape specimens until the required number of specimens are obtained. Each specimen is then marked to indicate the desired orientation of the applied loading on the specimen by drawing a diametral line on each end surface on the specimen. Each specimen is positioned inside the testing machine in such way that diametrical line is coincidental with the loading axis of the testing machine either curved or flat platens. Each specimen is then tested by applying a continuously increasing compressive load until it fails within 1 to 10 minutes of the start of loading.

## 5. Significance and Use

5.1 By definition the tensile strength is obtained by the direct tensile test. However, the direct tensile test is difficult

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[1] This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.12 on Rock Mechanics.

Current edition approved Nov. 1, 2016. Published November 2016. Originally approved in 1981. Last previous edition approved in 2008 as D3967 – 08. DOI:

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on

and expensive for routine application. The splitting tensile test appears to offer a desirable alternative, because it is much simpler and inexpensive. Furthermore, engineers involved in rock mechanics design usually deal with complicated stress fields, including various combinations of compressive and tensile stress fields. Under such conditions, the tensile strength should be obtained with the presence of compressive stresses to be representative of the field conditions.

5.2 The splitting tensile strength test is one of the simplest tests in which such stress fields occur. Also, by testing across different diametrical directions, possible variations in tensile strength for anisotropic rocks can be determined. Since it is widely used in practice, a uniform test method is needed for data to be comparable. A uniform test is also needed to make sure that the disk specimens break diametrically due to tensile stresses perpendicular to the loading diameter.

Note 2—The quality of the results produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

## 6. Apparatus

6.1 *Loading Device*—A device of sufficient capacity to apply and measure the load at a rate conforming to the requirements in 8.3. It shall be verified at suitable time intervals in accordance with Practices E4 and shall comply with the requirements prescribed therein.

6.1.1 *Bearing Platens*—The loading device shall be equipped with two opposing steel bearing platens having a Rockwell hardness of not less than 58 HRC through which loading is transmitted. The bearing faces shall not depart from a plane by more than 0.0125 mm (0.0005 in.) when the platens are new and shall be maintained within a permissible variation of 0.025 mm. The bearing platens diameter shall be at least as great as the specimen's thickness (see Note 3).

6.1.2 *Spherical Seating*—One of the bearing surfaces on the loading device should be spherically seated and the other one a plain rigid platen. The diameter of the spherical seat shall be at least as large as the test specimen, but the diameter of the spherical seat shall not exceed from twice the diameter of specimen. Center of the sphere in the spherical seat coincides with the center of loaded side of the specimen. The spherical seat shall be lubricated to assure its free movement. The movable part of the platen shall be held closely in the spherical seat, but the design shall be such that the bearing face can be rotated and tilted through small angles in any direction. If the spherical seat's diameter exceeds twice the diameter of the test specimen, then the spherical seat shall be placed in the locked position with the faces of the bearing platens meeting the requirements of 6.1.1.

6.1.3 *Rigid Seating*—If a spherical seat is not used, then the faces of the loading device bearing platens shall be parallel to 0.0005 mm/mm of the platen diameter. This criterion shall be met when the platens are in the loading device and separated approximately by diameter of the test specimen.

Note 3—False platens, due to the contact with abrasive rocks, these platens tend to roughen after a number of specimens have been tested, and hence need to be surfaced from time to time.

6.2 *False, Flat or Curved Bearing Platens*—During testing, the specimen can be placed in direct contact with the loading device bearing platens or false platens with bearing faces conforming to the requirements of this standard, may be used (see Fig. 1 for false flat platens). These shall be oil hardened to more than 58 HRC, and surface ground. With contact by abrasive rocks, these platens tend to roughen after a number of specimens have been tested, and hence need to be re-surfaced from time to time.

6.2.1 *False Flat Bearing*—The bearing faces of false flat bearing platens shall not depart from a plane by more than 0.0125 mm (0.0005 in.) when the platens are new and shall be maintained within a permissible variation of 0.025 mm. The bearing platen's diameter shall be at least as great as the specimen thickness.

6.2.2 *Curved Supplementary Bearing Platens*—These may be used to reduce the contact stresses on the test specimen. The radius of curvature of the supplementary bearing platens shall be so designed that their arc of contact with the specimen will in no case exceed 15° or that the width of contact is less than *D*/6, where *D* is the diameter of the specimen.

