PIT SLOPE MANUAL

supplement 3-2

LABORATORY TESTS FOR DESIGN PARAMETERS

This supplement has been prepared as part of the

PIT SLOPE PROJECT

of the

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THE PIT SLOPE MANUAL

The Pit Slope Manual consists of ten chapters, published separately. Most chapters have supplements, also published separately. The ten chapters are:

1. Summary
2. Structural Geology
3. Mechanical Properties
4. Groundwater
5. Design
6. Mechanical Support
7. Perimeter Blasting
8. Monitoring
9. Waste Embankments
10. Environmental Planning

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ABSTRACT

This supplement describes tests to determine strength and elastic properties of rock substance and of discontinuities in rock. Elastic modulus and Poisson's ratio are determined from stress-strain measurements during uniaxial compression. The ultrasonic elastic constants are determined from measurements of sound velocity. Triaxial compressive strength is determined by loading a cylindrical sample axially and laterally. Residual angle of friction of rock specimens is determined from shear strength measurements along a sawcut plane. Discontinuity shear strengths are determined by the direct shear test, and by triaxial testing. Strength properties of crushed rock are determined by triaxial testing. Time dependent deformation and strength properties of rock specimens are determined by long-term uniaxial compressive tests.

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M. Gyenge and G. Herget were responsible for this chapter. Address enquiries to them at: 555 Booth Street, Ottawa, K1A 0G1, Canada.

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The Pit Slope Group consisted of D.F. Coates*, M. Gyenge*, G. Herget, B. Hoare, G. Larocque, D.R. Murray, R. Sage* and M. Service.

* successive Pit Slope Group Leaders.

CONTENTS

FIGURES

INTRODUCTION

1. Supplement 3-2 covers test types related to the strength and elastic properties of rock substance and to discontinuities.

2. These tests are required to obtain the data necessary for determination of the representative strength parameters of the slope wall materials.

3. Due to the great variation in prevailing conditions, requirements and circumstances from one mining site to another, the supplement provides useful guidance on the testing procedures without attempting to set rigorous standards.

4. The specifications for the testing procedures were written as much as possible in general terms, while providing the essential steps required for any particular type of test.

5. Each type of test is demonstrated by an example based on a particular type of set-up and apparatus. Such an illustration however, is only for purposes of explanation and does not imply endorsement of any apparatus by CANMET nor does it represent a standard for testing procedures. The reader is even encouraged to seek alternatives of testing arrangement and apparatus best suited to his environment.

6. Some of the testing procedures, or parts thereof, are based on methods suggested by the Commission on Standardization of Laboratory and Field Tests of the International Society for Rock Mechanics, or on the Standards of the American Society for Testing and Materials, or on both. Proper references are given in each case at the end of the supplement with a list of selected publications related to the subject matter.

7. Certain tests, common to a number of determinations, have been repeated for each determination. This provides a complete specification for each case and is intended as a convenience to readers.

DETERMINATION OF ELASTIC MODULUS

SCOPE

8. a. The purpose of this test is to establish Young's modulus, E, by compression of cylindrical rock specimens.

b. In addition, the test method includes the procedure to obtain the uniaxial compressive strength, Q_u, of cylindrical rock specimens.

c. All procedures for determining the elastic modulus are based on the appropriate ASTM standards (2).

APPARATUS

9. a. A suitable compression machine, with sufficient capacity, capable of applying an axial load continuously at a constant stress rate and in such a way that failure will occur within five to fifteen minutes of loading. Alternatively the applied stress rate should be within the limits of 75 psi/s (0.5 MPa/s) to 150 psi/s (1.0 MPa/s). The principal features of a suitable compression machine (hydraulically operated) and specimen assembly are illustrated in Fig 1.

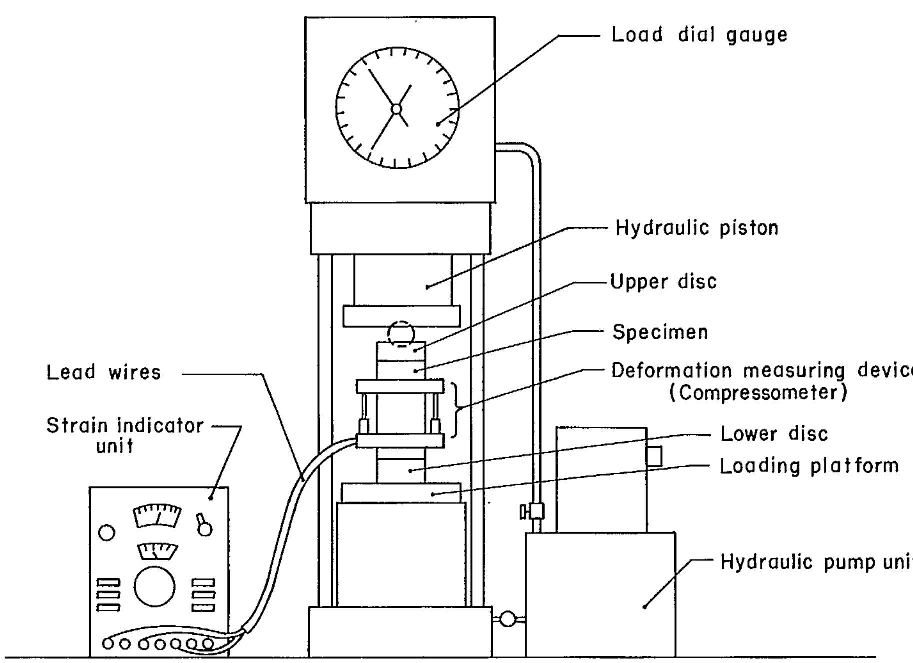


Fig 1 - Schematic arrangement for elastic modulus determination.

b. A load-measuring system to indicate the applied load to an accuracy of 1%. It should incorporate a maximum-indicating device, so that the reading is retained and can be recorded after specimen failure.

c. Steel discs at the specimens ends, having the same diameter as that of the specimen. The thickness of the discs should be at least 5/8 in. (15 mm). The surfaces of the discs should be ground, and their flatness should be 0.002 in. (0.05 mm). The Rockwell hardness of disc material should be at least C 30. One of the discs, usually the upper one, should incorporate a spherical seat to ensure axial load application to the specimen.

d. A suitable device to measure axial deformation or strain, such as a compressometer as shown in Fig 1 and described in Appendix A, or electrical resistance strain gauges, or optical device, etc. The design of the measuring device should be such that the average of the two axial strain measurements can be determined for each increment of load. Measurements should be taken simultaneously along two diametrically opposed generators, close to midheight of the cylindrical specimen. The measuring length, or gauge length, should not extend into that area which is a half diameter distance, or less, from the ends of the specimen. The gauge length should be at least 10 grain diameters in magnitude. The axial strain should be determined with an accuracy of 2% of the reading and a precision of 0.2% of full scale.

PREPARATION OF THE TEST SPECIMEN

10. a. The test specimen should be a straight circular cylinder having a length to diameter ratio of 2.5 to 3.0 and a diameter preferably not less than NX core size, approximately 2 1/8 in. (54 mm). The diameter of specimen should be related to the size of the largest grain in the rock by a ratio of at least 10:1. The ends of the specimen should be parallel to each other and at right angles to the longitudinal axis.

b. Guidance for sample and specimen handling and storage as well as method of specimen preparation together with allowable tolerance specifications is given in Supplement 3-5.

c. The diameter of the test specimen is measured to the nearest 0.005 in. (0.1 mm) by averaging two diameters measured at right angles to each other at about the upper height, mid height and lower height of the specimen. The average diameter is used to calculate the cross sectional area. The height of the specimen is determined to the nearest 0.05 in. (1.0 mm)

d. The inclination of bedding or foliation with respect to the specimen axis is recorded.

e. The number of specimens tested is determined by practical considerations; however, at least three specimens are recommended for each sample.

PROCEDURE

11. a. The specimen is placed on the lower disc and centered on the loading platform.

b. The compressometer is installed as described in Appendix A.

c. The upper disc, with the spherical seat, is placed on the specimen and after careful alignment of the whole assembly, a seating load equivalent to 1% of the estimated uniaxial strength is brought to bear on the specimen.

d. The strain indicator reading is recorded as zero reading.

e. The loading rate is set and compression is started.

f. When the applied load reaches the level equivalent to 5% of the estimated uniaxial strength further loading is temporarily stopped and the corresponding strain indicator reading is recorded together with the elapsed time. The level equivalent for a specimen having an estimated uniaxial strength of 20,000 psi and a cross-sectional area of 3.51 in.^{2} would be: $0.05 \times 20{,}000 \times 3.51 = 3510$ lb.

g. Step f. is repeated for load levels equivalent to 10, 15, 20, 25, 30, 40, 50 and 60 per cent of the estimated uniaxial strength.

h. The load is gradually released to the seating load and the corresponding strain indicator reading is recorded.

i. The compressometer is removed from the specimen after complete loading to protect it from damage.

j. The test set-up, without the compressometer, is reassembled with appropriate care to ensure that both the axial load and seating load are reapplied.

k. A cloth is wrapped around the specimen to prevent possible injury to the operator or any damage to the testing apparatus caused by flying rock. Alternatively, a plexiglas cylinder is placed around it while the set-up is assembled.

l. The loading rate is set and the specimen is compressed until failure.

m. A sketch of the failed specimen and a note of the specimen failure characteristics is made.

n. If determination of water content is required, the failed specimen is used for that purpose. The procedure is specified in paragraphs 10 and 12 of Supplement 3-1.

CALCULATIONS

12\. a. The strain, corresponding to each stress level (or equivalent load level), is obtained by multiplying the apparent strain by the calibration constant of the compressometer.

b. The uniaxial compressive strength is calculated as follows:

$$Q_u = P_u/A$$

where P_u = the maximum load carried by the specimen during the test and

A = the original cross-sectional area calculated in accordance with the specification given in paragraph 10 c.

c. The stress-strain curve, as shown in Fig 2, is plotted.

d. At the point of 0.5 Q_u a tangent is drawn to the stress-strain curve, and the Young's

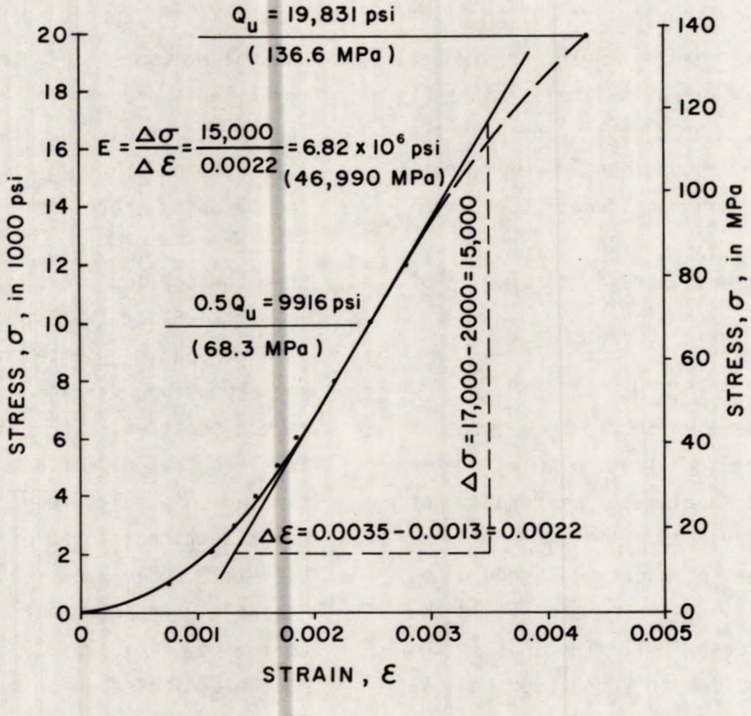


Fig 2 - Stress-strain curve for determination of Young's modulus.

modulus is calculated as follows:

Young's Modulus, $E = \Delta\sigma/\Delta\varepsilon$

where $\Delta\sigma$ = The stress increase between any two conveniently selected arbitrary points of the tangent and

$\Delta\varepsilon$ = the corresponding strain increase between the same two points.

e. Other methods of defining the elastic modulus are:

1. average modulus is defined by the slope of the more or less straight line portion of the stress strain curve.
2. secant modulus is defined by the slope of the line drawn from zero stress to some fixed percentage of Q_u (usually to 0.5 Q_u).

REPORTING OF RESULTS

13. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. average value of Young's modulus for the sample
c. average uniaxial compressive strength of the sample
d. method and date of specimen preparation, storage history of specimens and number of specimens tested within the sample
e. information on testing such as: date, type of testing apparatus and measuring device
f. average water content of the sample and degree of saturation where this is critical
g. any other observations or available physical data.

14. In addition, the report should include in convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. specimen diameter, height and cross-sectional area
c. orientation of the specimen axis with respect to anisotrophy, (eg with respect to bedding plane, foliation, etc)
d. test duration
e. Young's modulus
f. uniaxial compressive strength
g. descriptive notes on the failure characteristics of the specimen, such as shape, mode and number of fragments. The following terms are recommended to describe the failure characteristics of a specimen (1):
   i. For failure shape:
      cone
      axial
      diagonal
      parallel to discontinuity
      no data
   ii. For failure mode:
      violent
      quiet
      no data
   iii. For number of fragments:
      three or less
      more than three
      crushed
      no data
h. water content and degree of saturation where these are critical
i. any other observation related to the specimen.

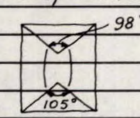
15. The working sheets and corresponding stress-strain curves are adequate substitutes for the report if only a relatively small number of specimens are tested (see Fig 2 and Fig 3).

ELASTIC MODULUS (by uniaxial compression)

Sample *foot-wall shale*
out-crop

Date *April 22, 1973*
Tested by *W. G.*
Compressometer calibration constant *0.54167*

Location *trial blasting area*
Water content *3.8* %
Bore Hole ______ Depth ______
Degree of saturation ______ %
Sample No. *TB-S-2*
Specimen No. *3*

Elapsed Time, min	Load lb	Stress psi	Strain ind. reading	Apparent Strain	Strain (in/in)10^{-6}	Notes
0	700	200	12,460	0	0	Seating load.
1	3510	1000	11,085	1375	745	Loading rate: 75psi/s
2	7020	2000	10,390	2070	1121	
3	10,530	3000	10,030	2430	1316	90° bedding to
4	14,040	4000	9,700	2760	1495	specimen axis.
4.5	17,750	5000	9,360	3100	1679	
5.5	21,060	6000	9,090	3370	1825	failed specimen
7	28,080	8000	8,450	4010	2172	
9	35,100	10,000	7,855	4605	2494	
11	42,120	12,000	7,335	5125	2776	
13.5	700	200	12,450	10	5	
0	700	200	failure			failure characteristics
4.5	69,600	19,831	test			shape: cone
						mode: violent
						fragment: more
						than three

Diameter: *2.115* in. (*53.7* mm)

Height, L_0: *6.15* in. (*156* mm)   Area, A: *3.51* in^2 (*22.6* cm^2)

Uniaxial compressive strength, $Q_u = \frac{P_u}{A} = \frac{69,600}{3.51} = 19,831$ psi (*136.6* MPa)

Remarks: *On April 15-th, after blast, samples of approx. 10 in. cubes were collected, wrapped in plastic and covered with damp rags kept in lab. until specimen preparation; NX core specimens were drilled and prepared on Apr. 21 which were wrapped and kept in damp rags until testing.*

Fig 3 - Working sheet for elastic modulus determination.

DETERMINATION OF POISSON'S RATIO

SCOPE

16. a. The purpose of this test is to establish the Poisson's ratio, μ, of a cylindrical rock specimen compressed axially.

b. The procedure also includes the determination of Young's modulus, E, of the specimen.

c. In addition, the testing procedure is extended to obtain the uniaxial compressive strength, Q_u, and also the stress-strain curve up to the ultimate strength of the specimen.

APPARATUS

17. a. A suitable compression machine with sufficient capacity, capable of applying an axial load continuously at a constant stress rate and in such a way that failure will occur within five to fifteen minutes of loading. Alternatively, the applied stress rate should be within the limits of 75 psi/s (0.5 MPa/s) to 150 psi/s (1.0 MPa/s). The principal features of a suitable hydraulically operated compression machine are illustrated in Fig 1.

b. A load measuring system to indicate the applied load to an accuracy of 1%. It should incorporate a maximum-indicating device, so that the reading is retained and can be recorded after specimen failure.

c. Steel discs at the specimen ends, having the same diameter as the specimen. The thickness of the discs should be at least 5/8 in. (15 mm). The surfaces of the discs should be ground, and their flatness should be 0.002 in. (0.05 mm). The Rockwell hardness of the disc material should be at least C 30. One of the discs, usually the upper one, should incorporate a spherical seat to ensure axial load application to the specimen.

d. A suitable device to measure circumferential and axial deformation or strains, such as electrical resistance strain gauges as shown in Fig 4. The design of the measuring device should be such that the average of the two circumferential and the two axial strain measurements can be determined for each increment of load. Axial strain measurements should be taken along two diametrically opposed

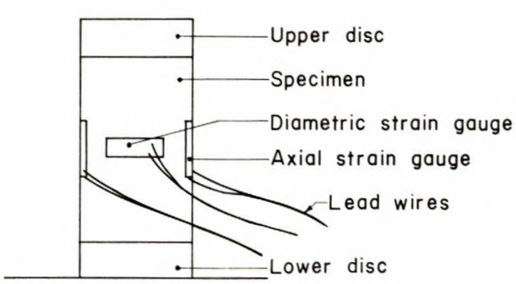


Fig 4 - Specimen assembly for Poisson's ratio determination.

generators, close to mid height of the cylindrical specimen. The measuring length, or gauge length, should not extend into that area which is a half-diameter distance, or less, from the ends of the specimen. The two circumferential gauges are attached to the specimen close to the mid height, diametrically opposed to each other and at 90° to the axial gauges. The length over which axial and circumferential strain is determined should be at least 10 grain diameters in magnitude. Both the axial and the circumferential, or diametric, strains should be determined with an accuracy of 2% of the reading and a precision of 0.2% of full scale.

PREPARATION OF THE TEST SPECIMEN

18. a. The test specimen should be a straight circular cylinder having a length to diameter ratio of 2.5 to 3.0 and a diameter preferably not less than NX core size, approximately 2 1/8 in. (54 mm). The diameter of the specimen should be related to the size of the largest grain in the rock by a ratio of at least 10:1. The ends of the specimen should be parallel to each other and at right angles to the longitudinal axis.

b. Guidance for sample and specimen handling and storage as well as method of specimen preparation, together with allowable tolerance specifications, is given in Supplement 3-5.

c. The diameter of the test specimen is measured to the nearest 0.005 in. (0.1 mm) by averaging two diameters measured at right angle to each other at about the upper height, mid height and lower height of the specimen. The average diameter is used to calculate the cross-sectional area. The height of the specimen is determined to the nearest 0.05 in. (1.0 mm).

d. The inclination of bedding or foliation with respect to the specimen axis is recorded.

e. The number of specimens tested is determined by practical considerations, however, at least three specimens are recommended for each sample.

f. The method of strain gauge application is given in Supplement 3-5.

PROCEDURE

19. a. The specimen with strain gauges attached is placed between the lower and upper discs; the specimen and discs are carefully aligned and the whole assembly is centred on the loading platform.

b. As the seating load, equivalent to 1% of the estimated uniaxial strength, is gradually brought to bear on the specimen, care is exercised to achieve uniform loading.

c. The electrical connections are made between the axial strain gauges and a strain-indicator unit and between the circumferential strain gauges and another strain-indicator unit. The indicator readings are recorded as zero readings.

d. A cloth is wrapped around the specimen to prevent possible injury to the operator or damage to the testing apparatus from flying rock. Alternatively a plexiglas cylinder is placed around it while the set-up is assembled.

e. The loading rate is set and compression is started.

f. When the applied load reaches the level equivalent to 5% of the estimated uniaxial strength further loading is temporarily stopped and the corresponding strain-indicator readings are recorded, together with the elapsed time. The load equivalent for a specimen having an estimated uniaxial strength of 20,000 psi and a cross-sectional area of 3.50 $in.^2$ would be: 0.05 x 20,000 x 3.50 = 3,500 lb.

g. Step f. is repeated for load levels equivalent to 10, 20, 30, 40, 50, 60, 70 and 75% of the estimated uniaxial strength.

h. The testing procedure is continued by applying further load increments, each equivalent to about 5% of the estimated uniaxial strength, until the specimen fails. No diametric strain readings are required for these load stages. The change in axial strain should be followed by continuously turning the balancing dial on the strain indicator to obtain the strain readings corresponding to the ultimate strength of the specimen. The approach of this stage is indicated by the increased axial strain rate during load application.

i. A sketch of the failed specimen and/or a note of the specimen failure characteristics is made.

CALCULATIONS

20. a. The uniaxial compressive strength is calculated as follows:

$$Q_u = P_u/A$$

where P_u = the ultimate load carried by the specimen during the test and
A = the original cross-sectional area calculated in accordance with the specification given in paragraph 18 c.

b. The stress-strain curves, as shown in Fig 5, for both the axial and the diametric strain are plotted. The diametric strain has a negative value in the adopted sign convention where compression is positive, and hence its absolute value is plotted.

c. Tangents are drawn to both stress-strain curves at the points of 0.5 Q_u.

d. The slope of the tangent drawn to the stress-strain curve for the axial strain defines Young's modulus, ie:

$$E = \Delta\sigma/\Delta\varepsilon$$

where $\Delta\sigma$ = the stress increase between any two conveniently selected arbitrary points of the tangent and
$\Delta\varepsilon$ = the corresponding strain increase between the same two points.

e. Similarly, the slope of the tangent drawn to the stress-strain curve of the diametric strain is calculated ie:

$$E_d = \Delta\sigma_d/\Delta\varepsilon_d$$

f. Finally, Poisson's ratio is calculated as follows:

$$\text{Poisson's ratio, } \mu = E/E_d$$

REPORTING OF RESULTS

21. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. average value of Poisson's ratio for the sample
c. average value of Young's modulus for the sample
d. average uniaxial compressive strength of the sample
e. average uniaxial failure strain of the sample
f. storage and environmental history of the sample
g. method and date of specimen preparation, storage history of specimen and number of specimens tested within the sample
h. information on testing such as: date, type of testing apparatus and measuring devices
i. any other observations or available physical data.