Note 4—Since the equation used in 9.1 for splitting tensile strength is derived based on a line load, the applied load should be confined to a very narrow strip if the splitting tensile strength test is to be valid. But a line

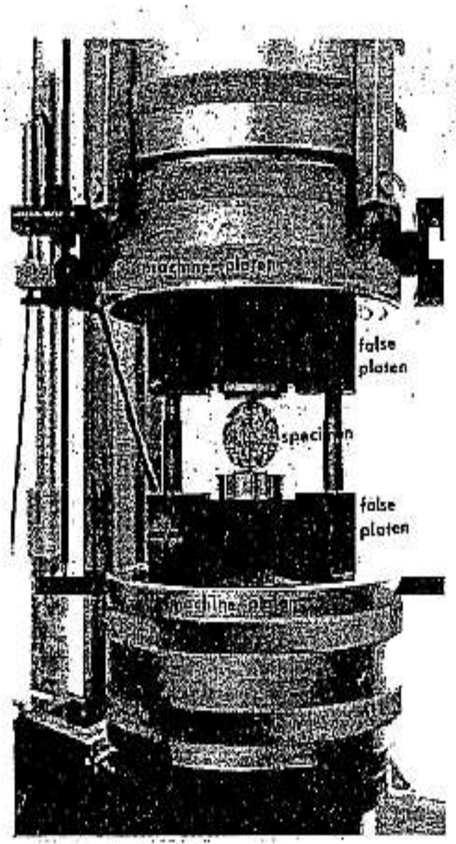


FIG. 1 One Proposed Testing Setup for Splitting Tensile Strength

load creates extremely high contact stresses which cause premature cracking. A wider contact strip can reduce the problems significantly. Studies show that an arc of contact smaller than 15° causes no more than 2 % of error in principal tensile stress while reducing the incidence of premature cracking greatly.

6.3 *Bearing Strips (optional)*—0.01 *D* thick cardboard cushions, where *D* is the specimen's diameter; or up to 6.4 mm (0.25 in.) thick plywood cushions are recommended to be placed between the machine bearing surfaces (or supplementary-bearing plates; if used) and the specimen to reduce high stress concentration.

Note 5—Experience has indicated that test results using the curved supplementary bearing plates and bearing strips, as specified in 6.2.2 and 6.3, respectively, do not significantly differ from the results of tests in which direct contact between the specimen and the machine platen is used.

## 7. Sampling, Test Specimens, and Test Units

7.1 The samples shall be selected by visual observation to include a range of specimens based on rock type, mineral constituents, grain sizes and shape, partings, and defects such as pores and fissures.

7.2 *Test Specimens:*

7.2.1 *Dimensions*—The test specimen shall be a circular disk with a thickness-to-diameter ratio ($t/D$) between 0.2 and 0.75. The diameter of the specimen shall be at least 10 times greater than the largest mineral grain constituent. A diameter of 54 mm (NX core) will generally satisfy this criterion.

Note 6—When cores smaller than the specified minimum must be tested because of the unavailability of material, notation of the fact shall be made in the test report.

Note 7—If the specimen shows apparent anisotropic features such as bedding or schistosity, care shall be exercised in preparing the specimen so that the orientation of the loading diameter relative to anisotropic features can be determined precisely.

7.2.2 *Number of Specimens*—At least ten specimens shall be tested to obtain a meaningful average value. If the reproducibility of the test results is good (coefficient of variation less than 5 %), a smaller number of specimens is acceptable.

7.2.3 The circumferential surface of the specimen shall be smooth and straight to 0.50 mm (0.02 in.).

7.2.4 Cut the ends of the specimen parallel to each other and at right angles to the longitudinal axis. The ends of the specimen shall not deviate from perpendicular to the core axis by more than 0.5°. This requirement can be generally met by cutting the specimen with a precision diamond saw.

7.2.5 Determine the diameter of the specimen to the nearest 0.25 mm (0.01 in.) by recording at least three measurements, one of which shall be along the loading diameter, and calculating the average.