22. In addition, the report should include, in convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. specimen diameter, height and cross-sectional area
c. orientation of the specimen axis with respect to anisotropy, (eg, with respect to bedding plane, foliation, etc)
d. test duration
e. Poisson's ratio
f. Young's modulus
g. uniaxial compressive strength
h. uniaxial failure strain
i. descriptive notes on failure characteristics such as shape, mode and fragment size of the specimen. To describe the failure characteristics of a specimen the use of terms included in paragraph 14 g. is recommended
j. any other observation related to the specimen.

23. The working sheets and the corresponding stress-strain curves are adequate substitutes for the report if only a relatively small number of specimens are tested (Fig 5, 6).

POISSON'S RATIO

Sample *foot-wall shale*
out-crop

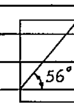
Date *May 18, 1973*
Tested by *W. G.*

Location *trial blasting area*

Bore Hole ______ Depth ______

Sample No. *TB-S-2*

Specimen No. *5*

Elapsed Time, min	Load, lb	Stress psi	Axial strain reading	Diam. strain reading	Axial strain (in/in) 10^{-6}	Diam. strain (in/in) 10^{-6}	Notes
0	700	200	14,255	7220	0	0	Seating load
1	3500	1000	13,720	7245	535	25	Loading rate: 75psi/s
2	7000	2000	13,360	7270	895	50	
3	14,000	4000	12,805	7315	1450	95	90° bedding to
4	21,000	6000	12,360	7375	1895	155	specimen axis.
5	28,000	8000	11,965	7430	2290	210	
5.5	35,000	10,000	11,585.	7490	2670	270	failed specimen
6.5	42,000	12,000	11,150	7550	3105	330	
7	56,000	14,000	10,770	7610	3485	390	
8	59,000	15,000	10,570	7640	3685	420	
9	63,000	16,000	10,345		3910		
10	66,500	17,000	10,085		4170		
11	70,000	18,000	9800		4455		failure characteristics
12.5	73,500	19,000	9475		4780		shape: diagonal
13.5	77,000	20,000	9050		5205		mode: violent
15	80,500	21,000	8655		5600		fragments: less
15.5	75,770	21,650			~6000		than three

Diameter: *2.110* in. (*53.6* mm)

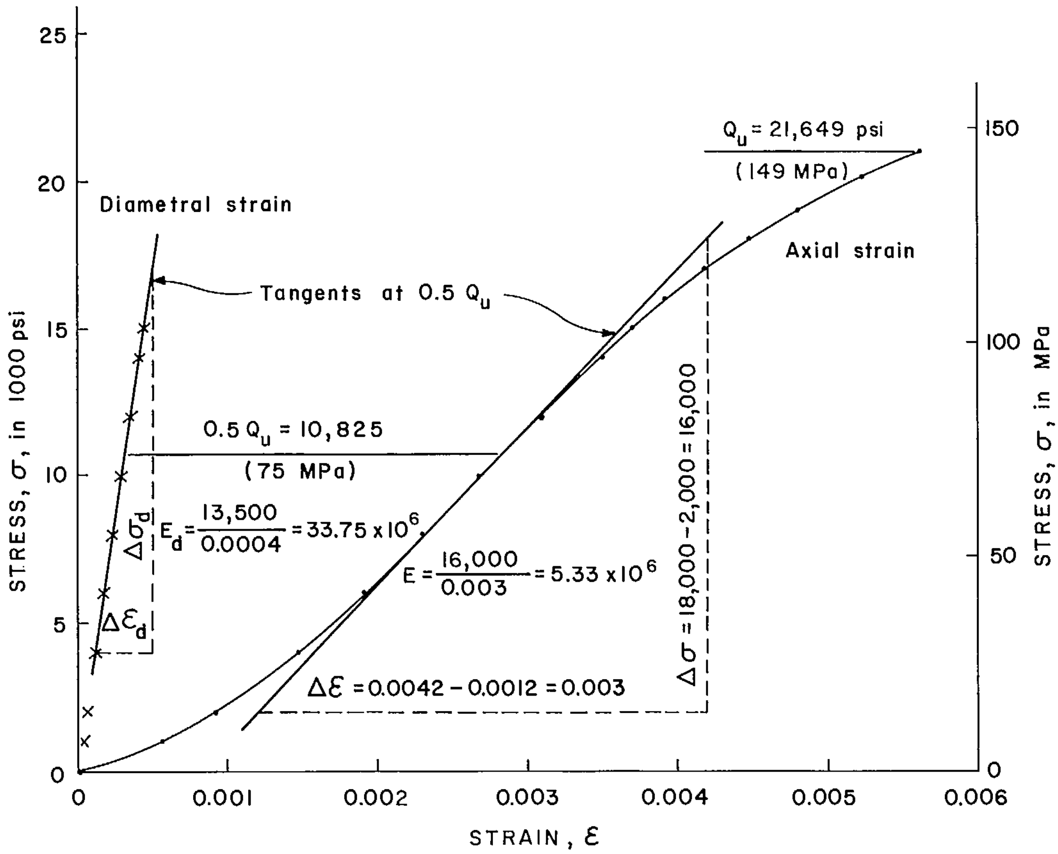
Height, L_0: *5.95* in. (*151* mm) Area, A: *3.50* in^2 (*22.6* cm^2)

Uniaxial compressive strength, $Q_u = \frac{P_u}{A} = \frac{75,770}{3.50} = 21,649$ psi (*149* MPa)

Uniaxial failure strain: *0.006* (approx.)

Remarks: *on Apr. 15-th., after blast samples of approx. 10 in. cubes were collected, wrapped in plastic and covered with damp rags kept in lab. until specimen preparation;*
Nx core specimens were drilled and prepared on Apr. 21 which were kept and allowed to dry at room temperature, strain gauges were attached on May 13-th.

Fig 5 - Working sheet for Poisson's ratio determination.



$$\text{Poisson's ratio, } \mu = \frac{E}{E_d} = \frac{5.33 \times 10^6}{33.75 \times 10^6} = 0.16$$

Fig 6 - Stress-strain curves for determination of Poisson's ratio.

DETERMINATION OF ULTRASONIC ELASTIC CONSTANTS

SCOPE

24. a. The purpose of this test is to establish the ultrasonic elastic constants of intact rock through laboratory measurements of the pulse velocities of compression and shear waves in cylindrical rock specimens.

b. The ultrasonic elastic constants are calculated from the measured wave velocities and the bulk density.

c. The method is valid for measurements in homogeneous and isotropic rocks or in rocks exhibiting slight anisotropy.

d. The values of elastic constants often do not agree with those determined by static laboratory methods or the in situ methods. Measured wave velocities likewise may not agree with seismic velocities, but offer good approximations. The ultrasonic evaluation of rock properties is useful for a preliminary estimation of static properties.

e. The method is useful for evaluating the effects of uniaxial stress and water saturation on pulse velocity which are, in turn, useful in engineering design.

f. All procedures for determing the ultrasonic elastic constants are based on the appropriate ASTM standards (3).

APPARATUS

25. a. The ultrasonic testing apparatus should have impedance-matched electronic components and shielded leads to ensure efficient energy transfer (Fig 7, 8).

b. A pulse generator unit consisting of an electronic pulse generator and external voltage or power amplifiers, if needed. A voltage output in the form of either rectangular pulses or a gated sine wave is satisfactory. The generator should supply a minimum 50 V pulse output into a 50 Ω impedance load. A variable pulse width, with a range of 1 to 10 μs is desirable. A range of 20 to 100 repetitions per second is recommended for the pulse repetition rate. The pulse generator should also have a trigger-pulse output to trigger the oscilloscope.

c. A transducer unit consisting of a transmitter which converts electrical pulses into mechanical pulses and a receiver which converts mechanical pulses into electrical pulses. Piezo-electric materials, such as lead-zinconate-titanate ceramics, are recommended for the transducer elements. These are suitable for the generation and sensing of both compression and shear wave energy. The transducers are encased in metal to improve the performance and to provide protection against mechanical damage. Because the wave velocities are usually determined for specimens subjected to uniaxial state of stress, the upper and lower loading disc of the uniaxial testing

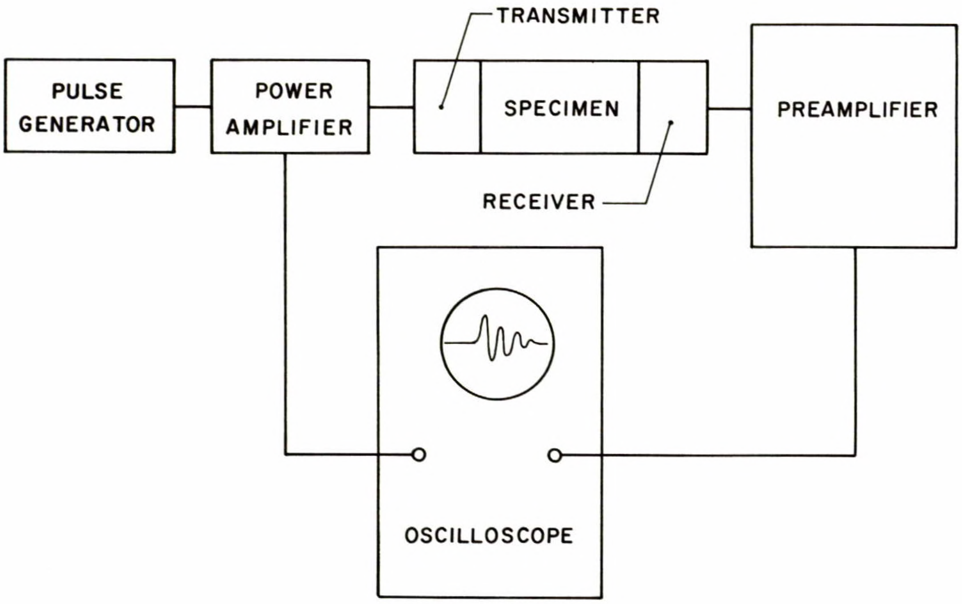


Fig 7 - Schematic arrangement for ultrasonic elastic constants determination.

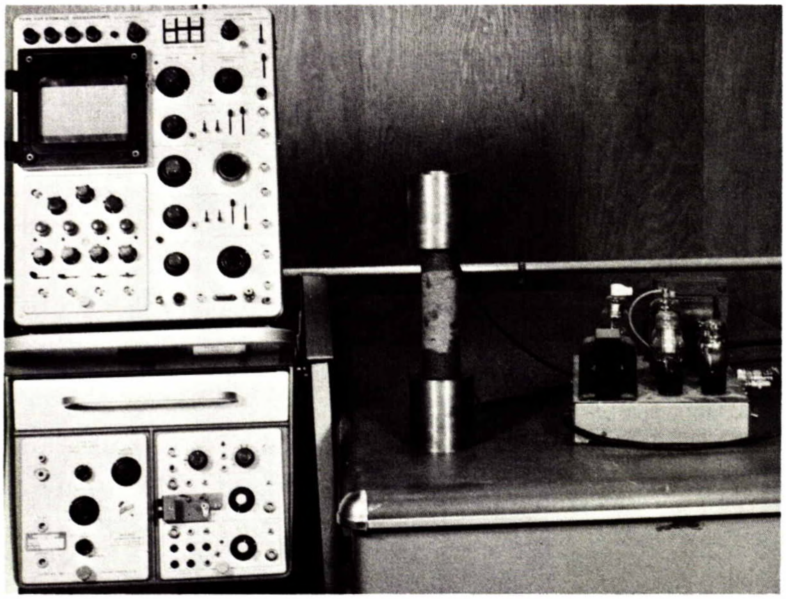


Fig 8 - Photograph of instruments used for ultrasonic elastic constants determination.

apparatus can be used for encasing the transmitter and receiver elements respectively (Fig 9).

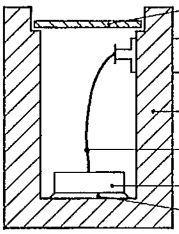


Fig 9 - Cross-section of a loading disc with the transducer element encased within.

d. A voltage preamplifier to increase the voltage output of the receiving transducer, and to increase the sensitivity of the timing and display units. The frequency response of the preamplifier should drop no more than 2 dB over a frequency range from 5 kHz to four times the resonance frequency of the receiver, to preserve fast-rise times.

e. A cathode-ray oscilloscope for visual observation of the wave forms. The oscilloscope should have an essentially flat response over a frequency range from 5 kHz to four times the resonance frequency of the transducers. It should have dual beams or dual traces so that the two wave forms can be displayed simultaneously and their amplitudes controlled separately. The oscilloscope should be triggered by a triggering pulse from the pulse generator.

f. A timing unit, capable of measuring intervals between 2 μs and 5 ms to an accuracy of one part in 100, such as a time-delay circuit (either a continuously variable-delay generator or a delayed-sweep feature on the oscilloscope). It is recommended that the time measuring circuit be checked periodically and after any severe impact which the instrument may receive.

PREPARATION OF THE TEST SPECIMEN

26. a. The test specimen should be a straight circular cylinder with a diameter preferably not less than AX core size, approximately 1 1/4 in. (31 mm). Since the propagation velocity, V_p, and grain size, d, are inherent properties of the material while the resonance frequency, f, is given for the particular transducers being used, the diameter, D, and the length, L, of the specimen should be selected such that the requirements shown in Fig 10 are satisfied. For any given value of V_p/f the permissible values of specimen diameter, D, lie above the diagonal line of Fig 10, while the permissible values of grain size, d, lie below the diagonal line. For a particular diameter, the permissible values for specimen length, ℓ, lie to the left of the diagonal line. The surface area under each transducer should be sufficiently flat so that a feeler gauge 0.001 in. (0.025 mm) thick will not pass under a straight edge placed on the surface. The two opposite surfaces on which the transducers will be placed should be parallel to within 0.005 in./in. (0.1 mm/25 mm) of lateral dimensions.

b. Guidance for sample and specimen handling and storage, as well as for the method of specimen preparation together with allowable tolerance specifications, is given in Supplement 3-5.

c. The number of specimens tested is determined by practical considerations; however, it is recommended that at least three specimens are tested from each sample.

PROCEDURE

27. a. The positions of the transducer on the specimen are marked, so that the line connecting the centres of the contact areas is not inclined more than 2° (approximately 0.1 in. in 3 in. or 1 mm in 30 mm) to a line perpendicular to either surface.

b. The pulse-travel distance from centre to centre of the transducer contact areas is measured, with an accuracy of 0.001 in. (0.025 mm). In the case of a cylindrical specimen, the pulse-travel distance is equal to the length of the

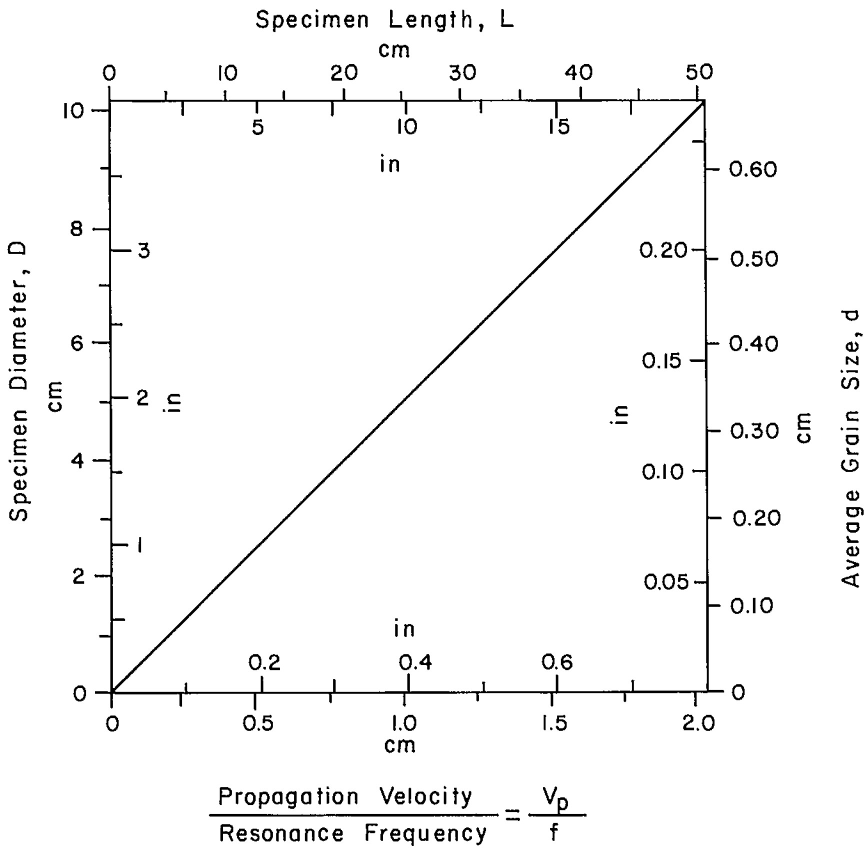


Fig 10 - Graph showing the permissible dimension of the specimen; in relationship with the ratio of propagation velocity and resonance frequency.

specimen L.

28. a. The transducers, encased in the metal housing, are placed in direct contact with each other. A thin layer of vaseline or high-vacuum grease is applied between the face plates of the metal housings to improve coupling.

b. The voltage output of the pulse generator, the gain of the amplifier, and the sensitivity of the oscilloscope are set to their optimum level to obtain a steep pulse front allowing accurate time measurement.

c. The zero time, t_o, of the circuit, including the encased transducers and the travel time measuring device, is measured to an accuracy of one part in 100. The measuring point should be selected either at the beginning of the curved transition region or at the zero-voltage intercept of the straight line portion of the first arrival of the transmitted pulse displayed on the oscilloscope.

29. a. The specimen is placed between the two transducers. A thin layer of coupling medium is used again between the face plates of the transducers and the specimen to improve the energy transmission.

b. The travelling time of the compressive wave, t_p, is measured to an accuracy of one part in 100. The selection of the measuring point should be consistent with the manner used in measuring the zero time in step 28 c. (Fig 11 a).

30. a. The vertical gain and the delayed sweep time of the oscilloscope are adjusted to a level which gives an optimum shear wave detection and display.

b. The travelling time of the shear wave, t_s, is measured to an accuracy of one part in 50. The measuring point should be selected at the spot where the character of the displayed wave form changes (Fig 11 b).

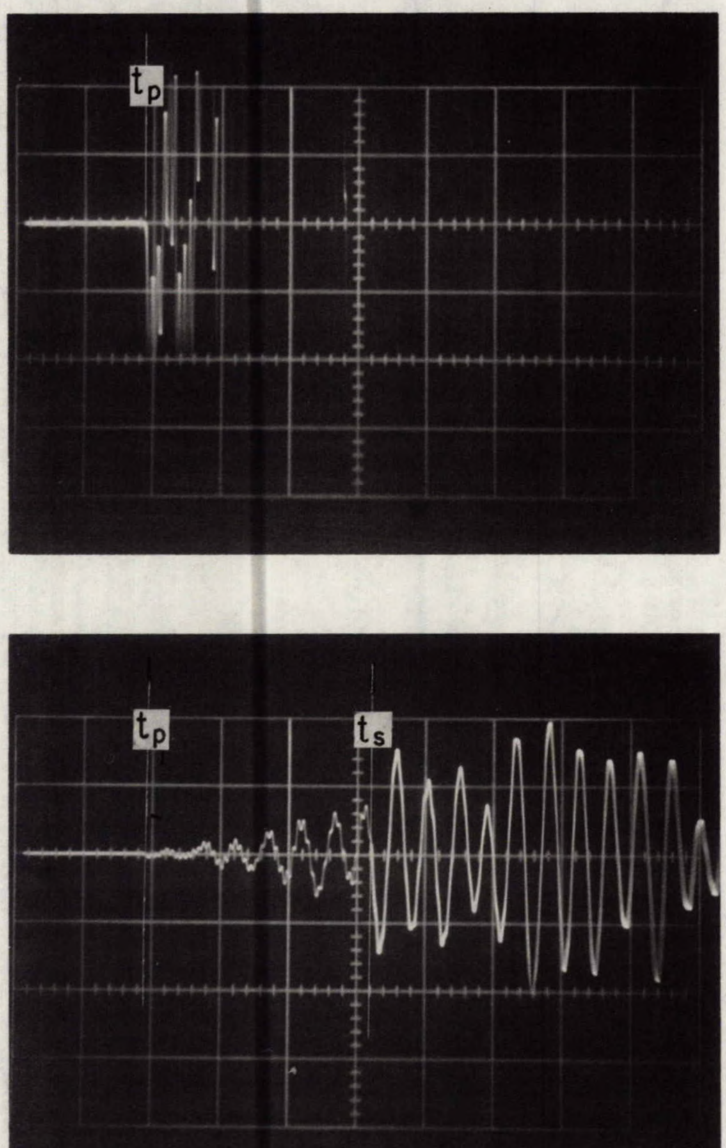


Fig 11 - Photographs of wave forms: (a) compression wave and its traveling time t_p; (b) compression and shear waves and their traveling times t_p and t_s.

31. a. The diameter of the test specimen, D, is measured to the nearest 0.005 in. (0.1 mm) by averaging two diameters measured at right angle to each other at about the upper height, mid height and lower height of the specimen. The volume of the specimen, V, is calculated from the diameter, D, and length, L.

b. The weight, W_t, of the specimen is measured to an accuracy of 0.01 g.

c. The specimen is placed in the oven, and after drying to a constant weight, its weight, W_o, is measured to an accuracy of 0.01 g.

d. The specimen is completely immersed under vacuum in filtered or distilled water at 20° ± 2°C for 24 hours. At the end of this period the specimen is removed from the water, the surface is wiped with a damp cloth and its saturated weight, W_s, is measured to an accuracy of 0.01 g.

32. Steps 29 and 30 are repeated on the saturated specimen if the effect of water saturation on pulse velocity needs to be evaluated.

33. a. If the effect of uniaxial stress on pulse velocity needs to be evaluated, the required measurements on the specimen should be performed after step 30, but before step 31, as follows:

b. The specimen is placed on the lower disc, which contains the transmitter element, and is centred on the loading platform of a compression machine. It may be necessary to insert a 1/4 in. (6 mm) thick sheet of insulator such as hard rubber between the leveling platform and the disc, and above that a 1/4 in. (6 mm) thick steel load-distributing plate to minize the signal reflection caused by the loading platform.

c. The upper disc containing the receiver unit is placed on the specimen and, after careful alignment of the whole assembly, a seating load, equivalent to 1% of the estimated uniaxial strength of the specimen, is brought to bear on it (Fig 12, 13).

d. The specimen is loaded to a load level equivalent to 5% of the estimated uniaxial strength of the specimen by applying a loading rate of 75 psi/s (0.5 MPa/s).

e. The travelling time of both the compression wave and the shear wave are measured according to steps 29 and 30.

f. Step e. is repeated for load levels equivalent to 10, 15, 20 and 25 per cent of the estimated uniaxial strength.

g. The procedure should continue with step 31 after removing the specimen.