7.2.6 Determine the thickness of the specimen to the nearest 0.25 mm (0.01 in.) by recording at least three measurements, one of which shall be at the center of the disk, and calculating the average.

7.2.7 The moisture conditions of the specimen at the time of test can have a significant effect upon the indicated strength of the rock. The field moisture condition for the specimen shall be preserved until the time of test. On the other hand, there may be reasons for testing specimens at other moisture contents, including zero, and preconditioning of specimen when moisture control is needed. In any case, tailor the moisture content of the test specimen to the problem at hand and record it in accordance with 10.4.2.

Note 8—It is recommended that the moisture condition be more precisely determined when possible and reported as either water content by Test Methods D2216 or degree of saturation.

## 8. Procedure

8.1 *Marking*—The desired vertical orientation of the specimen shall be indicated by marking a diametral line on each end of the specimen. These lines shall be used in centering the specimen in the testing machine to make sure proper orientation, and they are also used as the reference lines for thickness and diameter measurements.

Note 9—If the specimen is anisotropic, take care to make sure that the marked lines in each specimen refer to the same orientation.

8.2 Set up specimen in testing machine.

8.2.1 *Positioning*—Position the test specimen between the top and bottom loading platens so that the diametral plane of the two lines marked on the ends of the specimen lines up with the center of thrust of the spherically seated bearing surface to within 1.25 mm (0.05 in.). Each specimen is positioned inside the testing machine in such way that the marked diametrical line is coincidental with the loading axis of testing machine with either curved or false flat platens.

8.2.2 *Preloading*— To achieve it, slowly bring the loading platens together until the top platen barely and gently contacts the specimen, with little or no load on it. Assure the positioning criterion noted in 8.2.1 is still met.

Note 10—A good line loading can often be attained by rotating the specimen about its axis until there is no light visible between the specimen and the loading platens. Back lighting helps in making this observation.

Note 11—Application of bearing strips as it is noted in 6.3, or putting masking tape around specimen's circumference will help to better positioning of specimen and a good line loading.

8.3 *Loading*—After preloading, apply a continuously increasing compressive load to produce an approximately constant rate of loading such that failure will occur within 1 to 10 min of loading, which should fall between 0.05 and 0.35 MPa/s (500 and 3,000 psi/min) of loading rate, depending on the rock type. The maximum load sustained by the specimen shall be recorded. Load readings shall be recorded to the appropriate number of significant figures (usually 3).

Note 12—Results of tests by several investigators indicate that rates of loading at this range are reasonably free from rapid loading effects.

## 9. Calculation

9.1 The splitting tensile strength of the specimen with the flat platens (1) or curved platens (2) shall be calculated accordingly as follows:

$$\sigma_t = 2P/\pi tD \qquad (1)$$

$$\sigma_t = 1.272\, P/\pi tD \qquad (2)$$

Radius of jaws shall be 1.5× specimen's radius and the result shall be expressed to the appropriate number of significant figures (usually 3), where:

$\sigma_t$ = splitting tensile strength, MPa (psi),
$P$ = maximum applied load indicated by the testing machine, N (or lbf),
$t$ = thickness of the specimen, mm (or in.), and
$D$ = diameter of the specimen, mm (or in.).

## 10. Report: Test Data Sheet(s)/Form(s)

10.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.3.

10.2 Record as a minimum the following general information (data):

10.2.1 Sample/specimen identifying information, such as Project No., Boring No., Sample No., Depth (units). When possible, also record sources of the specimen including project name and location, dates of sampling, and if known, storage environment.

10.2.2 Physical description of the specimen including rock type; location and orientation of apparent weakness planes, bedding planes, and schistosity; large inclusions or inhomogeneities, if any. A sketch or photograph may be used to describe the specimen.

10.2.3 Dates of testing, name or initials of the person doing the testing.

10.3 Record as a minimum the following test specimen data:

10.3.1 Specimen diameter and length, conformance with dimensional requirements, direction of loading if anisotropy exists. Type of contact between the specimen and the loading platens.

10.4 Record as a minimum the following test data:

10.4.1 Rate of loading.

10.4.2 General indication of moisture condition of the specimen at time of test such as as-received, saturated, laboratory air dry, or oven dry.