CALCULATIONS

34. a. Mass density, $\rho = \gamma/g$

where $\gamma = W_t/V$, unit weight of the specimen,
W_t = weight of the specimen (at natural water content),
V = volume of the specimen and
g = acceleration of gravity, 386.2 in./s^2 (9.81 m/s^2).

b. Propagation velocities,

$$V_p = L/T_p$$
$$V_s = L/T_s$$

where V_p = propagation velocity of the compression wave,
V_s = propagation velocity of the shear wave,
L = pulse-travel distance (length of the cylindrical specimen),
$T_p = t_p - t_o$, effective travelling time of the compression wave.
$T_s = t_s - t_o$, effective travelling time of the shear wave,
t_p = measured travelling time of the compression wave,
t_s = measured travelling time of the shear wave and
t_o = measured zero time.

c. Ultrasonic constants,

$$E_u = \rho V_s^2 \, [3(V_p/V_s)^2-4]/[(V_pV_s)^2-1]$$

where E_u = Young's modulus of elasticity (ultrasonic).

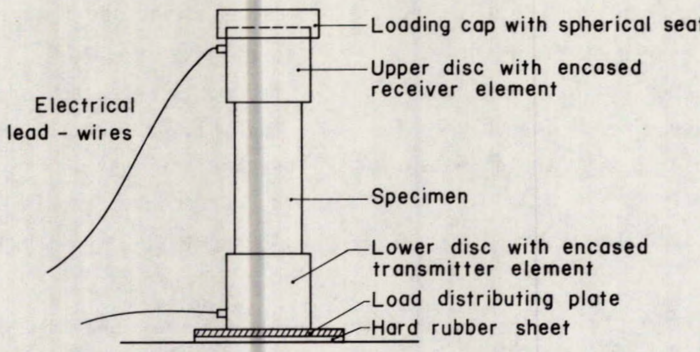


Fig 12 - Specimen assembly for ultrasonic elastic constants determination under axially loaded condition.

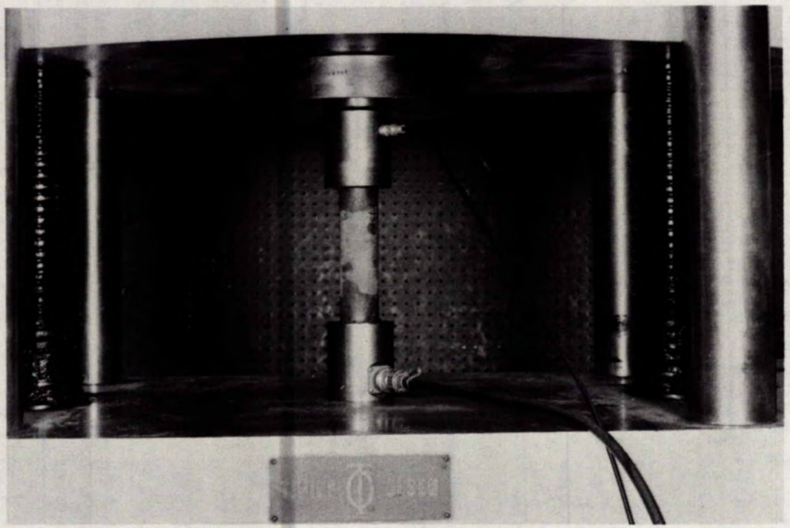


Fig 13 - Photograph of the specimen assembly axially loaded within a compression machine.

$G_u = \rho V_s^2$

where G_u = Modulus of rigidity (ultrasonic) or shear modulus (ultrasonic).

$\mu_u = 1/2[(V_p/V_s)^2-2]/[(V_p-V_s)^2-1]$

where μ_u = Poisson's ratio (ultrasonic).

d. Apparent porosity, $P\% = (W_s - W_o)/V\gamma_w$

where W_s = weight of saturated specimen,
W_o = weight of oven-dried specimen,
V = volume of the specimen and
γ_w = unit weight of water, $1.00\ g/cm^3 = 10^6\ g/m^3$

e. Degree of saturation,

$S\% = (W_t - W_o)/(W_s - W_o)$

REPORTING OF RESULTS

35. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. average unit weight of the sample
c. average apparent porosity and average degree of saturation of the sample
d. average values of calculated pulse velocities for compression and shear waves, corresponding to each testing condition for the sample (ie, natural water content, saturated state, applied uniaxial stress level)
e. average values of calculated ultrasonic constants (ie Young's modulus, shear modulus, and Poisson's ratio), corresponding to each testing condition for the sample (ie, natural water content, saturated state, applied uniaxial stress level)
f. coupling medium between transducers and specimen
g. storage and environmental history of the sample
h. method and date of specimen preparation storage history of specimens and number of specimens tested within the sample
i. information on testing such as: date, type of testing apparatus and measuring devices
j. any other observations or available physical data.

36. In addition, the report should include in convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. dimensions of the specimen
c. orientation of the specimen axis with respect to anisotropy, ie, with respect to bedding plane, foliation, etc.
d. unit weight of the specimen
e. apparent porosity and degree of saturation of the specimen
f. calculated pulse velocities for compression and shear waves, corresponding to each testing condition (ie, natural water content, saturated state, applied uniaxial stress level)
g. calculated ultrasonic constants (ie, Young's modulus, shear modulus and Poisson's ratio) corresponding to each testing condition (ie, natural water content, saturated state, applied uniaxial stress level)
h. photographs of the pulse waves, if available
i. any other observation related to the specimen.

37. The working sheets are adequate substitutes for a report if only a relatively small number of specimens are tested (Fig 14).

ULTRASONIC ELASTIC CONSTANTS

Sample *hanging wall granite out-crop, slightly schistous texture of feldspar surrounded by quartz.*

Date *Apr. 22, 1973*

Tested by *W. G.*

Location *trial blasting area*

Test condition : *at natural water content*

Bore Hole ______ Depth ______

Applied stress: *0* psi (*0* MPa)

Sample No *TB-G-3*

Specimen No *5*

Diameter, D: *1.735* in. (*44.1* mm)

Length, L : *6.110* in. (*155.195* mm)

Volume, V = *14.45* in^3 (*.000237* m^3)

Specimen weight, W_t: *1.3933* lb (*632* g)

Oven dried weight, W_o : *1.3932* lb (*631.92* g)

Saturated weight, W_s : *1.3936* lb (*632.12* g)

Unit weight, $\gamma = \frac{W_t}{V} = \frac{1.3933}{14.45} = 0.0963$ lb/in^3 (Mass : *2667* kg/m^3)

Mass density, $\rho = \frac{\gamma}{g} = \frac{0.0963}{32.17} = 2.49 \times 10^{-4}$ $lb.s^2/in^4$

Compressive wave :			Shear wave :		
t_p :	*0.0372*	ms	t_s :	*0.1088*	ms
t_o :	*0.0100*	ms	t_o :	*0.0100*	ms
T_p =	*0.0272*	ms	T_s =	*0.0988*	ms

$V_p = \frac{L}{T_p} = \frac{6.110}{2.72 \times 10^{-5}} = 224{,}632$ in./s (*5700* m/s)

$V_s = \frac{L}{T_s} = \frac{6.110}{9.88 \times 10^{-5}} = 61{,}840$ in./s (*1570* m/s)

$V_p / V_s = 3.632$ $\quad (V_p / V_s)^2 = 13.19$

Young's modulus (ultrasonic), $E_u = \rho V_s^2 \frac{3(V_p/V_s)^2 - 4}{(V_p/V_s)^2 - 1}$

$$E_u = 0.000249 \times 61840^2 \frac{3 \times 13.19 - 4}{13.19 - 1} = 2.78 \times 10^6 \text{ psi}$$

$$(E_u = 2667 \times 1570^2 \frac{3 \times 13.19 - 4}{13.19 - 1} = 19{,}182 \text{ MPa})$$

Shear modulus (ultrasonic), $G_u = \rho V_s^2 = 0.000249 \times 61840^2 = 0.952 \times 10^6$ psi

$$(G_u = 2667 \times 1570^2 = 6567 \text{ MPa})$$

Poisson's ratio (ultrasonic), $\mu_u = (\frac{1}{2}) \frac{(V_p/V_s)^2 - 2}{(V_p/V_s)^2 - 1} = (\frac{1}{2}) \frac{13.19 - 2}{13.19 - 1} = 0.459$

Apparent porosity, $P = \frac{W_s - W_o}{V \gamma_w} = \frac{632.12 - 631.92}{2.37 \times 10^{-4} \times 10^6} = 0.084$ %

Degree of saturation, $S = \frac{W_t - W_o}{W_s - W_o} = \frac{632.00 - 631.92}{632.12 - 631.92} = 40.0$ %

Remarks : *Samples of approx. ft. cubes were collected on April 16 after blast; wrapped in plastic sheets kept in lab. covered with damp rags. BX cores specimens were drilled and prepared on April 21.*

Fig 14 - Working sheet for ultrasonic elastic constants determination.

DETERMINATION OF TRIAXIAL COMPRESSIVE STRENGTH OF THE ROCK SUBSTANCE

SCOPE

38. a. The purpose of this test is to establish the peak strength of cylindrical rock specimens under triaxial loading.

b. The test provides data useful in determining the strength properties of rock substance, namely peak shear strengths at various lateral pressures, coefficients of friction and cohesion intercepts.

c. The testing method makes no provision for pore pressure measurement, therefore the strength values determined are in terms of total stress.

d. All procedures for determining the rock substance's triaxial compressive strength are based on the appropriate ASTM standards (4).

APPARATUS

39. a. A suitable compression machine (Fig 15, 16 and 17) with sufficient capacity, capable of applying an axial load continuously at a constant rate and in such a way that failure will occur within five to fifteen minutes of loading. Alternatively, the applied stress rate should be within the limits of 20 psi/s (140 kPa/s) to 150 psi/s (1000 kPa/s).

b. A load-measuring device to indicate the applied load to an accuracy of 1%.

c. A pressure system of sufficient capacity to maintain the desired lateral pressure constant.

d. A triaxial compression cell in which the test specimen is enclosed in an impermeable flexible membrane and placed between two hardened platens, one of which is spherically seated. The platens, having a portion with a diameter the same as the specimen, should be made of tool steel hardened to at least a Rockwell hardness of C 30. The surfaces of the platens should be ground, and their flatness should be 0.0002 in. (0.005 mm). The apparatus consists of a high-pressure cylinder with overflow valve, a base, suitable entry parts for filling the cylinder with hydraulic oil and applying the lateral pressure, and of hoses, gauges and valves as needed. A piston is fitted into the cylinder through a high-pressure seal (Fig 18).

e. A deformation-measuring device, such as micrometer screws, dial micrometer or linear variable differential transformers to measure the movement of the piston (ie, axial deformation). The measuring device should be graduated to read in 0.0001 in. (0.0025 mm) units, and accurate to within 0.0001 in. (0.0025 mm) in any 0.001 in. (0.025 mm) range, and within 0.0002 in. (0.005 mm) in any 0.01 in. (0.25 mm) range.

f. A flexible membrane of suitable material to exclude the confining fluid from the specimen. It should be sufficiently long to extend well onto the platens and, when slightly stretched, should be of the same diameter as the rock

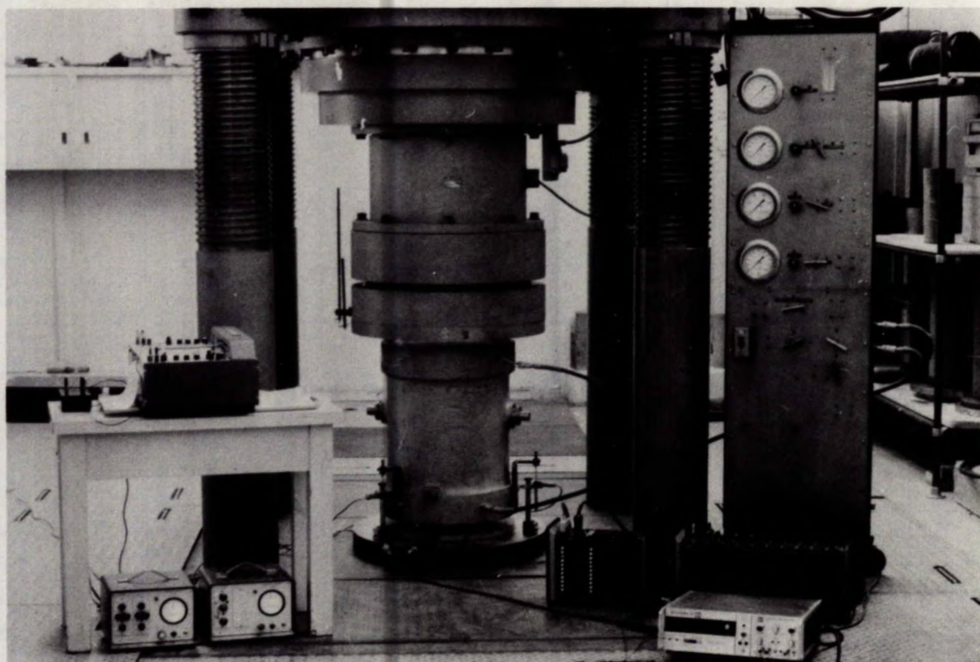


Fig 15 - High capacity testing machine; used at Elliot Lake Laboratory of CANMET to test up to 12 in. (30.5 cm) diameter specimens. The maximum capacity of the machine is 4×10^6 lb (17.8 MN).

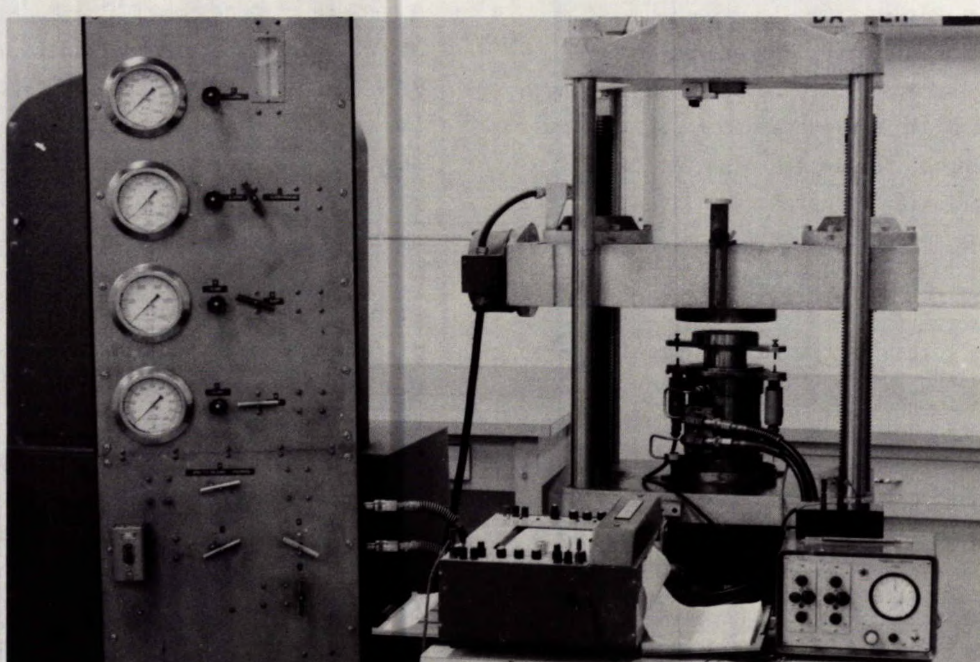


Fig 16 - Medium range capacity testing machine; used at Elliot Lake Laboratory of CANMET to test specimens with diameter up to NX core size. The maximum capacity of the machine is 120,000 lb (534 kN).

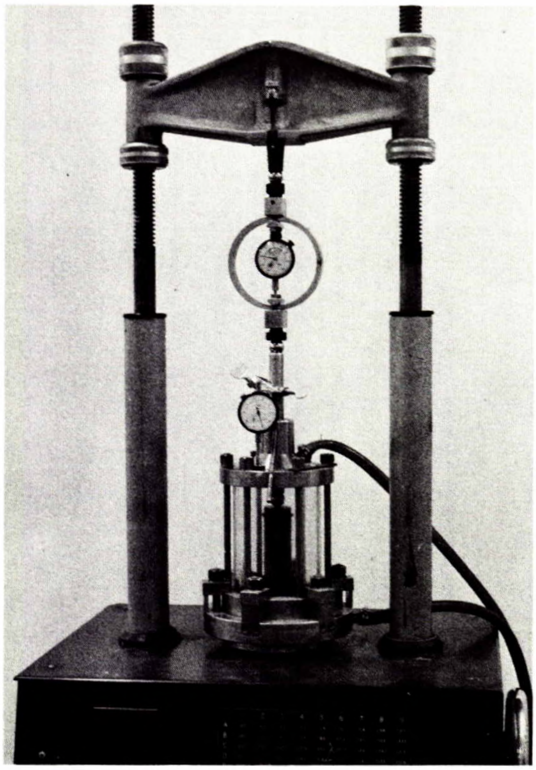


Fig 17 - Low capacity testing machine; used at Elliot Lake Laboratory of CANMET to test overburden and weak rock materials. The maximum capacity of the machine is 22,500 lb (100 kN).

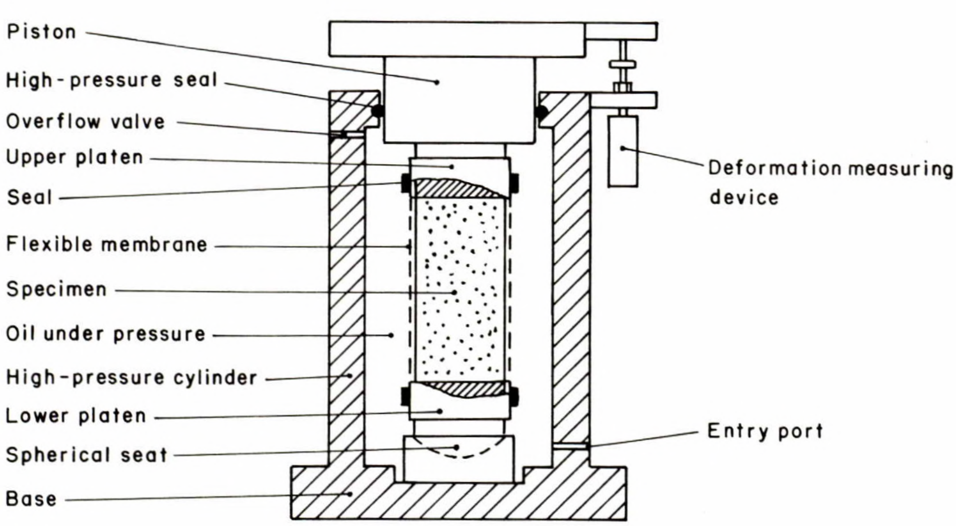


Fig 18 - Schematic cross-section of a triaxial cell; similar to the one shown in Fig 16.

specimen.

PREPARATION OF THE TEST SPECIMEN

40. a. The test specimen should be a straight circular cylinder having a length to diameter ratio of 2.0 to 2.5 and a diameter preferably not less than NX core size, approximately 2 1/8 in. (54 mm). The diameter of the specimen should be related to the size of the largest grain in the rock by a ratio of at least 10:1. The ends of the specimen should be parallel to each other and at right angles to the longitudinal axis.

b. Guidance for sample and specimen handling and storage, as well as the method of specimen preparation together with allowable tolerance specifications, is given in Supplement 3-5.

c. The diameter of the test specimen is measured to the nearest 0.005 in. (0.1 mm) by averaging two diameters measured at right angles to each other at about the upper height, mid height and lower height of the specimen. The average diameter is used for calculating the cross-sectional area. The height of the specimen is determined to the nearest 0.05 in. (1.0 mm).

d. The inclination of bedding or foliation, with respect to the specimen axis, is recorded.

e. The number of specimens tested is determined by practical considerations. It is considered good practice to make three tests of essentially identical specimens at three different confining pressures or single tests at nine different confining pressures covering the range investigated. The bare minimum is three specimens from each sample which are tested at three different confining pressures.

PROCEDURE

41. a. The specimen with the flexible membrane over it is placed between the lower and upper platens, and the seals above the membrane are installed around the platens (Fig 19). The whole assembly is then carefully centred and aligned within the high-pressure cylinder and the piston inserted.

b. The triaxial cell is centred on the loading platform of the compression machine, the deformation measuring device positioned and hydraulic pressure lines connected (Fig 20), and while the overflow valve is kept open, the cell is filled with oil.

c. A small axial load of approximately 25 lb (111 N) is applied to the piston by means of the loading device to properly seat the bearing parts of the assembly; then, after closing the overflow valve, an initial reading on the deformation device is taken.

d. The lateral fluid pressure is slowly raised to the predetermined test level and at the same time an axial load, sufficient to prevent the deformation measuring device from deviating off the initial reading, is applied. When the predetermined test level of fluid pressure is reached, the axial load registered by the loading device is recorded as the zero or starting load for the test.

e. The loading rate of the compression machine is set and the loading is started.

f. Axial load is applied continuously and without shock until the load becomes constant, or reduces, or a predetermined amount of axial strain is achieved. The predetermined confining pressure is maintained constant throughout the test.

g. The axial load readings, corresponding to each 0.005 in. (0.1 mm) axial deformation level, are recorded throughout the test together with time readings.

h. The axial load and the confining pressure are simultaneously and slowly released and the assembly is dismantled.

i. The flexible membrane is cut lengthwise and a sketch of the failed specimen and/or a note of the specimen failure characteristics is made.

j. A sample from the failed specimen is taken to establish the water content and degree of saturation according to the specifications given in Supplement 3-1.