10.4.3 Splitting tensile strength of each specimen as calculated, average splitting tensile strength of all specimens, standard deviation or coefficient of variation; see Guide E2586.

10.4.4 Type and location of failure.

NOTE 13—A sketch or photograph of the fractured specimen is recommended.

10.4.5 For purposes of comparing calculated values with specified limits, the calculated values shall be rounded to the nearest decimal given in the specification limits in accordance with the provisions of Practice D6026 as it is referenced in 1.3 and 1.3.1.

## 11. Precision and Bias

11.1 An inter-laboratory study was conducted in which seven laboratories each tested five specimens of four different rocks. The specimens were cored by a single laboratory from a common set of samples and randomly distributed to the testing laboratories for testing. The study was carried out in accordance with Practice E691. Details of the study are given in ISR Research Report No. PS #D18.12-R01, 1992, and its Addendum, 1994. The table below gives the repeatability limit (within a laboratory) and reproducibility limit (between laboratories) for the method.

11.1.1 The probability is approximately 95 % that two test results obtained in the same laboratory on the same material will not differ by more than the repeatability limit. Likewise, the probability is approximately 95 % that two test results obtained in different laboratories on the same material will not differ by more than reproducibility limit.

TABLE 1 Splitting Tensile Strength (MPa)

| | Berea Sandstone | Salem Limestone | Tennessee Marble | Barre Granite |
|---|---|---|---|---|
| Average Value | 3.85 | 4.92 | 9.39 | 13.66 |
| Repeatability Limit | 1.24 | 1.56 | 3.63 | 4.31 |
| Reproducibility Limit | 1.37 | 1.74 | 5.36 | 4.98 |