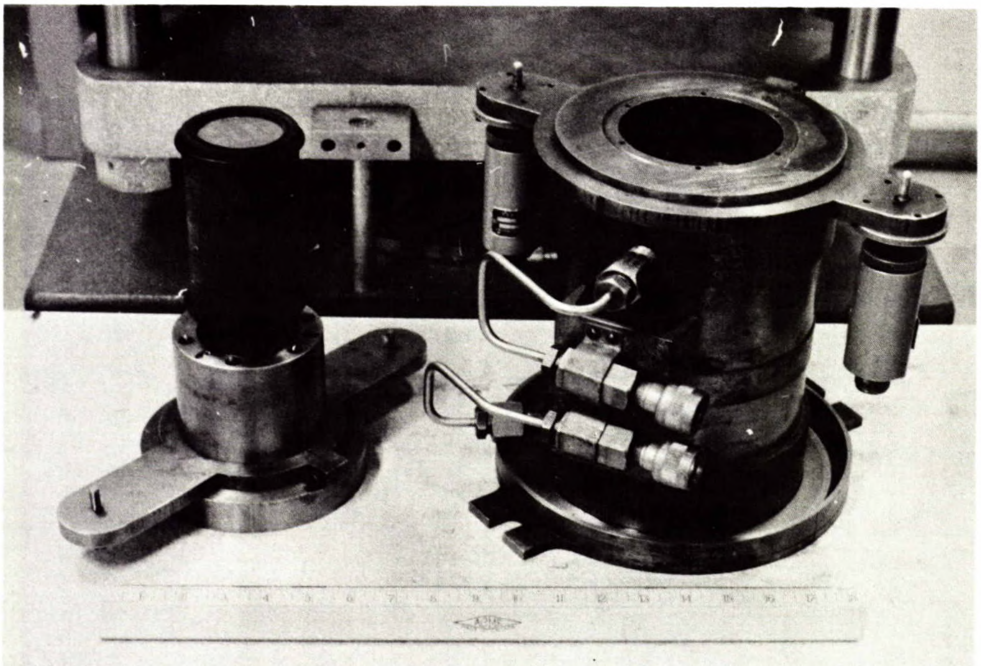


Fig 19 - Photograph of specimen with the flexible membrane around it; as placed on the piston ready for assembly. The high-pressure cylinder is shown on the right.

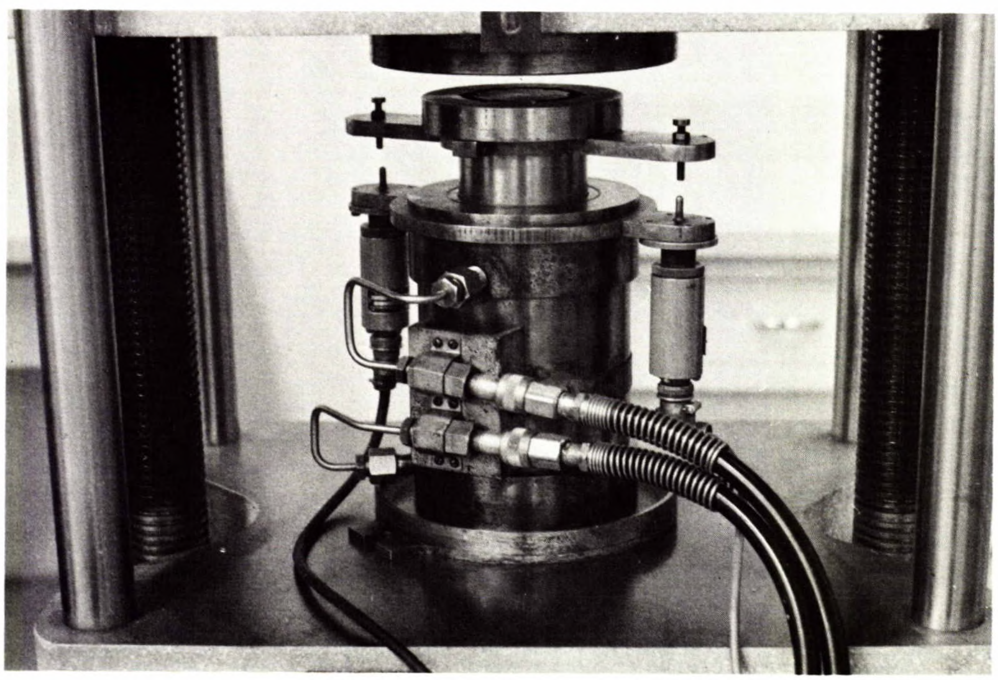


Fig 20 - Photograph of the assembled triaxial cell; positioned on the loading platform of the machine. The lead wires of the deformation measuring device and also the hydraulic pressure lines are connected.

CALCULATIONS

42. a. The axial strain, ε, is calculated at each deformation level as follows:

$$\varepsilon = \delta/L_0$$

where δ = axial deformation and
L_0 = height of the specimen.

b. The stress-difference, $(\sigma_1 - \sigma_3)$, is calculated at each deformation level as follows:

$$(\sigma_1 - \sigma_3) = P/A$$

where P = applied load corresponding to the deformation level (ie, measured load less the initial load due to the lateral pressure acting on the piston) and
A = cross-sectional area of the specimen.

c. The stress-difference versus axial strain curve is plotted for each test. The values of peak stressdifferences and the corresponding axial strains are established from these curves (Fig 21).

d. A Mohr's stress circle on an arithmetic plot, with shear stress as ordinate and normal stress as abscissa, corresponding to the peak stress-difference, is constructed for each test (Fig 22).

e. A best-fit smooth curve (the Mohr's envelope) tangent to the Mohr's circles is drawn. If the envelope is a straight line, the angle the line makes with the horizontal is reported as the

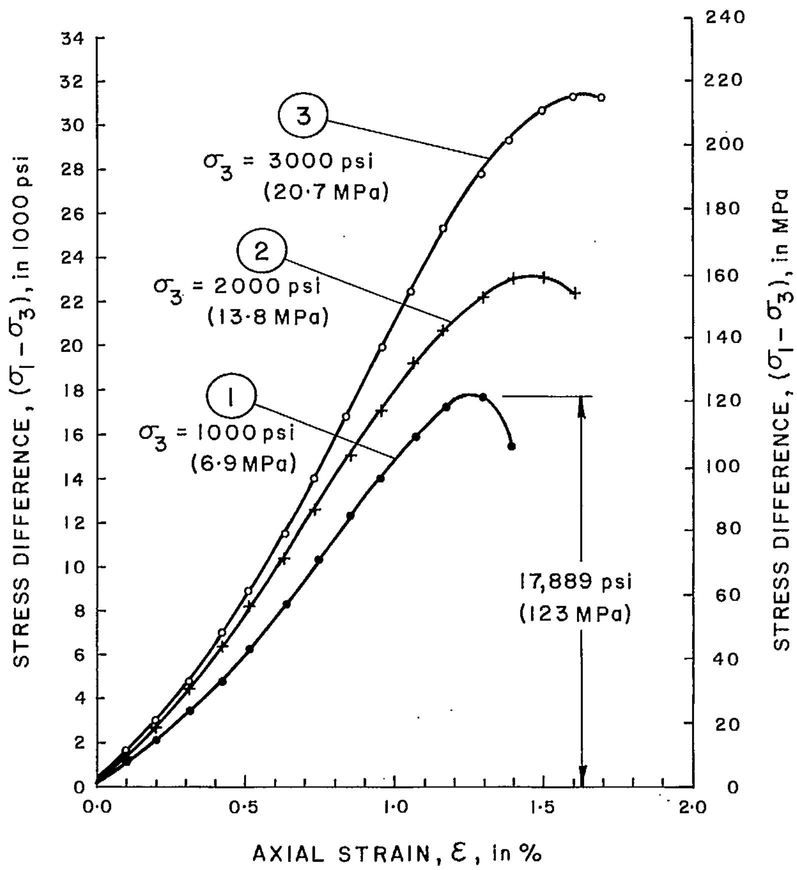


Fig 21 - Stress-strain curves corresponding to various lateral pressures.

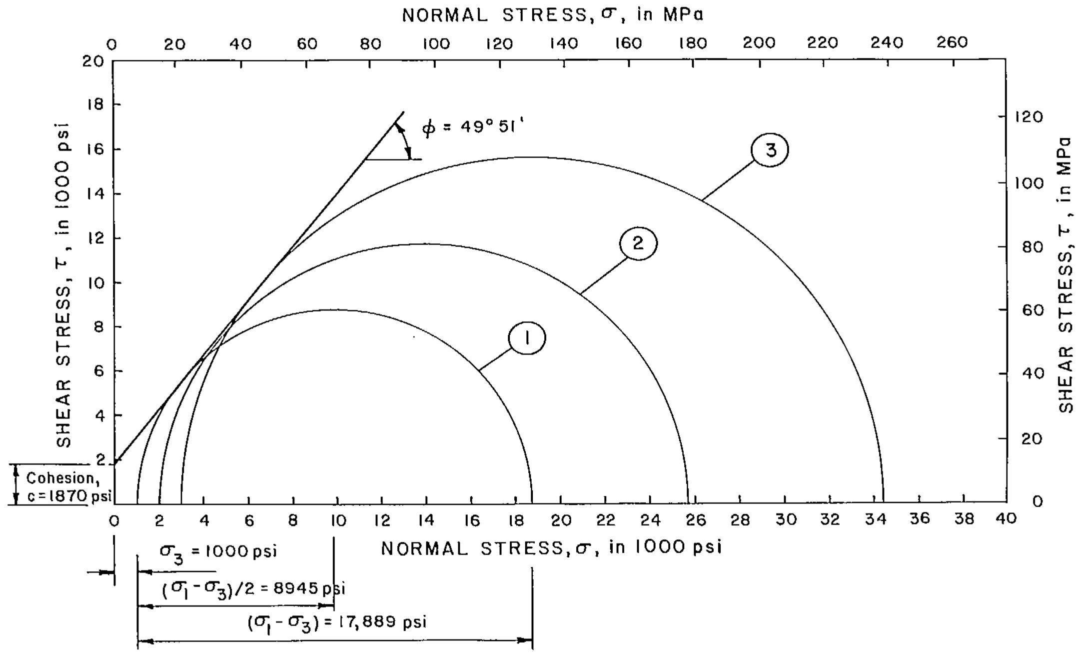


Fig 22 - Mohr's stress circles with the Mohr's envelope.

angle of friction, ϕ; the intercept of this line on the vertical axis is reported as the cohesion intercept, c, (Fig 22). If the envelope is not a straight line, values of ϕ should be determined by constructing a tangent to the Mohr's circle for each confining stress at the point of contact with the envelope and the corresponding cohesion intercepts noted.

REPORTING OF RESULTS

43. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. stress-difference versus axial strain curves (Fig 21)
c. Mohr's stress circles, angle of friction and cohesion intercept (Fig 22)
d. specimen diameter and height
e. average water content and average degree of saturation of the specimens
f. storage and environmental history of the sample
g. method and date of specimen preparation and storage history of specimens
h. information on testing such as: date, type of testing apparatus and test rate
i. any other observations or available physical data.

44. In addition, the report should include in convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. specimen diameter, height and cross-sectional area
c. orientation of the specimen axis with respect to anisotropy, (eg, with respect to bedding plane, foliation, etc)
d. test duration
e. water content and degree of saturation
f. confining pressure
g. peak strength and strain
h. descriptive notes on the failure characteristics, such as shape and mode of failure and number of fragments. The use of terms included in paragraph 14 g. is recommended to describe the failure characteristics of a specimen

i. any other observation related to the specimen.

45. Alternatively the working sheets of the tests (Fig 23) could be substituted for the report requirements specified under paragraph 44.

TRIAXIAL TEST

Sample *foot - wall sandstone with angular sandgraines of 0.5 mm size*

Location

Bore Hole *16* Depth *between 26-34 ft.*

Sample No *16 - S*

Date *July 12, 1969*

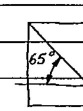
Tested by *W. G.*

Cell pressure *1000* psi (*6.9* MPa)

Water content *1.6* %

Degree of saturation *72.3* %

Specimen No *1*

Elapsed Time, min	Axial deform., 0.001 in.	Strain, ε	Load, P lb	$(\sigma_1 - \sigma_3)$, psi	Notes
	0		9,800		Cell pressure applied
0	0	0	9,800	0	Loading rate set at
	5	.0011	13,300	1026	~ 75 psi/s
0.5	10	.0021	17,800	2346	
1.0	15	.0032	22,300	3666	failed specimen
	20	.0043	26,800	4985	
1.5	25	.0053	30,800	6158	
2.0	30	.0064	38,300	8651	
2.5	35	.0074	46,300	10,704	
3.0	40	.0085	53,300	12,757	non-graded texture,
	45	.0096	58,800	14,370	no foliation
4.0	50	.0106	63,800	15,982	
4.5	55	.0117	68,800	17,302	failure characteristics:
5.0	60	.0128	70,800	17,889	shape : diagonal
5.5	65	.0138	62,800	15,543	mode : quiet
					fragment: less than
					three

Diameter : *2.085* in. (*53.0* mm)

Height, L : *4.70* in. (*119* mm) Area, A : *3.41* in^2 (*22.1* cm^2)

Peak Strength : *17,889* psi (*129* MPa) Peak Strain : *1.28* %

Remarks:

NX core samples, collected on June 18, were wrapped in plastic bags, specimens were prepared according to standard specification and kept in humid box, individually wrapped in plastic, until test.

Fig 23 - Working sheet for determination of triaxial compression strength of rock substance.

DETERMINATION OF RESIDUAL ANGLE OF FRICTION

SCOPE

46. a. The purpose of this test is to establish the shear strength of rock specimens along a saw-cut plane under direct shear test conditions.

b. The test provides data useful in determining the residual strength properties of rock substance, namely shear strength on the saw-cut plane at various normal pressures and the residual angle of friction of the saw-cut plane.

c. The test is used either to complement the triaxial tests of rock substance which provide data relating only to the peak strength properties of the rock, or to check the residual angle of friction of a natural discontinuity of rock, which is obtained by calculation from direct shear tests on the natural discontinuity.

d. The test is usually performed on cylindrical specimens with the saw-cut plane oriented at an angle which suits the purpose of the test. If the test is intended to complement a triaxial test, the saw-cut plane is oriented at the failure angle of the triaxial test specimen. If the purpose of the test is to check the calculated residual angle of friction of a natural discontinuity, the saw-cut plane is oriented at the angle parallel to the plane of natural discontinuity. Obviously, the test specimens should be prepared from the same sample (core or block) as the test specimen containing the natural discontinuity. The test method, however, is equally suitable to test specimens of irregular shapes.

APPARATUS

47. a. A shear device, consisting of a box made of two frames, to hold the two halves of the specimen. One of the frames, usually the lower, is stationary, while the other is moveable along a horizontal plane. The two halves of the specimen are positioned and secured (by the method described in Supplement 3-5) within each frame in such a way that the plane of the saw-cut coincides with the plane of the frame movement. The shear device is provided with a means of applying normal force to the plane of the saw-cut and for measuring displacement in a direction normal to the plane. The device is also capable of applying a shearing force along the plane of the saw-cut, and of measuring the displacement in the direction of the shearing force. The frames that hold the specimen should be sufficiently rigid to prevent their distortion during shearing. The various parts of the shear device should be made of material not subject to corrosion by the water which is applied to the saw-cut surfaces (in cases when the effect of the water on the shear strength is considered). The principal features of the shearing device are schematically shown in Fig 24

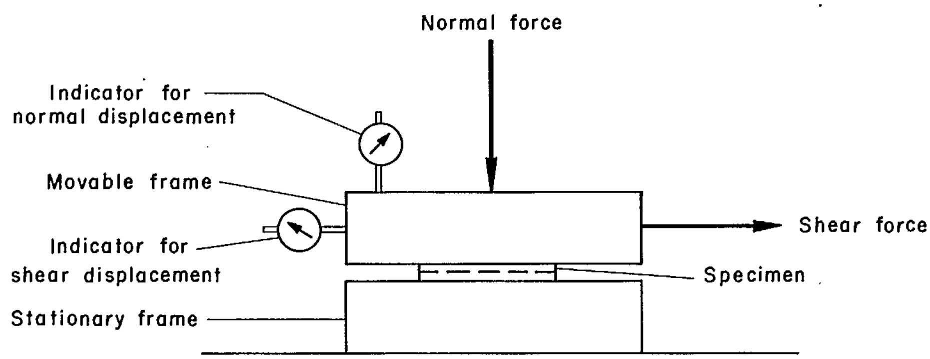


Fig 24 - Principal features of the shearing device.

while the photographs in Fig 25 show a commonly used portable device.

b. A device for applying the normal force such as a hand-operated hydraulic pump or mechanical loading system with or without hydraulic features. This device will be capable of applying the specified force quickly but without exceeding it, and be capable of maintaining it with an accuracy of 1% for the duration of the test. Dead weights are recommended in test cases when low normal forces are required (Fig 26).

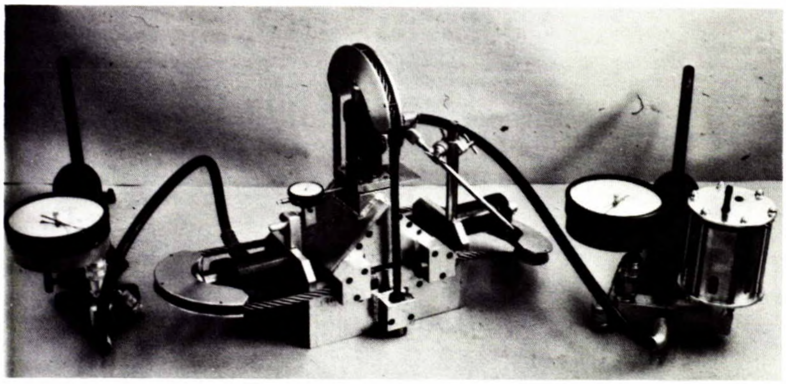
c. A device for applying the shear force. This device should be capable of shearing the specimen at a uniform rate of displacement, with less than 10 per cent deviation, and permitting adjustment of the rate of displacement over a relatively wide range. The rate is usually maintained with a motor - and gear-box arrangement or with a hydraulic system, with or without mechanical features. The device should also be capable of applying the shear force in two directions so that the test procedure can be repeated in the reverse direction after the specimen is sheared in one direction. The shear force is determined by a load indicating device such as a proving ring or load cell with electronic read-out features, or a hydraulic dial gauge. The shear force can be applied by a hand screw via a proving ring in test cases of low normal force (Fig 26).

d. A displacement indicator, to measure the displacement in the direction of the normal force, and having a sensitivity of 0.001 in. (0.02 mm). Actually, the underlying requirement of the testing method is zero displacement in the direction of the normal force, consequently, no significant normal displacement should occur if the two halves of the specimen are properly positioned and secured in the shear device. Therefore, the displacement indicator is used mainly to check that proper alignment has been achieved.

e. A displacement indicator, to measure the shear displacement with a sensitivity of 0.001 in. (0.02 mm) and capable of measuring up to 2 in. (50 mm) total displacement.

PREPARATION OF THE TEST SPECIMEN

48. a. The test specimen should be a straight circular cylinder having a length and a diameter large enough so that the saw-cut plane, which is oriented at an angle required by the specific purpose of the test stated in paragraph 46 d., would have an approximate area of 6 in.^{2} (39 cm^2) and be of an elongated shape with a length of approximately 3 in. (7.5 cm) and a width of approximately 2 in. (5 cm). Similar dimensions of the saw-cut plane are recommended for specimens of irregular shape.



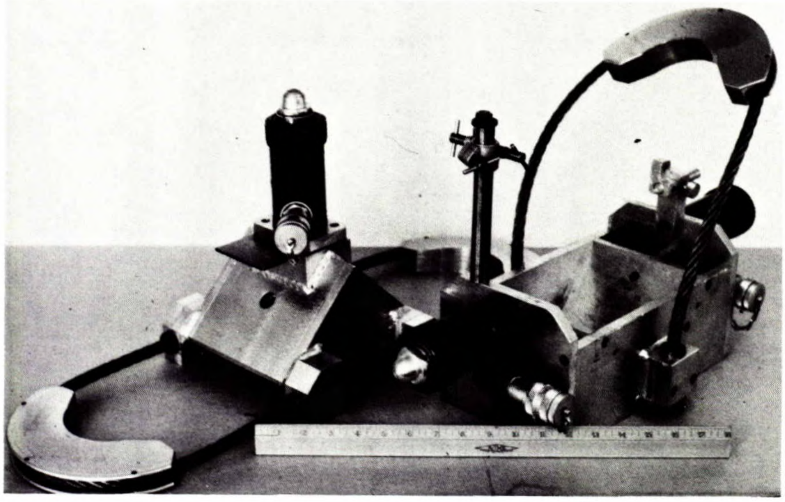
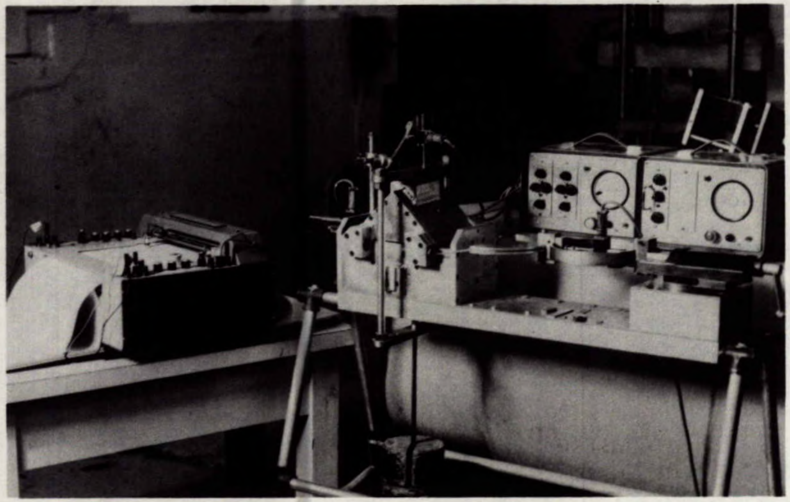


Fig 25 - Photographs of a commonly used portable shearing device (manufactured by Robertson Research Mineral Technology Limited, Wales): (a) assembled for testing; (b) the two frames of the shear device.

b. Guidance for sample and specimen handling and storage as well as specimen preparation and cutting is given in Supplement 3-5.

c. The area of the saw-cut plane is established. In the case of drill core specimens, the dimensions of the saw-cut plane (rectangle, ellipse or combination of the two) are measured to the nearest 0.01 in. (0.2 mm) and the area is calculated. It is somewhat more difficult to establish the area if the saw-cut plane has an irregular shape. In this case, for example, the method of approximate integration can be used (eg, by covering the area with a transparent square grid).

d. The following information is recorded: orientation of the specimen axis with respect to anisotropy, orientation of the saw-cut plane with respect to specimen axis, orientation of anisotropy with respect to the longitudinal axis of the saw-cut plane, and direction of shear displacement of the moving half of the specimen with respect to the other half and with respect to the anisotropy of the saw-cut plane.



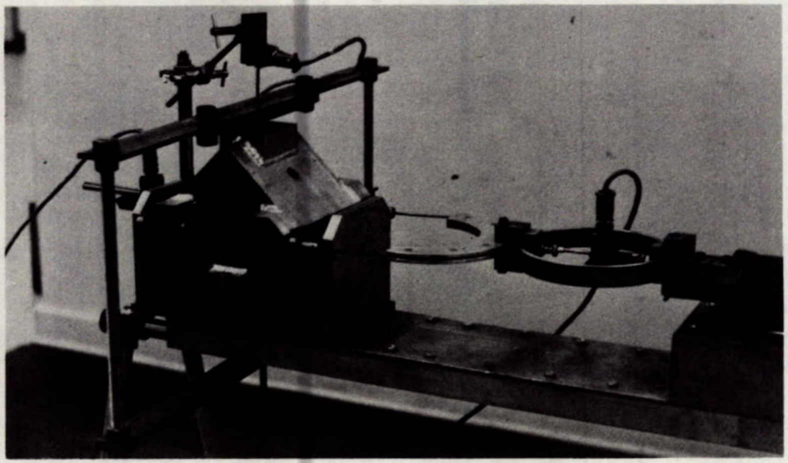


Fig 26 - Direct shear test arrangement in case of low normal force application: (a) normal force is supplied by dead weight; (b) shear force is applied by a hand screw via a proving ring.

e. The two halves of the specimen are positioned and moulded into the moulding forms suitable for the frames of the shear device (Fig 27). The procedure for moulding is given in Supplement 3-5.

f. The number of specimens tested is determined by practical considerations. It is considered good practice to test, within each sample, a total of nine essentially identical specimens at three different normal forces or to test single specimens at nine different normal forces. The bare minimum is three specimens for each sample; each specimen is tested at two different normal forces.

PROCEDURE

49. a. The shear device, with the specimen properly positioned within the frames, is assembled, proper care being taken that the two halves of the specimen coincide perfectly.

b. The normal displacement measuring device is positioned and the reading recorded.

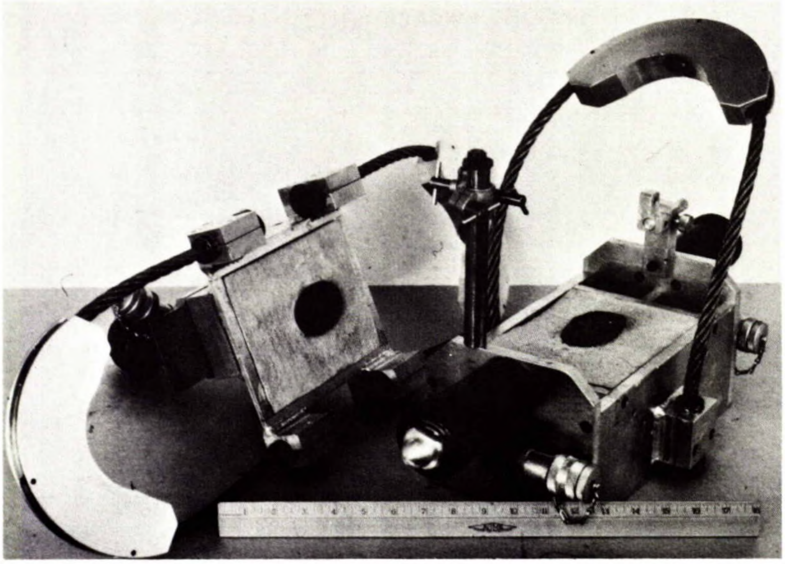


Fig 27 - Photograph shows the two halves of the specimen within the moulded grout material.

c. The normal force, equivalent to the predetermined normal stress, is applied and the reading on the normal displacement device is taken as the zero reading.

d. The shear displacement measuring device is positioned and zero readings of both the shear displacement and shear force are read.

e. The shear displacement is started and continued at a rate of between 0.1 in./min (2.5 mm/min) and 0.3 in./min (7.5 mm/min) until a total displacement of a maximum of 1/3 of the length of the saw-cut plane is reached. Normal displacement, shear displacement and shear force readings are taken at intervals approximately equal to 10% of the total displacement.

f. After the required total displacement is reached and without removing the normal load, the shear force mechanism is reversed and the procedure is repeated in the reverse direction.

g. The elapsed time of the shearing (both forward and reverse) is recorded separately.

50. a. The test assembly is completely dismantled and the specimen with its moulding is removed from the frames after completion of the reverse shearing.

b. Notes on the after-shear conditions of the saw-cut plane are made.

CALCULATIONS

51. a. A graph of shear displacement versus shear force is plotted for each test run (Fig 28).

b. The shear resistance forces, S'_r and S''_r, are established from these graphs

where S'_r = the average shear resistance force of the forward shearing test run, corresponding to the region of over 50% of the total displacement and

S''_r = the average shear resistance force of the reverse shearing test run, corresponding to the region of over 50% of the total displacement.

c. The values of the residual shear stresses are calculated as follows:

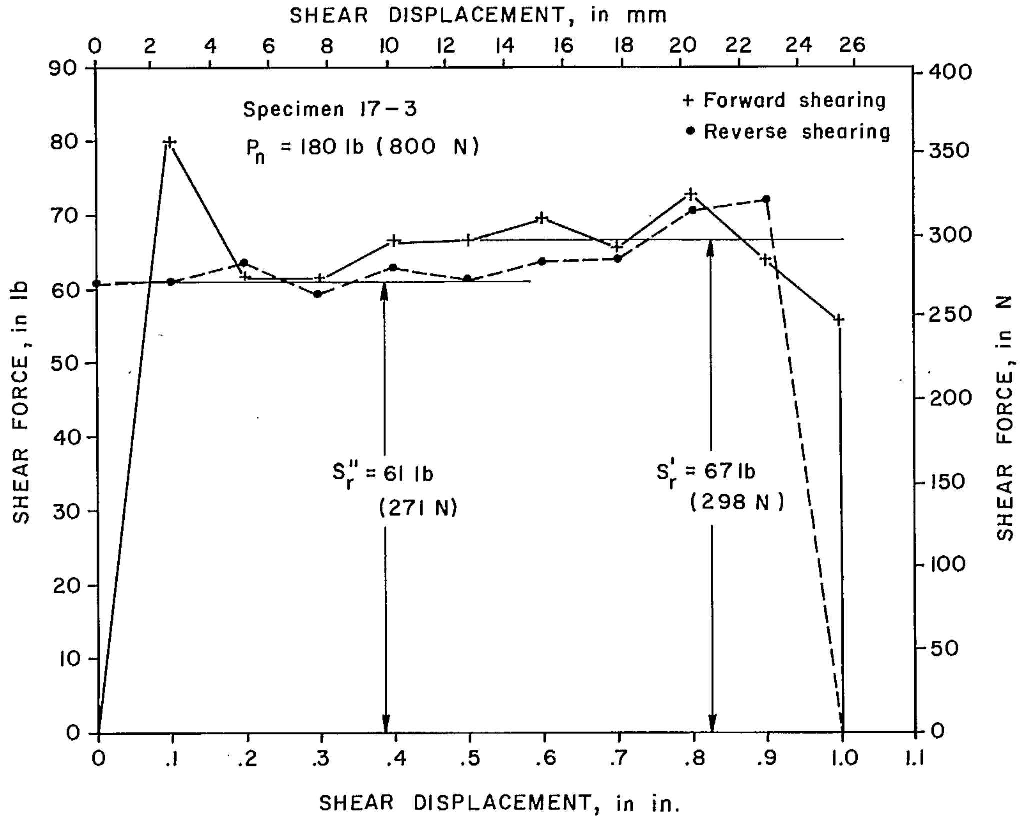


Fig 28 - Graphs of shear displacement vs shear force.

Residual shear stress, $\tau_r = S_r/A$

where $S_r = (S_r' + S_r'')/2$

d. The normal stress is calculated as follows:

Normal stress, $\sigma_n = P_n/A$

where P_n = applied normal force and
A = area of shear surface.

e. A graph of normal stress versus residual shear stress is plotted (Fig 29).

f. A best-fit straight line, starting from the origin, is drawn to the plotted points and the angle the line makes with the horizontal is reported as the residual angle of friction, ϕ_r, (Fig 29).

REPORTING OF RESULTS

52. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. petrological description of the sample
c. graph of normal stress versus residual shear stress and residual angle of friction (Fig 29)
d. storage and environmental history of the sample
e. method and date of specimen preparation and grout material used
f. information on testing such as: dry surface, wet surface
g. any other observation or available physical data.

53. In addition, the report should include in

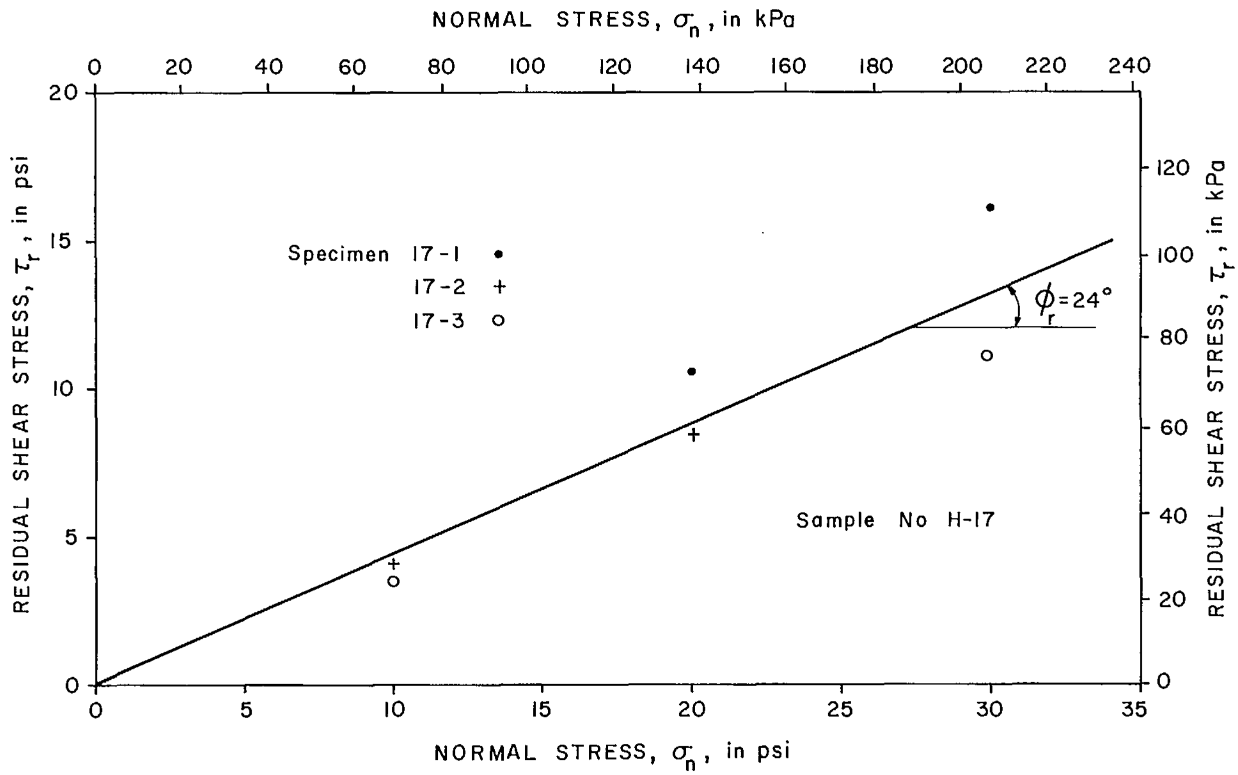


Fig 29 - Graph of normal stress vs residual shear stress.

convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. dimensions of the saw-cut shear surface (length, width, area)
c. orientation of the specimen's axis with respect to anisotropy (eg, with respect to bedding plane, foliation, etc)
d. orientation of the saw-cut plane with respect to the axis of the specimen
e. orientation of the longitudinal axis of the saw-cut plane with respect to anisotropy (eg, with respect to bedding, foliation, etc)
f. direction of the shear displacement of the moving half of the specimen with respect to the other half of the specimen and with respect to the anisotropy of the saw-cut plane
g. test condition (ie, dry surface, wet surface)
h. test duration
i. residual shear stress with the corresponding normal stress
j. notes on the after-shear condition of the saw-cut plane
k. any other observation related to the specimen, such as excessive normal displacement that might invalidate the test results.

54. Alternatively, the working sheets of the tests (Fig 30) accompanied by the shear displacement versus shear force graphs (Fig 28) could be substituted for the report requirements specified under paragraph 53.

DIRECT SHEAR TEST

Sample *quartz - chlorite gneiss of the hanging wall*

Location *section H-150*

Bore Hole *17* Depth *7'-0" to 11'-3"*

Sample No *H-17*

Date *Nov. 21, 1974*

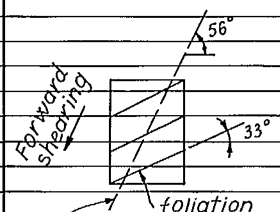
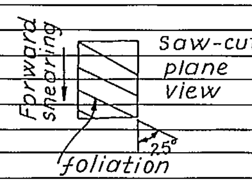
Tested by *W.G.*

Proving ring *0.25* lb/div

Normal load *180* lb (*800* N)

Test condition *dry surface*

Specimen No *17-3*

Elapsed time, min.	Normal displacement Readings	Normal displacement displacement	Shear displacement Readings	Shear displacement displacement	Shearing force Readings div.	Shearing force lb	Notes
	0.001 in.		0.001 in.				
	276						*Normal load applied.*
	269						
Forward shearing	269	0	0	0	0	0	
	269	0	910	90	320	80	
	269	0	795	205	248	62	
	268	-1	702	298	248	62	
	267	-2	605	395	264	66	
	265	-4	501	499	264	66	
	264	-5	406	594	276	69	
	263	-6	298	702	248	66	
	262	-7	195	805	288	72	
	261	-8	108	892	256	64	
5.5	260	-9	10	990	224	56	
	260	0	15	985	0	0	
Reverse shearing	260	0	108	892	288	72	
	259	-1	195	805	276	69	
	259	-1	310	690	256	64	
	258	-2	403	597	256	64	
	258	-2	516	484	244	61	
	256	-4	595	405	252	63	
	255	-5	689	311	236	59	
	254	-6	803	197	256	64	
	253	-7	910	90	244	61	*Some rock powder*
6.25	252	-8	1000	0	240	60	*on the saw-cut*
	252	-8	1000	0	0	0	*surface after test.*

Saw-cut plane, length : *2.98* in. (*75.6* mm); width : *2.03* in. (*51.6* mm)
area, A = *6.0* in^2 (*39.0* cm^2)

Normal stress, $\sigma_n = \frac{P_n}{A} = \frac{180}{6.0} = 30.0$ psi (*207* kPa)

$S_r' =$ *67* lb (*298* N) $S_r'' =$ *61* lb (*271* N) $S_r =$ *64* lb (*285* N)

Residual shear stress, $\tau_r = \frac{S_r}{A} = \frac{64}{6.0} = 10.7$ psi (*74* kPa)

Remarks: *NX core samples were collected on Nov. 5 ; samples were wrapped in plastic bags and kept in lab. until specimen preparation; Specimens were prepared and the saw-cut made on Nov. 15 ; the moulding was done on Nov. 16.*

Fig 30 - Working sheet for determination of residual angle of friction.

DETERMINATION OF STRENGTH PROPERTIES OF ROCK DISCONTINUITIES BY DIRECT SHEAR TEST

SCOPE

55. a. The purpose of this test is to establish the shear strength of the natural discontinuities of rock, such as joints, fractures or bedding planes.

b. The test provides data useful in determining the strength properties of the natural discontinuities, namely shear strength on the plane at various normal pressures, the geometrical component of the shear strength which results from the interlocking of surface irregularities, and the frictional component of the shear strength due to the sliding of two surfaces.

c. The test can be performed on a rock specimen of either irregular or cylindrical shape containing the particular discontinuity.

APPARATUS

56. a. A shear device consisting of a box made of two frames to hold the two halves of the specimen which is separated by the plane of discontinuity. One of the frames, usually the lower, is stationary, while the other is moveable along a horizontal plane. The two halves of the specimen are positioned and secured within the two frames in such a way that the plane of discontinuity coincides with the plane of the frame movement. The shear device is provided with means for applying normal force to the plane of the discontinuity, and for measuring displacement in the direction normal to the plane. The device is also capable of applying a shearing force along the plane of discontinuity, and of measuring displacement in the direction of the shearing force. The frames that hold the specimen should be sufficiently rigid to prevent their distortion during shearing. The various parts of the shear device should be made of material not subject to corrosion by the water applied to the surfaces of the discontinuity (in cases where the effect of the water on the shear strength is considered). The principal features of the shearing device are schematically shown in Fig 24. Figure 25 shows a commonly used portable shear device.

b. A device for applying the normal force, such as a hand-operated hydraulic pump or other loading system with or without hydraulic features. The device should be capable of applying the specified force quickly, without exceeding it, and be capable of maintaining it with an accuracy of 1% for the duration of the test.

c. A device for applying the shear force, capable of shearing the specimen at a uniform rate of displacement, with less than 10 per cent deviation, which should permit adjustment of the rate of displacement over a relatively wide range. The rate is usually maintained with a motor- and gear-box arrangement (Fig 32) or with an hydraulic system, with or without mechanical features. The device should be capable of applying the shear force in two directions, so that after the specimen is sheared in one direction, the test procedure can be repeated in the reverse direction. The shear force is determined by a load-indicating device, such as a proving ring or hydraulic dial gauge. It is convenient to use a load cell with electronic transducers to facilitate automated data recording (Fig 31).

d. A displacement indicator such as dial gauges, to measure the displacement in the direction normal to the plane of discontinuity with a sensitivity of 0.001 in. (0.02 mm). Automated data recording is achieved by using measuring devices of the electronic transducer type, such as differential transformers, (Fig 26 and Fig 31).

e. A displacement indicator, to measure the shear displacement with a sensitivity of 0.001 in. (0.02 mm) and capable of measuring over a relatively large total displacement. An electronic transducer type of measuring device, such as differential transformers, is used to automate the data recording (Fig 26 and Fig 31).

f. An automatic data recording system, such as two XY recorder units or a XY_1Y_2 unit, to record shear displacement versus shear force and shear displacement versus normal displacement graphs (Fig 31, 32).

PREPARATION OF THE TEST SPECIMEN

57. a. The shape of the test specimen can be either cylindrical or irregular, approximately halved by the particular discontinuity being tested. The specimen size should be large enough so that a firm grip is achieved within the frame of the shear device, by means of the grout material used in the moulding process. At the same time it should be small enough so that the space along the sides of the mould left for the grout is about the same all-around; if necessary the excess rock is cut off. The shear surface should have a shape elongated in the shearing direction with an approximate length-to-width ratio of 3 to 2. The area of shear surface should be at least 6 in.^{2} (39 cm^2). The maximum size of the shear surface is obviously limited by the dimension of the shear box and by the load capacity of the shear device.

b. Guidance for sample and specimen handling and

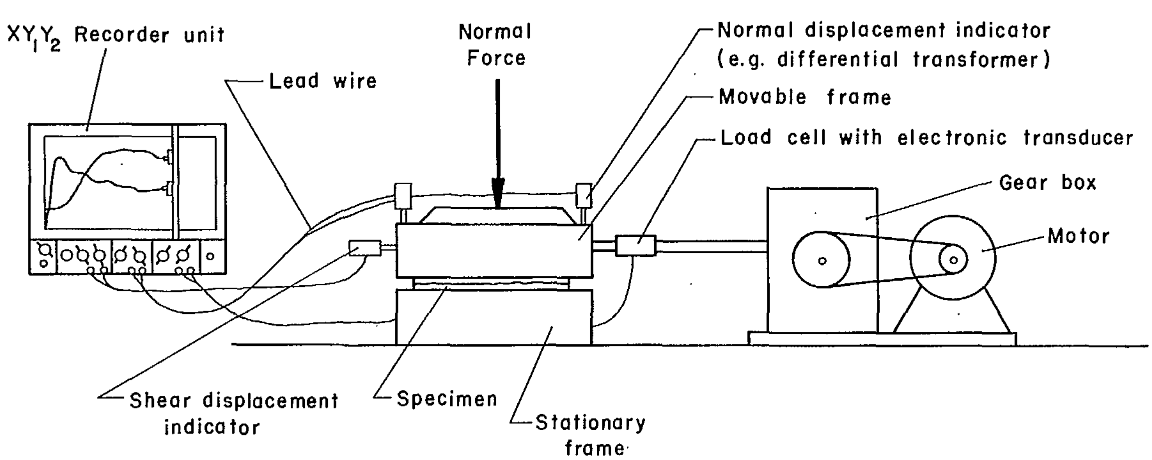


Fig 31 - Schematic arrangement of direct shear test with automated data recording system.