11.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

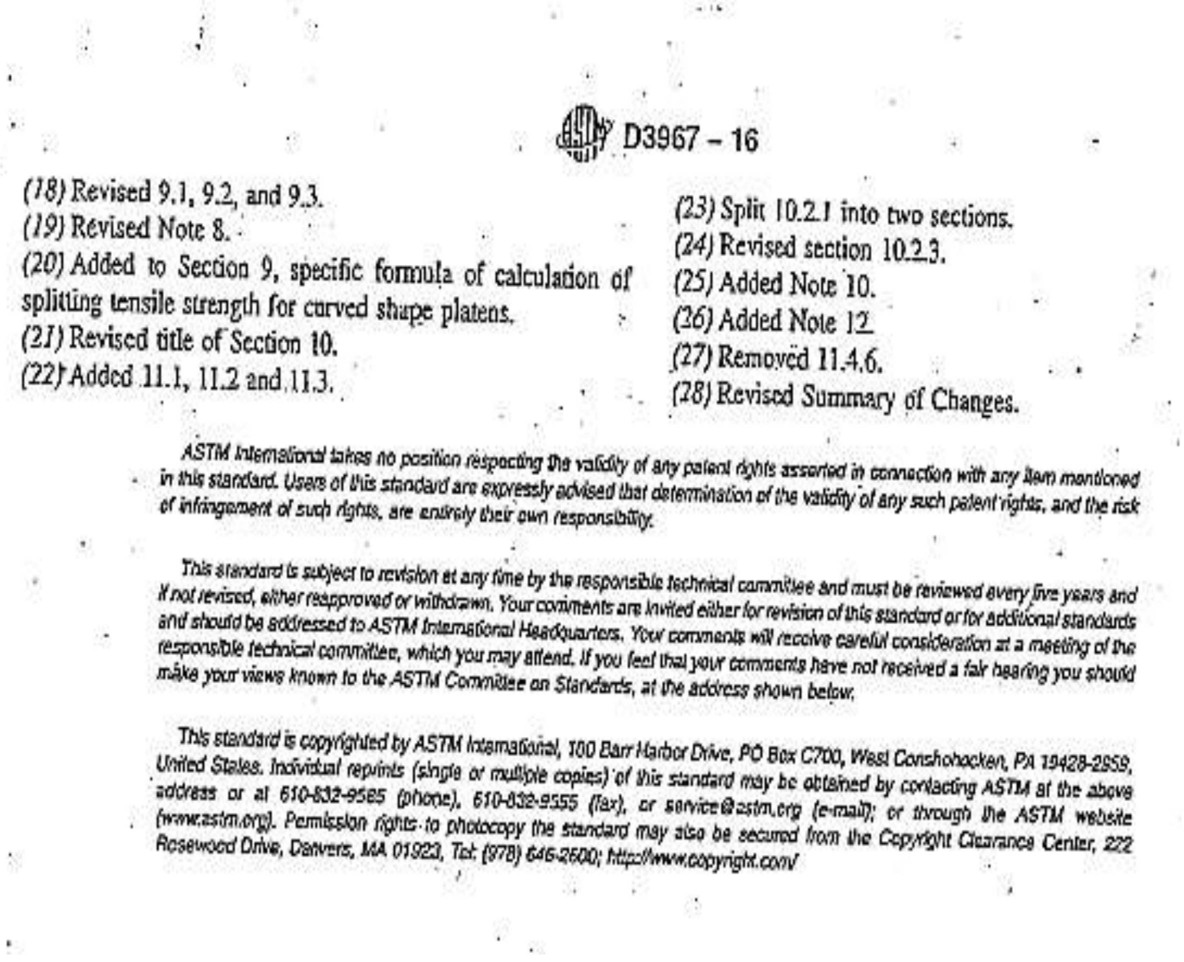
## 12. Keywords

12.1 compression testing; indirect tensile strength; loading tests; rock; splitting tensile strength; tension (tensile) properties/tests

## SUMMARY OF CHANGES

Committee D18 has identified the location of selected changes to this standard since the last issue (D3967 – 09) that may impact the use of this standard. (November 1, 2016)

*(1)* Revised 1.2.
*(2)* Added D2216 and E2586 to 2.1.
*(3)* Revised 3.1.1.
*(4)* Added Section 4, Summary of Test Method.
*(5)* Renumbered sections 4-12 and renumbered all references to sections.
*(6)* Revised 5.1.
*(7)* Revised Note 2.
*(8)* Revised 6.2, 6.2.1, 6.2.2, 6.2.3 and 6.3.
*(9)* Added dimension in English system, 6.2.1 and 6.3.
*(10)* Revised Note 4.
*(11)* Removed 6.2.3 and 6.2.4.
*(12)* Revised title of Section 7.
*(13)* Revised 7.1.
*(14)* Revised title of 8.2.
*(15)* Added 8.2.2.
*(16)* Revised 8.3.
*(17)* Revised 8.5, 8.6 and 8.7.



*(18)* Revised 9.1, 9.2, and 9.3.

*(19)* Revised Note 8.

*(20)* Added to Section 9, specific formula of calculation of splitting tensile strength for curved shape platens.

*(21)* Revised title of Section 10.

*(22)* Added 11.1, 11.2 and 11.3.

*(23)* Split 10.2.1 into two sections.

*(24)* Revised section 10.2.3.

*(25)* Added Note 10.

*(26)* Added Note 12.

*(27)* Removed 11.4.6.

*(28)* Revised Summary of Changes.

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Año de publicación: 2023

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| Estudios de Maestría en Ingeniería de Minas | 1990-1992 | UNI | Perú |
| Estudios de Maestría en Gestión Minera | 2017-2018 | UNI | Perú |

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| UNI – FIGMM | Instructor Centro de Formación Técnica Minera CFTM-UNI | 2018- a la fecha |

**Experiencia profesional**

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| UNI – FIGMM | Jefe del Centro de Computo FIGMM | Abril 18 -fecha |
| Registro Público de Minería | Jefe Área de Digitalización | 1995-2000 |
| DELAE EIRL | Gerente General | 2010- a fecha. |
| ACOMISA | Consultor - Fiscalizador | 2008 - 2009 |
| SYSTEM EDISA | Gerente General | 1996-2004 |

**Trabajos de investigación de los últimos 3 años**

| **Trabajo de investigación** | **Participación (jefe o investigador)** | **Situación** |
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| | | |

| | | | |
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| | Microsoft Visual Studio con C# | Sistemas -UNI | 2018 |

| | | | |
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| **Participación como asistente en: cursos, conferencias, seminarios, talleres, simposios** | Training Course on Exploration and Development of Mineral Resources | KOICA<br>Seul – Corea del Sur | 1994 |
| | Procesamiento Digital de Imágenes de Satélite | CONIDA | 1999 |
| | Software AMINE, mine desing, geology and graphical document management | Noranda Technology Center – Flairbase inc. – Montreal – Canada | 2002 |
| | IV Seminario de Geoingenieria | Sociedad Peruana de Geoingenieria - ISRM | 2019 |
| | | | |
| **Otras actividades de apoyo técnico, social, etc.** | Implementación del Sistema SCUD | Registro Público de Minería – Consultoría y desarrollo | |
| | Desarrollo e Implementación del Programa de Digitalización de Expedientes de Concesiones Mineras | Registro Público de Minería Consultoría y desarrollo | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Idiomas. A: avanzado I: Intermedio B: Básico** | Ingles | **A** | | **I** | **x** | **B** | |
| | | **A** | | **I** | | **B** | |

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NATIONAL UNIVERSITY OF ENGINEERING

## College of Geological, Mining and Metallurgical Engineering
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|---|---|---|---|
| Mining Engineering | 1990 | National University of Engineering UNI | Peru |
| Mining Engineer P.E. | 1991 | National University of Engineering UNI | Peru |
| Master in Mining Engineering (candidate) | 1990-1992 | National University of Engineering UNI | Peru |
| Master in Mining Management (candidate) | 2017-2018 | National University of Engineering UNI | Peru |

### Academic Experience

| Institution | Position | Period |
|---|---|---|
| UNI – FIGMM | Assistant Professor | 1990 to date |
| UNI – FIGMM | Instructor, Mining Technical Training Center CFTM-UNI | 2005 - 2008 |
| UNI – FIGMM | Instructor, Mining Technical Training Center CFTM-UNI | 2018 to date |

### Professional Experience

| Institution | Position | Period |
|---|---|---|
| National University of Engineering | Coordinator, Rock Mechanics Laboratory | 2018 to date |
| National University of Engineering | Computing Manager | 2018 to date |
| National Mining Registrar | Head, Digitalization Area | 1995 - 2000 |
| DELAE Co. | General Manager | 2010 to date |
| ACOMISA Co. | Mining Consultant | 2008 - 2009 |
| SYSTEM EDISA Co. | General Manager | 1996 - 2004 |

### Research work, last five years

| Research work | Participation (head, researcher) | State |
|---|---|---|
| Dynamic Support Systems for Underground Mining | Researcher | In development |

| | | | |
|---|---|---|---|
| **Professional Licensure** | Peruvian Engineers Association | | |
| | | | |
| **Participation in courses, conferences, symposiums, courses, workshops** | **Event** | **Organizer** | **Year** |
| | Microsoft Visual Studio - C# | National University of Engineering, Peru | 2018 |
| | Training Course on Exploration and Development of Mineral Resources | KOICA<br>Seoul, South Korea | 1994 |

<table>
<tr><td rowspan="4"></td><td colspan="5">Digital Processing of Satellite Images</td><td>Aero-Spatial Agency, CONIDA, Peru</td><td>1999</td></tr>
<tr><td colspan="5">Software AMINE, mine desing, geology and graphical document management</td><td>Noranda Technology Center – Flairbase Inc., Montreal –Canada</td><td>2002</td></tr>
<tr><td colspan="5">IV Symposium Geo-Engineering</td><td>Peruvian Society of Geo-Engineering, Peru</td><td>2019</td></tr>
<tr><td colspan="5"></td><td></td><td></td></tr>
<tr><td rowspan="2"><b>Other Activities</b></td><td colspan="5">Responsible of implementation of digital system SCUD for</td><td>National Mining Registrar, Peru</td><td>2018</td></tr>
<tr><td colspan="5">Digitalization of mining concession records</td><td>National Mining Registrar, Peru</td><td>2018</td></tr>
<tr><td><b>Foreign Language</b><br><b>A: Advanced</b><br><b>I: Intermediate B: Basic</b></td><td>English</td><td><b>A</b></td><td></td><td><b>I</b></td><td><b>x</b></td><td><b>B</b></td><td></td></tr>
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