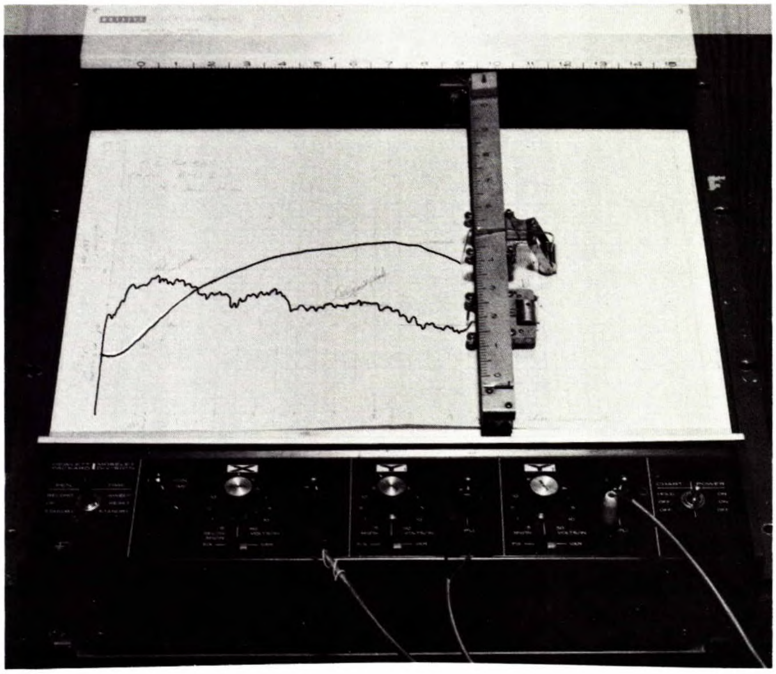


Fig 32 - Photograph of a XY_1Y_2 recorder unit with the recorded graphs.

storage as well as specimen preparation and cutting is given in Supplement 3-5.

c. The area of shear surface is measured. This is a relatively simple matter in the case of drill core specimens with a well defined fracture or joint plane. However, it is more difficult to establish the shear surface between the halves of an irregular specimen. Consequently, good judgement coupled with ingenuity is required to devise a method best suited for a given case of establishing the shear surface area. One possible method is to insert a sheet of carbon paper facing a sheet of white paper between the two halves of the specimen and to establish by approximate integration the area of imprint when the two halves are slightly pressed together.

d. Detailed information of the specimen and of the discontinuity plane are recorded, including: petrographic description of the specimen, type of discontinuity, description of infilling material, signs of previous displacements, weathering condition of the shear surfaces and/or infilling material and notes on their hardness, on the dimension and surface characteristics of the roughness features on the direction of shearing with respect to the roughness features and with respect to the previous displacement and qualitative remarks regarding the shear surface.

e. The two halves of the specimen are positioned and moulded into the moulding forms suitable for the frames of the shear device (Fig 27). The procedure for moulding is given in Supplement 3-5.

f. The number of specimens tested within a sample is determined by practical considerations. It is considered good practice to test three specimens containing essentially the same discontinuity at each of three different normal forces, or to test nine specimens at nine different normal forces. The bare minimum is three specimens of each sample which are tested at the same normal force.

PROCEDURE

58\. a. The shear device, with the specimen inside the frames, is assembled, care being taken that the natural contact along the plane of discontinuity between the two halves of the specimen, is reproduced.

b. The normal force, equivalent to the predetermined normal stress, is applied.

c. The shear force mechanism is connected, displacement devices positioned and electrical connections made between the load and displacement transducers and the recorders.

d. The proper recording scales, based on the estimated peak shear force and estimated total shear and normal displacement, are selected to suit the dimensions of the graph paper; the corresponding recorder outputs are then set to these scales. The recorder pens are placed into zero positions.

e. The shear displacement is started and continued at a rate of between 0.1 in./min (2.5 mm/min) and 0.3 in./min (7.5 mm/min) until a total displacement of approximately 1/3 of the lengthwise dimension of the shear surface is reached. Graphs of the developed shear force and of the normal displacement as functions of the shear displacement are continuously recorded (Fig 33).

f. The shear force mechanism is reversed and the procedure repeated in the reverse direction after the required total displacement is reached without removing the normal force. It

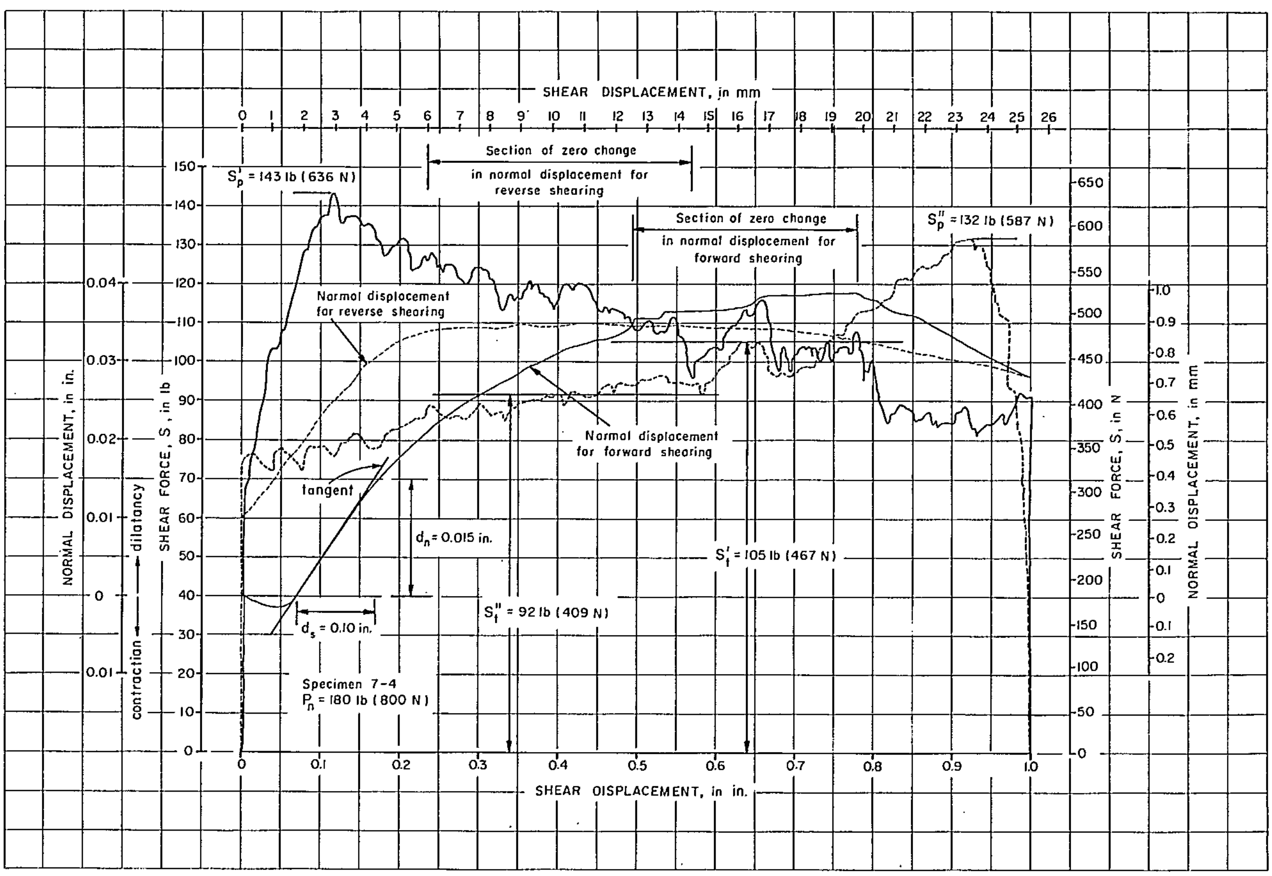


Fig 33 - Graphs of shear force and of normal displacement as the function of the shear displacement.

is recommended that graphs corresponding to the reverse movement be recorded with a second set of recording pens filled with ink of a different colour.

g. The elapsed time of shearing (both forward and reverse) is recorded separately.

CALCULATIONS

59. a. The recorded graphs are analyzed and evaluated after providing the axis with the proper scales (Fig 33).

b. The peak shear force values, S_p' and S_p'', which refer respectively to the highest shear force reached during forward and reverse shearing, are established, together with their corresponding shear displacement.

c. The average values of the residual shear resistance forces, S_r' and S_r'', corresponding to those sections of the shear displacement where the dilatancy becomes virtually zero (ie, approximately zero change in the normal displacement) for both the forward and the reverse shearing, are established (Fig 33).

d. A tangent line is drawn to the rising leg of the normal displacement versus shear displacement graph and the normal and shear components, d_n and d_s, of this line are established.

e. The peak shear stress is calculated as follows:

$$\text{Peak shear stress, } \tau_p = S_p/A$$

where $S_p = (S_p' + S_p'')/2$,
A = area of shear surface,
S_p' = highest shear force reached during the forward shear and
S_p'' = highest shear force reached during the reverse shear.

f. The residual shear stress is calculated as follows:

$$\text{Residual shear stress, } \tau_r = S_t/A$$

where $S_r = (S_r' + S_r'')/2$,
A = area of shear surface,
S_r' = average value of the residual shear resistance force of the forward shearing test run, corresponding to the section of the shear displacement where the change in normal displacement is approximately zero,
S_r'' = average value of the residual shear resistance force of the reverse shearing test run, corresponding to the section of the shear displacement where the change in normal displacement is approximately zero.

g. The normal stress is calculated as follows:

$$\text{Normal stress, } \sigma_n = P_n/A$$

where P_n = the applied normal force and
A = area of shear surface.

h. The effective dilatancy, d, is obtained by:

$$d = \text{arc tan } (d_n/d_s)$$

where d_n = normal component of the tangent line drawn to the rising leg of the normal displacement versus shear displacement graph and
d_s = shear component of the tangent line drawn to the rising leg of normal displacement versus shear displacement graph.

i. The ratio of τ_p/σ_n is formed and then the peak angle of friction is calculated as follows:

$$\text{Peak friction angle, } \phi_p = \text{arc tan } (\tau_p/\sigma_n)$$

j. Subtraction of the effective dilatancy d, from the peak angle of friction results in the basic friction angle, ϕ_b, that is:

$$\text{Basic friction angle, } \phi_b = \phi_p - d$$

k. The ratio of τ_t/σ_n is formed and then the residual angle of friction is calculated as follows:

Residual angle of friction,

$$\phi_r = \text{arc tan } (\tau_t/\sigma_n)$$

60\. a. The mathematical averages of the values obtained for the individual specimens are reported as the peak angle of friction, the basic friction angle and the residual angle of friction of the sample tested (Fig 34).

b. Alternatively, the peak shearing stresses and residual shearing stresses versus normal stresses are plotted. Best-fit straight lines are drawn from the origin to both sets of data (Fig 35). The slope angle of the lines are established and respectively reported as the peak angle of friction and as the residual angle of friction of the sample tested.

REPORTING OF RESULTS

61\. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. petrographic description of the sample
c. the angles of friction (ie, peak, residual and basic) are presented either in tabulated form (Fig 34) or in graph form (Fig 35)
d. storage and environmental history of the sample
e. method and date of specimen preparation, moulding material used
f. information on testing such as: date, type of testing apparatus, rate of displacement, testing condition (ie, dry surface, wet surface)

DIRECT SHEAR TEST OF DISCONTINUITY

Sample No H-12

Specimen	σ_n psi	τ_p psi	τ_p/σ_n	ϕ_p deg.	i_e deg.	ϕ_c deg.	τ_r psi	τ_r/σ_n	ϕ_r deg.
4-1	10	6.9	0.690	34.6	14.0	20.6	3.6	0.360	19.8
4-2	20	16.2	0.810	39.0	9.0	30.0	11.9	0.595	30.8
4-3	30	23.3	0.777	37.8	5.0	32.8	19.1	0.637	32.5
5-1	10	9.4	0.940	43.2	11.5	31.7	6.1	0.610	31.4
5-2	20	19.5	0.975	44.3	20.0	33.0	11.3	0.565	29.5
5-3	30	25.8	0.860	40.7	9.5	31.2	17.7	0.590	30.5
7-4	10	8.0	0.800	38.7	4.0	34.7	6.8	0.680	34.2
7-5	20	15.5	0.775	37.8	5.0	32.8	13.4	0.670	33.8
7-6	30	23.3	0.777	37.8	8.5	29.3	16.7	0.557	29.1
average	values			39.3		30.7			30.2

Fig 34 - Presentation of the test results in tabulated form.

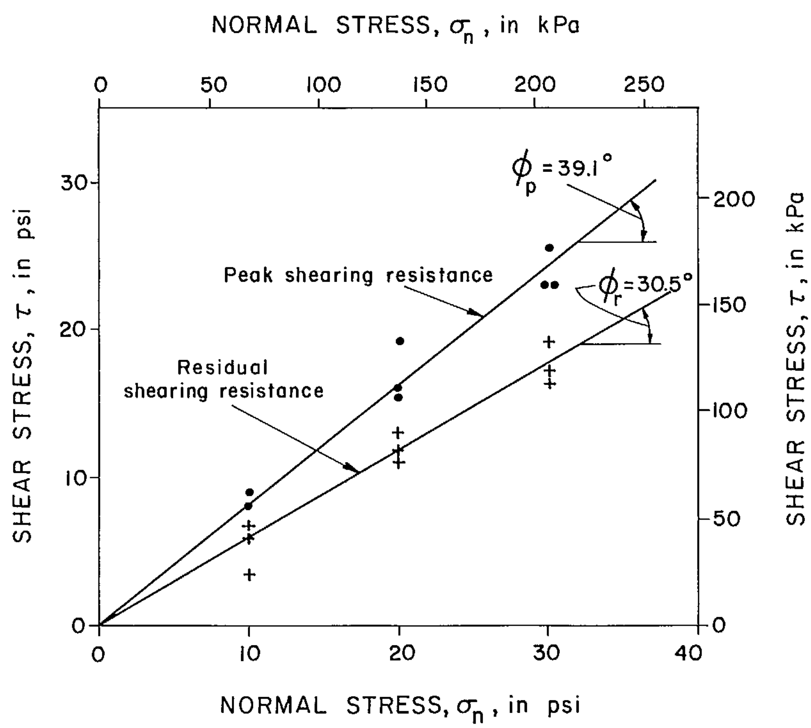


Fig 35 - Graphs of peak shear stresses and of residual shear stresses vs normal stresses.

g. any other observation or available physical data.

62. In addition, the report should include in convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. dimensions of the shear surface (length, width), shape and area of the shear surface
c. type of discontinuity, description of the infilling material, any signs of previous displacement, weathering condition of the contact surfaces and/or infilling material and notes on their hardness, dimension and characteristic records of the roughness features, direction of shearing with respect to the roughness features and with respect to the previous displacement, direction of shearing with respect to any orientation identifiable in relation to the in situ position of the sample and qualitative remarks with respect to the shear surface
d. test condition
e. test duration
f. notes on the after-shear conditions of the shear surface
g. applied normal stress
h. peak shearing stress
i. transient shearing stress
j. effective dilatancy
k. any other observation related to the specimen.

63. Alternatively, the working sheets of the tests (Fig 36) accompanied by the recorded graphs of shear displacement versus shear force and shear displacement versus normal displacement (Fig 33) could be substituted for the report requirements specified in paragraph 62.

DIRECT SHEAR TEST

Sample *quartz-chlorite gneiss of the hanging-wall, with varying amount of biotite and garnet.*

Location *Section H-150*

Bore Hole *12* Depth *4' to 9'*

Sample No *H-12*

Date *October 17, 1974*

Tested by *W.G.*

Test duration: *217 + 253 sec.*

Normal load *180* lb (*800* N)

Test condition *dry surface*

Specimen No *12-4*

Shape of shear surface: *elliptical*

Length of shear surface: *3.61* in. (*92* mm)

Width of shear surface: *2.08* in. (*53* mm)

Area of shear surface: *5.9* in^2 (*38.1* cm^2)

Description of shear surface: *clean moderately smooth geological fracture, 95% slickensided, patches of calcite covering ≈ 15%, dull asperities up to ≈ .08 in. (2 mm) high, specimen sheared along slickensides at 15° left of the established vertical, good surface contact.*

Post-shear condition of shear surface: *mainly rock powder with few small rock chips.*

Normal stress, $\sigma_n = \frac{P_n}{A} = \frac{180}{5.9} =$ *30.5* psi (*210* kPa)

S'_p = *143* lb (*636* N) S'_r = *105* lb (*467* N)

S''_p = *132* lb (*587* N) S''_r = *92* lb (*409* N)

S_p = *137.5* lb (*612* N) S_r = *98.5* lb (*438* N)

Peak shear stress, $\tau_p = \frac{S_p}{A} = \frac{137.5}{5.9} =$ *23.3* psi (*161* kPa)

Residual shear stress, $\tau_r = \frac{S_r}{A} = \frac{98.5}{5.9} =$ *16.7* psi (*115* kPa)

d_n = *0.015* in. (*0.38* mm)

d_s = *0.100* in. (*2.54* mm)

$d = \arctan\left(\frac{0.015}{0.100}\right) =$ *8.5°*

Remarks: *oriented NX core samples after marking the in-situ vertical direction were collected and wrapped in plastic bags on Oct. 3; specimens were selected and moulded on Oct. 10.*

Fig 36 - Working sheet for determination of strength properties of rock discontinuities by direct shear.

DETERMINATION OF STRENGTH PROPERTIES OF ROCK DISCONTINUITIES BY TRIAXIAL TEST

SCOPE

64. a. The purpose of this test is to establish the shear strength of a geological discontinuity in a cylindrical specimen under triaxial loading.

b. The test provides data useful in determining the strength properties of the natural discontinuities, namely peak shear strengths at various lateral pressures, peak angle of friction and apparent cohesion.

c. The test is performed on a cylindrical rock specimen containing a single geological discontinuity with a degree of surface roughness and with an angle of orientation permitting sliding under the triaxial test conditions.

d. The test method makes no provision for pore-pressure measurements, so that the strength values determined are in terms of total stress.

APPARATUS

65. a. A suitable compression machine (Fig 15, 16 and 17), with sufficient capacity, capable of applying an axial load continuously at a constant rate. Sliding along the discontinuity should occur within two to ten minutes of loading; alternatively the applied stress rate should be within the limits of 20 psi/s (140 kPa/s) to 150 psi/ (1000 kPa/s).

b. A load measuring device to indicate the applied load to an accuracy of 1%. A load cell with electronic transducer is placed into the triaxial cell beneath the lower platen to increase accuracy and facilitate automatic data recording (Fig 37).

c. A pressure system of sufficient capacity to maintain the desired lateral pressure constant.

d. A triaxial compression cell in which the test specimen is enclosed in an impermeable flexible membrane and placed between two hardened platens. The platens, having a diameter slightly larger than the specimen, should be of tool steel, hardened to at least a Rockwell hardness of C 30. The surfaces of the platens should be ground, and their flatness should be 0.0002 in. (0.005 mm). A teflon disc approximately 0.03 in. (0.75 mm) thick, greased on the surface in contact with the platen, is placed between the end of the specimen and platen. This decreases the friction between the end of the upper platen and the specimen and consequently allows sideways movement without tilting the upper half of the specimen. The apparatus consists of a high-pressure cylinder with an overflow valve, a base, suitable entry ports for filling the cylinder with hydraulic oil and applying lateral pressure, and hoses, gauges and valves as needed. A piston is fitted into the cylinder through a high-pressure seal (Fig 37).

e. A deformation measuring device, such as microm-

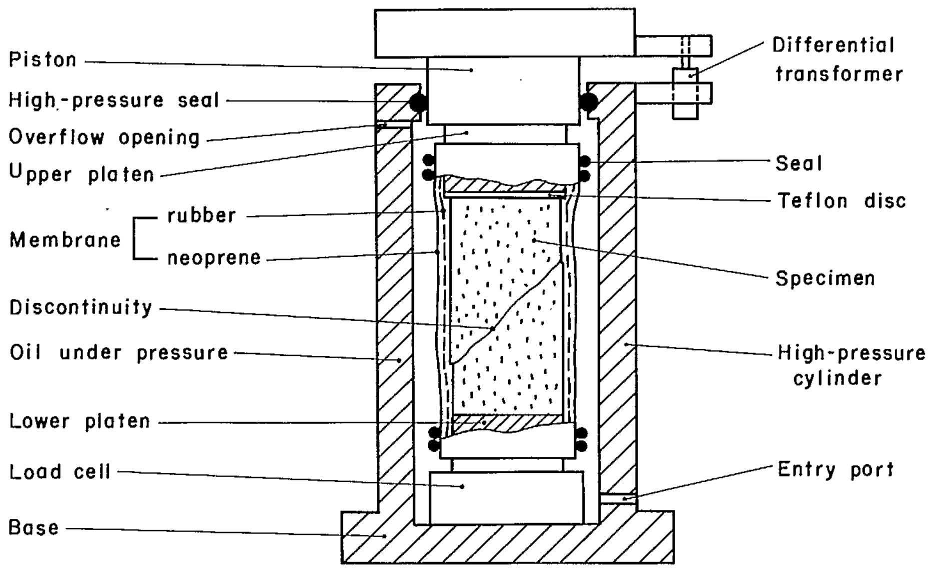


Fig 37 - Schematic cross-section of a triaxial cell with the specimen containing a fracture plane.

eter screws or a dial micrometer to measure the movement of the piston (ie, axial deformation). The measuring device should be graduated to read at least in 0.0001 in. (0.0025 mm) units, and be accurate to within 0.0001 in. (0.0025 mm) in any 0.001 in. (0.025 mm) range, and within 0.0002 in. (0.005 mm) in any 0.01 in. (0.25 mm range. It is convenient to use differential transformers to measure the axial deformation either in terms of inches or in terms of strain (ie, inches per inch) to facilitate automatic data recording.

f. A flexible membrane of suitable material to exclude the confining fluid from the specimen. To decrease the chance of puncturing the membrane by the sharp edges of the specimen halves the combination of a 1/8 in. (3 mm) soft rubber jacket on the inside and of a 1/8 in. (3 mm) neoprene jacket on the outside is recommended. The membrane should be sufficiently long to extend well onto the platens and should have an inside diameter which, when slightly stretched, would fit over the specimen.

g. An automatic data-recording system such as an XY recorder, to record the movement of piston versus axial load.

PREPARATION OF TEST SPECIMEN

66. a. The test specimen should be a straight circular cylinder having a length-to-diameter ratio of 2.0 to 2.5 and a diameter preferably not less than NX core size, approximately 2 1/8 in. (54 mm). The ends of the specimen should be parallel to each other and at right angles to the longitudinal axis. The specimen should contain a single plane of geological discontinuity intersecting the cylindrical specimen preferably at mid height at an angle, measured between the specimen axis and the plane of discontinuity, of between 25° and 40°. All specimens in which the discontinuity plane intersects the specimen end should be rejected. The degree of roughness on the geological discontinuity plane should be small so that sliding is possible. Specimens with very rough and interlocking fracture surfaces are likely to fail along new shear surfaces, thus

invalidating the test results.

b. Guidance for sample handling and storage, and for specimen preparation and allowable tolerance specifications, is given in Supplement 3-5.

c. The diameter of the test specimen, while the discontinuity surfaces are carefully matched and the two halves taped together, is measured to the nearest 0.005 in. (0.1 mm) by averaging two diameters measured at right angle to each other at about the upper height, mid height and lower height of the specimen. The average diameter is used for calculating the cross-sectional area. The height of the specimen is determined to the nearest 0.05 in. (1.0 mm).

d. Detailed information about both the specimen and the discontinuity plane is recorded, including: petrographic description of the specimen, type of discontinuity, description of infilling material, signs of previous displacement, weathering condition of the contact surfaces and/or infilling material and notes on their hardness, dimension and characteristic records of the roughness features, direction of shearing with respect to the roughness features and with respect to the previous displacement and qualitative remarks with respect to the contact surface.

e. The number of specimens tested is determined by practical considerations. It is considered good practice to test six essentially identical specimens from each sample. Three specimens are tested at various ranges of multistage confining pressures, involving three pressure increments within each range. The other three specimens are tested at various but constant confining pressures. The magnitudes of these confining pressures should be the same as the final pressure levels of the multistage confining pressures. The bare minimum is two essentially identical specimens from each sample; both are tested at the same multistage confining pressures, involving four increments.

PROCEDURES

67. a. One end of the jacket is stretched over the lower platen and the two halves of the specimen are pushed into the jacket, taking care that surfaces of the discontinuity are matched. After placing the teflon disc (slightly greased on its top surface) between the specimen and the upper platen, the other end of the jacket is stretched over the upper platen.

b. Seals such as O-rings or hose clamps are placed around the platens at both ends of the jacket.

c. The whole assembly is carefully centred and aligned within the high-pressure cylinder, and the piston inserted.

d. The triaxial cell is centred on the loading platform of the compression machine; the deformation measuring device is positioned; the electrical connections between the transducer of the load cell and of the deformation measuring device and the XY recorder are made; the proper recording scales, based on the estimated maximum axial load and estimated maximum axial displacement, are selected to suit the dimensions of the graph paper. The corresponding recorder outputs are set to these scales and while the overflow valve is kept open, the cell is filled with oil.

e. A small axial load of approximately 25 lb (111N), is applied to the piston by means of the loading device to properly seat the bearing parts of the assembly and after closing the overflow valve, the recording pen is placed into zero position.

f. The lateral fluid pressure is slowly raised to the lowest of the four predetermined test levels and at the same time an axial load, sufficient to prevent the deformation measuring device from deviating off the initial reading is applied (ie, the recording pen moves only in a vertical direction).

g. The loading rate of the compression machine is set and the loading is started when the required lateral pressure is reached.

h. Axial load is applied continuously and without shock until sliding occurs which is indicated by a continuing axial displacement without any load increase (ie, the recording pen moves essentially in a horizontal direction only). The test is continued until the amount of axial displacement, without load increase, becomes approximately equal to the axial displacement which corresponds to the loading phase.

i. The lateral fluid pressure is slowly raised to the next of the four predetermined test levels according to the procedure described in step f.

j. Testing procedures described in steps g. and h. are followed for the second predetermined cell pressure.

k. Steps f., g. and h. are repeated for the remaining two determined lateral pressures.

l. The axial load and the confining pressure of the final stage are simultaneously and slowly released and the assembly is dismantled after draining the cell.

m. The flexible membrane is cut lengthwise and notes are made on the post-test condition of the specimen and of the sheared surfaces.

68. a. While, generally speaking, the described steps are similar for every triaxial test, there are, however, some variations from one case to another. These variations can be necessitated by the following factors: size of specimen and consequently of the triaxial cell required, weight of specimen and weight of parts of the triaxial cell, the load and deformation measuring systems and the degree of automation and complexity of such systems.

b. The procedures described in paragraph 67 are applicable to test specimens of smallish size (ie, up to NX core size), within a triaxial cell similar to the one shown in Fig 18, 19, 20 and 37 when using a medium range testing machine, such as shown in Fig 16. For practical purposes this specimen size range is usually adequate.

c. Situations could, however, arise in which specimens with a larger diameter are tested. A high capacity testing machine, appropriate for this case, is shown in Fig 15. The sequence of procedures involved in testing a 9.5 in. (24.13 cm) diameter specimen, is shown by a series of photographs (Fig 38, 39, 40, 41, 42, 43, 44 and 45).

CALCULATIONS

69. a. The recorded graph, after providing the axes with the proper scales, is analyzed and the axial loads required to induce sliding are established for each confining pressure (Fig 46).

b. The stress-difference, $(\sigma_1 - \sigma_3)$, is calculated for each stage as follows:

$$\sigma_1 - \sigma_3 = (P - P_L)/A$$

where P = axial load at which sliding occurred,
$P_L = A_p \times \sigma_3$,
A_p = area of piston
σ_3 = applied confining pressure and
A = cross-sectional area of specimen.

c. The normal stress acting on the plane of discontinuity is calculated by the following equation:

$$\text{Normal stress, } \sigma_n = (\sigma_1 - \sigma_3)\sin^2\alpha + \sigma_3 + \mu_p\sigma_1 \sin\alpha\cos\alpha$$

where α = angle measured between the axis of the specimen and the plane of discontinuity and
μ_p = coefficient of friction between rock and teflon disc and between teflon disc and steel platen, having values of 0.02 to 0.04 if a coat of grease is applied to the teflon disc surface.

d. The shear stress acting on the plane of discontinuity is calculated as follows:

$$\text{Shear stress, } \tau = (\sigma_1 - \sigma_3)\sin\alpha\cos\alpha - \mu_p\sigma_1\sin^2\alpha$$

e. The calculated values of normal stresses, σ_n, and shear stresses, τ, are plotted (Fig 47). A best-fit straight line is drawn from the origin to the points. The slope angle of this line is established and reported as the peak angle of friction, ϕ_p, and the intercept of the line with the vertical axis is reported as the

Fig 38 - Photograph of 9.5 in. (24.13 cm) diameter specimens. The specimen on the right was used to establish the triaxial compressive strength of the rock substance. The specimen on the left was used to determine the shear strength along the natural fracture plane (the other half of the specimen is not shown).

apparent cohesion, c_a.

REPORTING OF RESULTS

70. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. petrological description of the sample
c. the peak angle of friction and apparent cohesion
d. storage and environmental history of the sample
e. method and date of specimen preparation
f. information on testing such as: date, type of testing apparatus, rate of loading
g. any other observation or available physical data.

71. In addition, the report should include in convenient tabulated form the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. specimen diameter, height and cross-sectional area
c. angle of discontinuity, measured on the upper half of the specimen in a clockwise direction from the specimen axis to the plane of discontinuity
d. type of discontinuity, weathering condition of the shear surfaces and/or infilling material and notes on their hardness, dimension and characteristic records of the roughness features, direction of shearing with respect to the roughness features and with respect to the previous displacement, direction of shearing with respect to any orientation identifiable in relation to the in situ position of the sample and qualitative remarks with respect to the

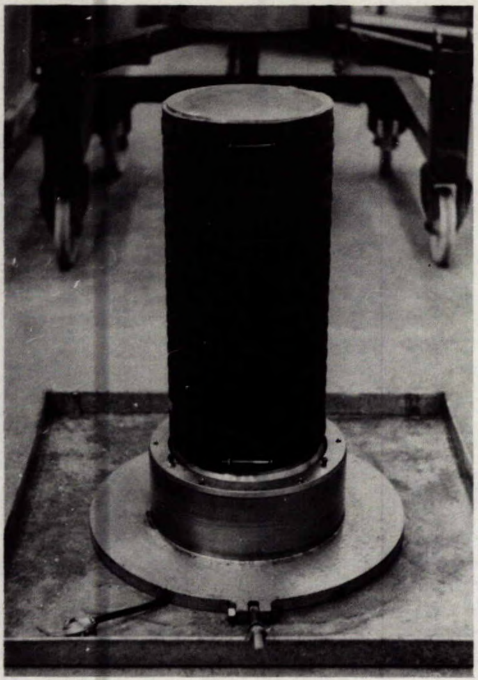


Fig 39 - The rubber jacket is installed around a 9.5 in. (24.13 cm) diameter specimen, containing the discontinuity plane. It is standing on the piston of the triaxial cell.

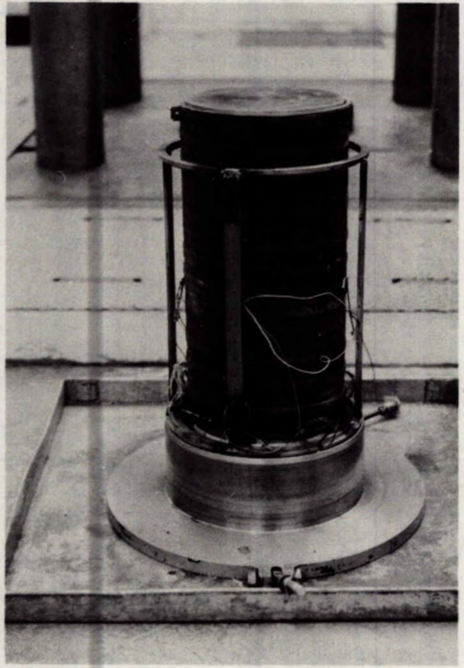


Fig 40 - The device for measuring lateral deformation is installed.

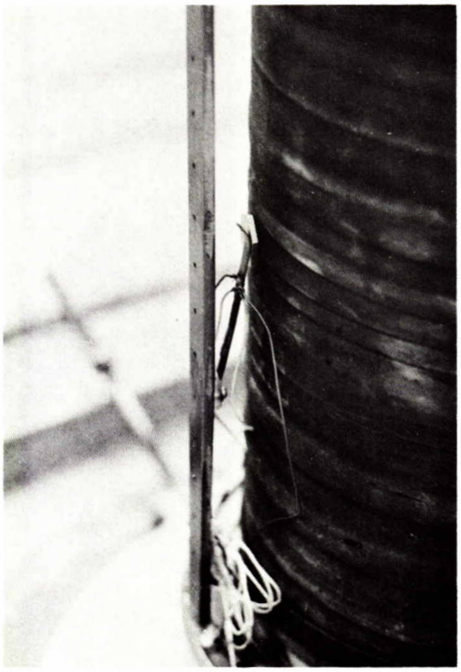


Fig 41 - Close-up of the device for measuring lateral deformation. Note the strain gauged cantilever pressed against the metal plate moulded within the rubber jacket.

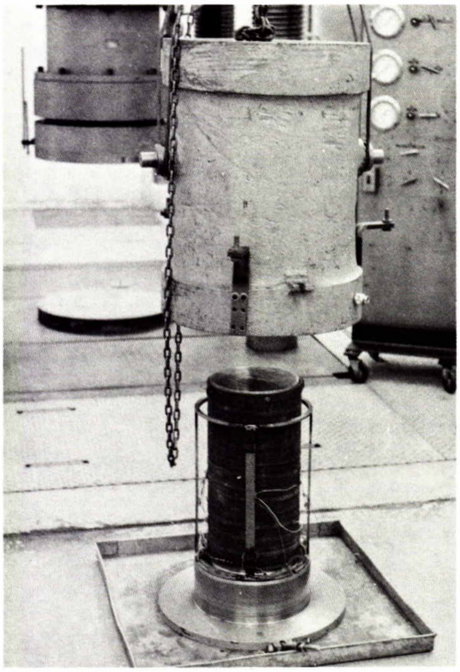


Fig 42 - Installation of the high-pressure cylinder. Note the testing machine and the hydraulic pump unit in the background.

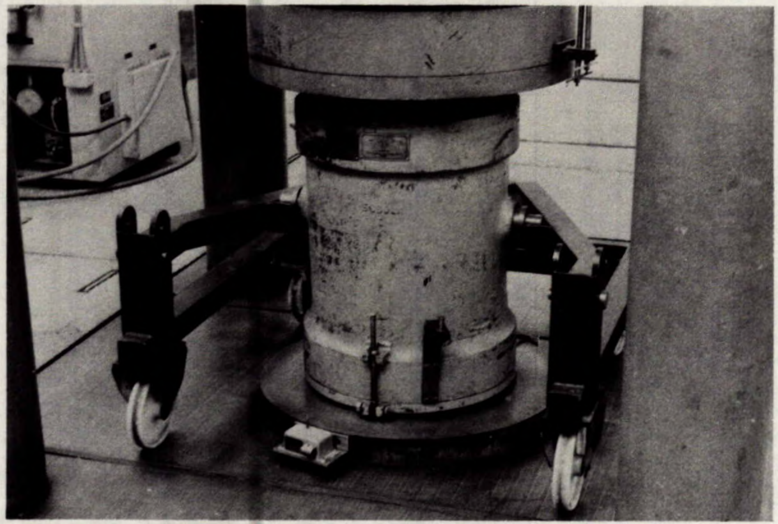


Fig 43 - The triaxial cell assembly, on the trolley, is positioned within the testing machine.

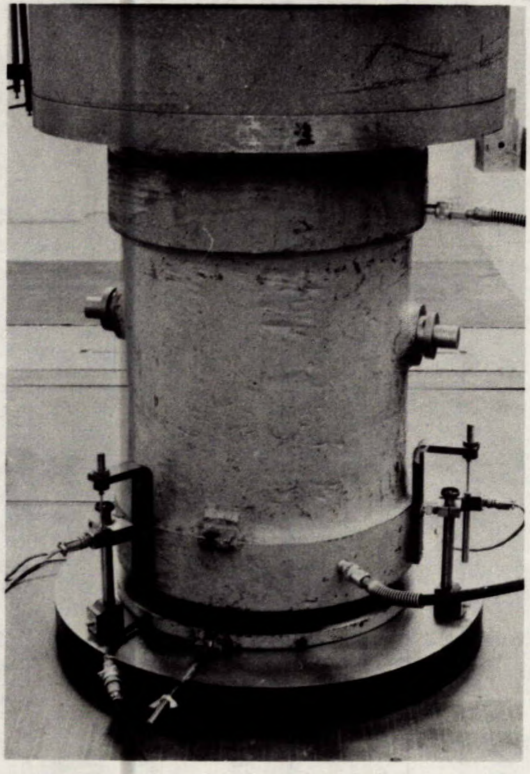


Fig 44 - The triaxial cell assembly is ready for test. The hydraulic pressure lines and the lead wires of the deformation measuring devices are connected.

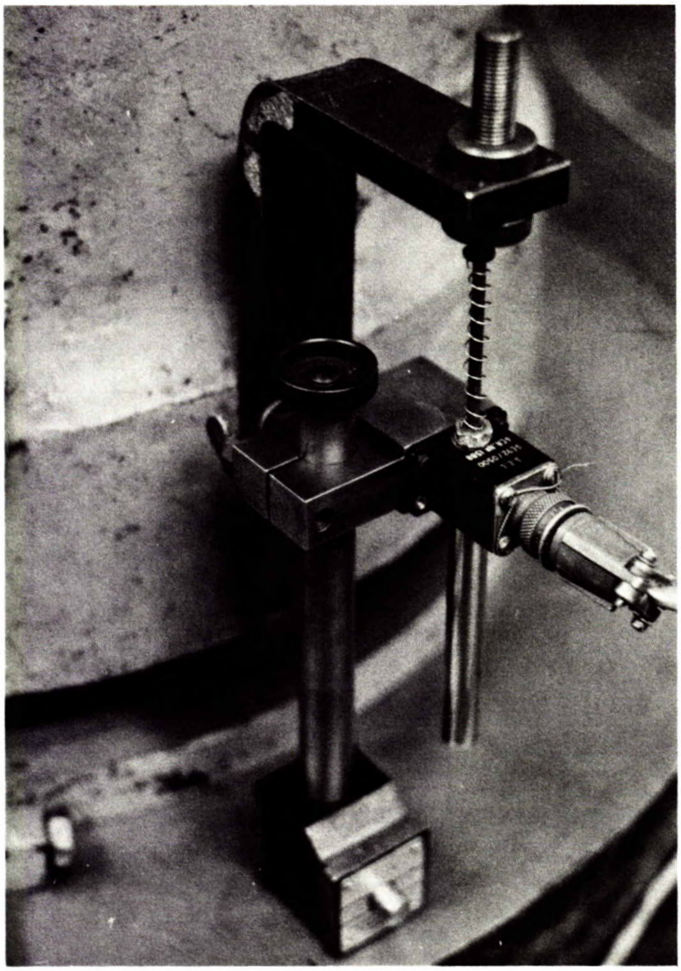


Fig 45 - Close-up of the device for measuring the axial deformation. Note that the rod holding the magnetic core of the differential transformer is secured to the cylinder, while the windings of the transformer is secured to the base plate of the piston.

shear surface

e. duration of actual shearing
f. notes on the post-shear condition of the discontinuity plane
g. applied confining pressures
h. calculated axial stresses, σ_1
i. calculated normal stresses, σ_n
j. calculated shear stresses, τ
k. any other observation related to the specimen.

72. Alternatively the working sheets of the tests (Fig 48) accompanied by the graph of axial strain (or deformation) versus axial load (Fig 46) could be substituted for the report requirements specified under paragraph 70.

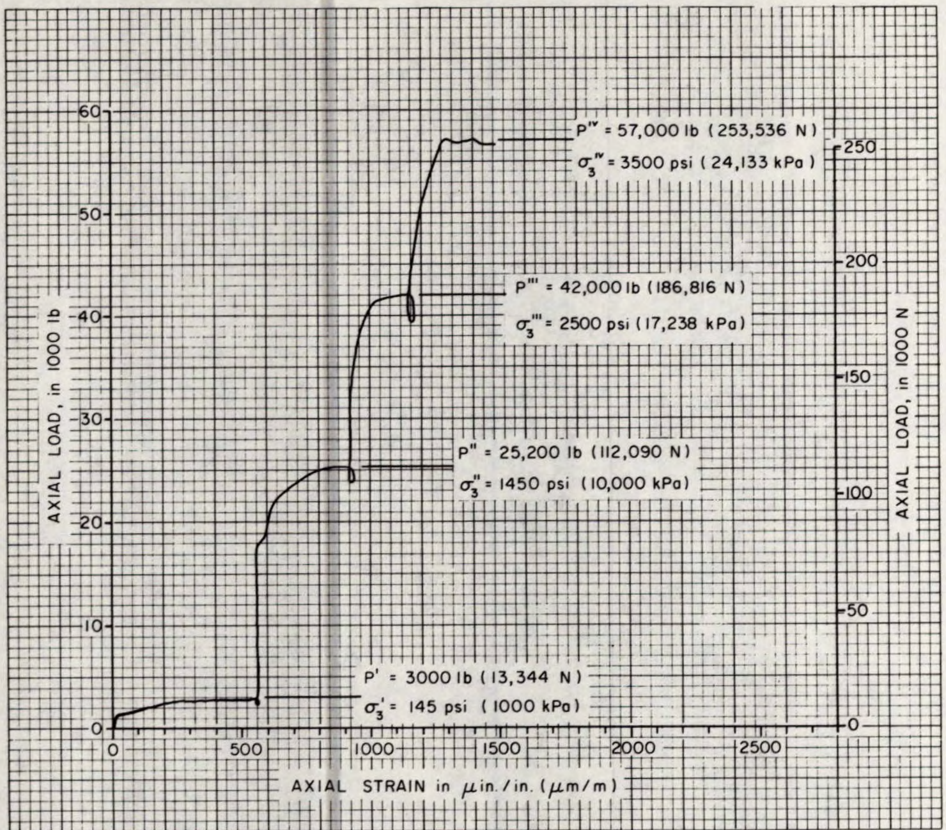


Fig 46 - Recorded graph of axial loads and axial strains.

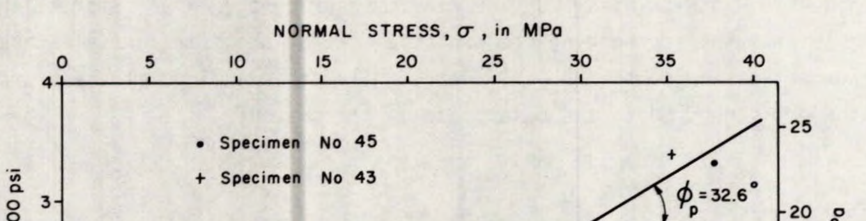


Fig 47 - Graph of shear stress vs normal stress obtained for the discontinuity plane.

TRIAXIAL TEST ON DISCONTINUITY

Sample *unaltered footwall phyllite*

Date *Jan. 5, 1972*

Tested by *W. G.*

Area of piston *11.5* in^2 (*74.2* cm^2)

Location *Section 21*

μ_p *0.03*

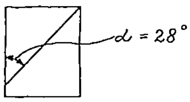
Bore Hole *26* Depth *10'-15'*

Specimen No *45*

Diameter: *1.615* in. (*41.0* mm)

Height: *3.55* in. (*90.0* mm)

Area, A: *2.05* in^2 (*13.2* cm^2)



Description of discontinuity plane: *clean smooth geological fracture along bedding plane, dull interlocking asperities up to ≈ .06 in. (1.5 mm) high, good surface contact, no alteration and previous displacement, for orientation see structural report.*

Post-shear condition of discontinuity plane: *no noticable change, small amount of rock powder.*

Test durations, First stage: *1.0* min. Second stage: *4.0* min.
Third stage: *3.0* min. Fourth stage: *2.5* min.

σ_3	P_L	P	$\sigma_1 - \sigma_3$	σ_1	$\mu_p \sigma_1$	σ_n	τ
145	1668	3000	650	795	24	298	264
1450	16,675	25,200	4159	5609	168	2437	1687
2500	28,750	42,000	6463	8963	269	4036	2620
3500	40,250	57,000	8171	11,671	350	5446	3310

Remarks: *blocks, appr. 8" cubes in size, containing the particular discontinuity were obtained in Oct. 1971, halves wired together, wrapped in plastic, kept in lab. until specimens prepared between Dec. 10 and 20, due to the limited numbers and sizes of blocks only BX cores could be drilled, specimens after preparation were kept in humid box until testing.*

Fig 48 - Working sheet for determination of strength properties of rock discontinuities by triaxial test.

DETERMINATION OF STRENGTH PROPERTIES OF CRUSHED ROCK MATERIAL BY TRIAXIAL TEST

SCOPE

73. a. The purpose of this test is to establish the shear strength of crushed or decomposed rock material by testing recompacted cylindrical specimens under triaxial conditions.

b. The test provides data useful in determining the strength properties of the shear zone or infilling material, namely shear strengths at various lateral pressures, angles of frictions and cohesion intercepts.

c. The strength values are required in terms of effective stresses and tests are therefore performed under drained conditions.

d. The test is usually performed on specimens prepared by compaction with the natural water content. However, in some cases a knowledge of the effect of water on the compacted density and/or on the strength values is required. Consequently, tests are performed on specimens compacted at various water contents and/or on specimens which are saturated prior to testing.

e. The test method described here is basically the same as that specified under paragraphs 38 to 45 but is suitable when drilled core specimens are very difficult or even impossible to obtain.

APPARATUS

74. a. A suitable compression machine (Fig 15, 16 and 17), with sufficient capacity, capable of applying an axial load continuously at a constant rate and in such a way that failure will occur within two to six hours of loading. Alternatively, the applied stress rate should be within the limits of 1 psi/s (6.9 kPa/s) to 5 psi/s (34.5 kPa/s).

b. A load measuring device to indicate the applied load to an accuracy of 1%. If an automatic data recording system is used, the load is measured by a load cell and placed in the triaxial cell beneath the lower platen (Fig 37).

c. A pressure system of sufficient capacity to maintain the desired lateral pressure constant.

d. A triaxial compression cell, consisting of a high-pressure cylinder with overflow valve, a base, suitable entry ports for filling the cylinder with hydraulic oil and applying the lateral pressure, suitable ports for saturating and draining the specimen, and hoses, gauges and valves as required. A piston is fitted into the cylinder through a high-pressure seal (Fig 37). The specimen is enclosed in an impermeable flexible membrane. The drainage and the saturation of the specimen is performed through porous metal discs (such as sintered bronze or stainless steel) placed at both ends between the specimen and the steel platens. The porous metal discs, having the same diameter as the specimen, should be made of tool steel hardened to at least a Rockwell hardness of C 30. The platens, one of which is spherically seated, should be manufactured in such a way that water flow is ensured through the porous discs, either out of or into the specimen.

e. A deformation measuring device, such as a micrometer screw or dial micrometer to measure movement of the piston (ie, axial deformation of the specimen). The measuring device should be graduated to read to at least 0.0001 in. (0.0025 mm) units, and accurate within 0.0001 in. (0.0025 mm) in any 0.001 in. (0.025 mm) range, and within .0002 in. (0.005 mm) in any 0.01 in. (0.25 mm) range. It is convenient to use a differential transformer to measure the axial deformation to facilitate automatic data recording.

f. A flexible membrane of suitable material to exclude the confining fluid from the specimen. If the compacted material contains coarse rock fragments with sharp corners, it is recommended that a membrane with a soft rubber jacket on the inside and neoprene jacket on the outside be used, to decrease the chance of puncturing. The membrane should be sufficiently long to extend well onto the platens.

g. In case of an automatic system, an XY recorder to record the axial deformation versus axial load.

PREPARATION OF THE TEST SPECIMEN

75. a. The test specimen should be a straight circular cylinder having a length to diameter ratio of 2.0 to 2.5 and a diameter preferably not less than 2 in. (50 mm). The diameter of the specimen should be related to the size of the largest particle in the compacted material by the ratio of at least 10:1. The ends of the specimen should be parallel to each other and at right angles to the longitudinal axis.

b. The specimen is compacted within the membrane. The end of the membrane is stretched over the lower platen and the porous disc, and a seal placed around the platen above the membrane; the two halves of a steel cylindrical mould are placed around the membrane and clamped together to provide the side support (Fig 49). The sample material is poured into the jacket and compacted layer by layer. The cylindrical specimen is made with the desired density by using suitable tools or equipment and by applying adequate compaction energy (Fig 50). Finally, the upper end of the membrane is stretched over the upper porous disc and platen, and the seal is placed around the platen.

c. Further details on specimen preparation, as well as guidance for sample handling and storage is given in Supplement 3-5.

d. The cross-sectional area, A, of the specimen is calculated using the diameter, obtained to the nearest 0.05 in. (1.0 mm) as follows:

$$D = D_m - 2t$$

where D_m = inside diameter of the mould and
t = thickness of the membrane.

e. The height of the specimen, L_o, is obtained to the nearest 0.05 in. (1.0 mm) as follows:

$$L_o = H_m - h - h_1$$

where H_m = height of the mould,
h = thickness of the lower platen and
h_1 = thickness of the porous disc.

f. The weight W_t of the specimen is established, to an accuracy of 1.0 g, as follows:

$$W_t = W_1 - W_2$$

where W_1 = weight of the sample prior to specimen preparation and
W_2 = weight of the remaining portion of the sample after the specimen is prepared.

g. A sample for initial water content determination is taken. Specifications for water content determination are given in Supplement 3-1.

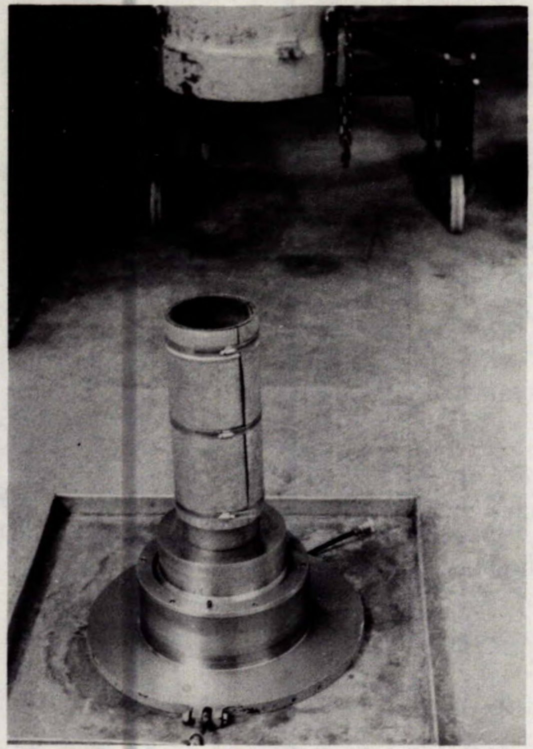


Fig 49 - The rubber jacket is supported by a cylindrical metal mould; as it stands on the piston of the triaxial cell.

Fig 50 - Compaction of specimen, by using a steel rod of 1 in. (2.54 cm) diameter.

h. Lithological description of the sample is recorded, including rock type, texture and weathering condition of the rock fragments. Notes on the shape of the particles should also be recorded together with particle sizes and their distribution within the sample. The latter is usually given in terms of range and percentage, however, in some cases a more exact definition is required. The procedure for analyzing grain sizes is given in Supplement 3-4.

i. The triaxial test is combined with compaction tests when knowledge of the effect of water on the compacted density, and as a consequence, on the strength properties of broken rock, is essential. The compaction test procedure is given in Supplement 3-4.

j. The number of specimens tested within a sample is determined by practical considerations. It is considered good practice to test nine essentially identical specimens at nine different and constant confining pressures, alternatively, to test three essentially identical specimens at various ranges of multistage confining pressures, involving three pressure increments within each range. The bare minimum is to test either three specimens at three different and constant confining pressures, or two specimens at the same range of multistage confining pressures, involving three pressure increments within the range. To obtain the most information out of a test, it is recommended that the load be cycled three times within each stage of the confining pressures. Testing with load cycling is especially feasible if the data are recorded automatically.

PROCEDURES

76. The specimen, prepared according to paragraph 75 b, is carefully centred and aligned within the pressure cylinder (Fig 51).

77. The properly sealed connections between the water vents of the platens and the ports of the pressure cylinder are made and the piston inserted.

78. a. If specimen saturation is involved, the port on the pressure cell, which is connected with the upper platen, is connected by a hose to a vacuum source, such as a vacuum pump or a water faucet aspirator. The other port is then connected to a tank preferably containing the same water as is in the sample (ie, the original groundwater).

b. While the water inlet valve of the port is kept closed, the specimen is evacuated under 20 in. (50 cm) Hg for 15 min.

c. The water inlet valve is opened following evacuation and the specimen is saturated under full vacuum. The full saturation is indicated by a continuous trickle of water in the vacuum line.

d. The lines leading to the vacuum source and to the water tank are disconnected after saturation. The valves of both ports are kept open during the entire test.

79. The triaxial cell is centred on the loading platform of the compression machine; the deformation measuring device is positioned; if applicable, the electrical connections between the transducers of the load cell, and of the deformation measuring device and the XY recorder are made; the proper recording scales, based on the estimated maximum axial displacement, are selected to suit the dimensions of the graph paper and the corresponding recording outputs are set to these scales; the cell is filled with oil while the overflow valve is kept open.

80. a. A small axial load of approximately 25 lb (111 N) is applied to the piston by means of the loading device to properly seat the bearing parts of the assembly; then, after closing the overflow valve, either an initial reading is taken manually on the deformation device, or the recording pen is placed in the zero position, whichever is applicable.

b. The lateral fluid pressure is slowly raised to the predetermined test level and at the same time an axial load, sufficient to prevent the deformation measuring device from deviating off the initial reading is applied (the recording pen moves only in a vertical direction, in case

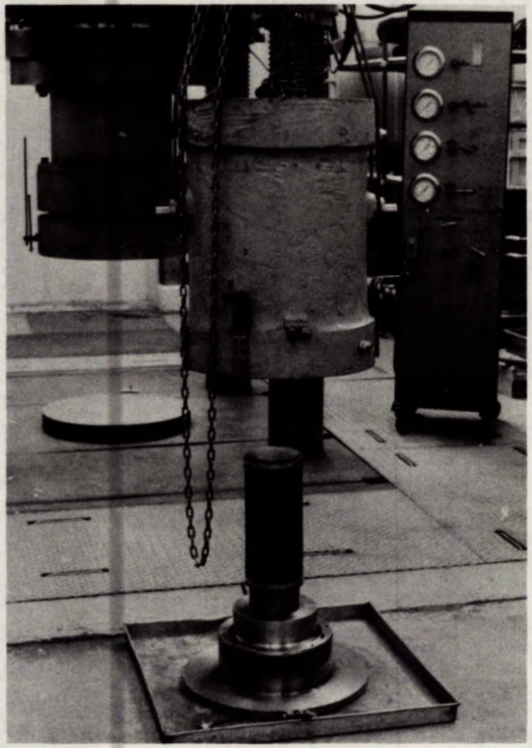


Fig 51 - The high-pressure cylinder is being installed. Note the seals around the platens at both ends of the specimen.

of automatic recording).

c. When the required lateral pressure is released, the loading rate of the compression machine is set and the loading is started.

d. Axial load is applied continuously and without shock until the load becomes constant, or reduces, or a predetermined axial strain is achieved.

e. In case of manual recording, the axial load, corresponding to each 0.005 in (0.1 mm) axial deformation interval, is recorded throughout the test.

81. a. In case of a multistage test, the lateral fluid pressure is slowly raised to the second predetermined value, according to the procedure described in step 80 b.

b. Testing procedures included in steps 80 c., d., and e. are followed for the second predetermined cell pressure.

c. Steps 80 b., c., d. and e. are repeated for the third predetermined confining pressure.

82. a. If the load cycling option of the testing method is followed then before the cell pressure is increased to the value of the second stage, the axial load is released to the value of $\sigma_3 \times A$ (where σ_3 is the cell pressure for the first stage, and A is the cross-sectional area of the specimen).

b. Axial load is then reapplied and the steps of paragraphs 80 d. and e. are followed.

c. Steps 82 a. and b. are repeated for the third cycle of the first stage of confining cell pressure.

d. Steps 82 a., b. and c. are repeated for the second and third stages of cell pressures.

83. a. The axial load and confining pressures are simultaneously and slowly released and the assembly is dismantled.

b. A sample from the failed specimen is taken to establish water content and degree of saturation which prevailed during the test.

CALCULATIONS

84. a. The stress-difference, $(\sigma_1 - \sigma_3)$, corresponding to any deformation level is calculated as follows:

$$\sigma_1 - \sigma_3 = (P - P_L)/A$$

where P = axial load corresponding to the deformation,

P_L = $A_p \times \sigma_3$,

A_p = area of piston,

σ_3 = applied lateral pressure and

A = cross-sectional area of specimen.

b. The axial strain, ε, corresponding to any deformation level is calculated as follows:

$$\varepsilon = \delta/L_o$$

where δ = axial deformation and

L_o = height of the specimen.

c. An axial stress-difference versus strain curve is plotted for each specimen tested (Fig 52).

d. A tangent is drawn to the curve at the point corresponding to 50% of the peak stress-difference. The slope of the tangent is established and reported as the deformation modulus, D, of the specimen.

85. The following general rule is recommended in multistage testing:

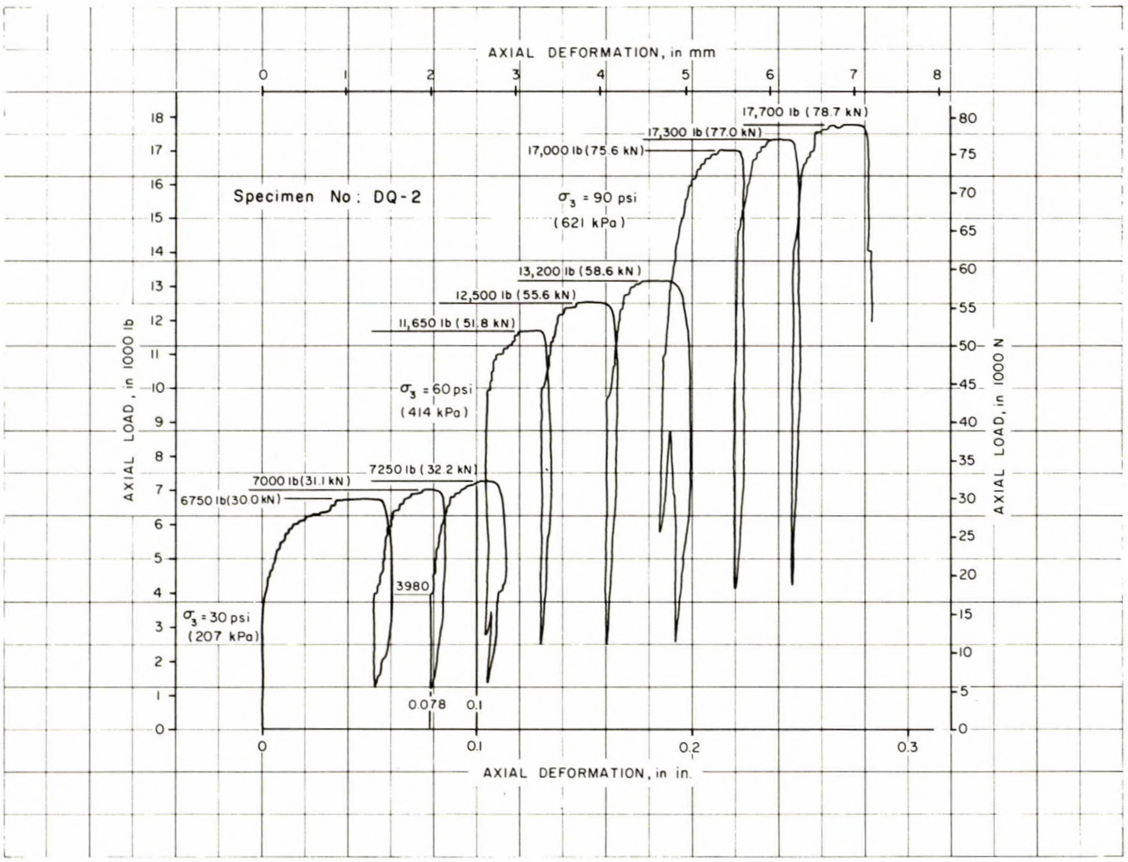


Fig 52 - Recorded graph of axial load vs axial deformation with the peak load of each cycle.

a. Deformation modulus is established for the test data which correspond to the first multistage confining pressure, if no load cycling is involved.

b. Deformation modulus is established for the test data which correspond to the third load cycle of the first multistage cell pressure, if load cycling is also involved (Fig 53, 55).

86. a. A Mohr's stress circle on an arithmetic plot, with shear stresses on the ordinate and normal stresses on the abscissa corresponding to the peak stress-difference, is constructed for each test or test phase (Fig 56).

b. A best-fit smooth curve (the Mohr's envelope) is drawn tangent to the Mohr's circle. If the envelope is a straight line, a single value is established for the angle which is formed by the line and the horizontal, and a single value is established for the intercept of this line on the vertical axis. If the envelope is not a straight line, values of the angle are determined by constructing a tangent to the Mohr's circle for each confining stress at the point of contact with the envelope, and the corresponding intercepts are noted.

87. The calculation procedure is demonstrated by an example involving a multistage undrained triaxial test with load cycling.

a. Specimen data, including information (ie, water content, degree of saturation and porosity) obtained by procedures specified in Supplement 3-1, are shown in Fig 54.

b. The recorded axial load versus axial deformation graph, together with the peak loads of each load cycle, is shown in Fig 52.

c. The second table of Fig 55 shows calculation of the intermediate values of the axial strains and the corresponding stress-differences of the third cycle of the first stage, which were used to obtain the stress-strain curve of Fig 53 to establish the deformation modulus.

d. The first table in Fig 55 summarizes the cal-

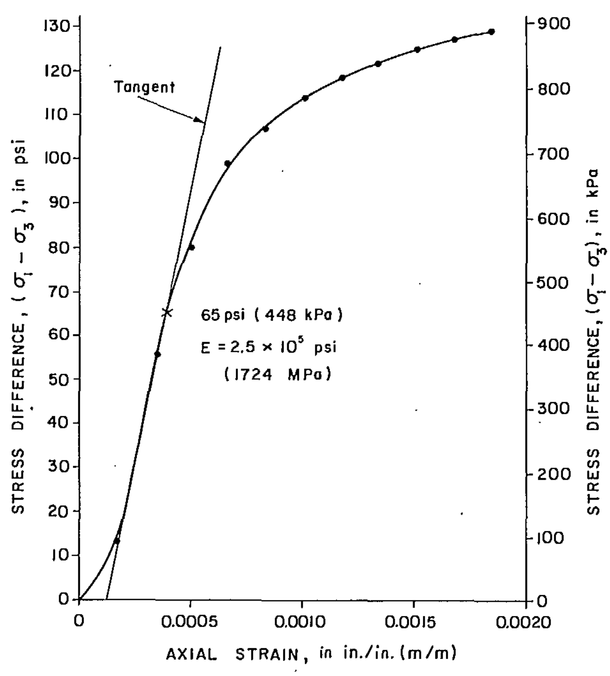


Fig 53 - Stress-strain curve corresponding to the third cycle of the first stage cell pressure.

TRIAXIAL TEST OF COMPACTED SPECIMEN

Sample *fractured and oxidized diopsidic quartzite of main fault zone.*

Date *Oct. 16, 1974*

Tested by *W. G.*

Location *20840 N, 24930E, 1680 ft.*

Bore Hole ______ Depth ______

Sample No *DQ*

Specimen No *DQ-2*

D_m : *6.00* in. (*152* mm)

$2t$: *0.30* in. (*7* mm)

D : *5.70* in. (*145* mm)

H_m : *13.00* in. (*330* mm)

h : *0.50* in. (*12.5* mm)

h_1 : *0.50* in. (*12.5* mm)

L_o : *12.00* in. (*305* mm)

Area, A : *25.5* in.^{2} (*165* cm^2)

Volume, V_b : *306* in.^{3} (*5033* cm^3)

W_1 : *12,937* g

W_2 : *3425* g

W_b : *9512* g

Density, $\gamma = \frac{W_b}{V_b} = \frac{9512}{5033} =$ *1.89* g/cm^3 (*118* lb/ft^3)

Water contents, initial w : *6.3* %, failed specimen w : *5.9* %

Degree of saturation, S_r : *32.6* %

Porosity, w : *32.2* %

Description of compacted material : *angular shape fragments; about 10% of sample was discarded (over 1 in. size), estimated size distribution of specimen : 10% between 1 cm to 2.5 cm, 15% between 0.5 cm to 1 cm, 20% between 1 mm to 5 mm, 55% finer than 1 mm.*

Compaction : *at natural water content, 5 layers, 25 drop of compaction rod at each layer.*

Remarks : *sample of about 25 kg was obtained on Oct. 5, natural water content was preserved by wrapping and sealing it in plastic bag, kept in humid box without removing from bag until testing.*

Fig 54 - Data sheet of the recompacted specimen.

TRIAXIAL TEST OF COMPACTED SPECIMEN

Sample No DQ   Date Oct. 16, 74

Specimen No DQ-2   Tested by W. G.

Test type natural water content, multistage, load cycling

Area of piston, A_p : 132.66 in.^{2} (856 cm^2)

Specimen area, A = 25.5 in.^{2} (165 cm^2)

height, L_0 = 12.0 in. (305 mm)

Mohr circles data :

Stage	Cycle	σ_3	P_L	P	$\sigma_1 - \sigma_3$	Test duration, (min.)
1	1	30	3980	6750	109	127
1	2	30	3980	7000	119	138
1	3	30	3980	7250	129	115
2	1	60	7960	11,650	145	121
2	2	60	7960	12,500	179	108
2	3	60	7960	13,200	206	132
3	1	90	11,939	17,000	199	135
3	2	90	11,939	17,300	211	119
3	3	90	11,939	17,700	227	126

Stress-strain curve data :

Axial deformation reading, in.	Axial deformation, in.	Axial strain, in./in.	Axial load reading, lb	Axial load, lb	$\sigma_1 - \sigma_3$ psi
0.078	0	0	3980	0	0
80	0.002	0.00017	4300	320	13
82	4	34	5380	1400	55
84	6	50	6000	2020	80
86	8	67	6500	2520	99
88	10	84	6700	2720	107
90	12	101	6880	2900	114
92	14	117	7000	3020	119
94	16	134	7080	3100	122
96	18	151	7150	3170	125
98	20	168	7210	3230	127
0.100	0.022	0.00184	7250	3270	129

Fig 55 - Working sheet for determination of strength properties of crushed rock materials by triaxial test.

culation of the peak stress-differences which were used to construct the Mohr's circles of Fig 56.

e. The Mohr's envelopes, belonging to the family of Mohr's circles obtained during the first, second and third load cycles were drawn separately. The variation in the angles of friction, ϕ, and the cohesion intercepts, c, is due to a change in density which occurred during the test. The angle of friction and cohesion intercept of the first cycle are regarded as representative values of the compacted specimen.

REPORTING OF RESULTS

88. The report should include the following information for each sample tested:

a. sample identification (rock type and origin)
b. lithological description of the sample, including: texture and weathering condition of the rock fragments, particle shape, particle size ranges, and their distribution within the sample and uniformity coefficient, if the latter is established by grain-size analysis
c. specimen diameter and height and the specimen number tested within the sample
d. average water content of the specimens including initial (compaction) water content and water content of the failed specimen
e. average degree of saturation and average porosity of the specimens
f. average unit weight of the specimens
g. type of test (ie, natural and saturated), constant or multistage confining pressure, with or without load cycling
h. average value of deformation modulus obtained for individual specimens
i. Mohr's stress circles (Fig 56), angle of fric-

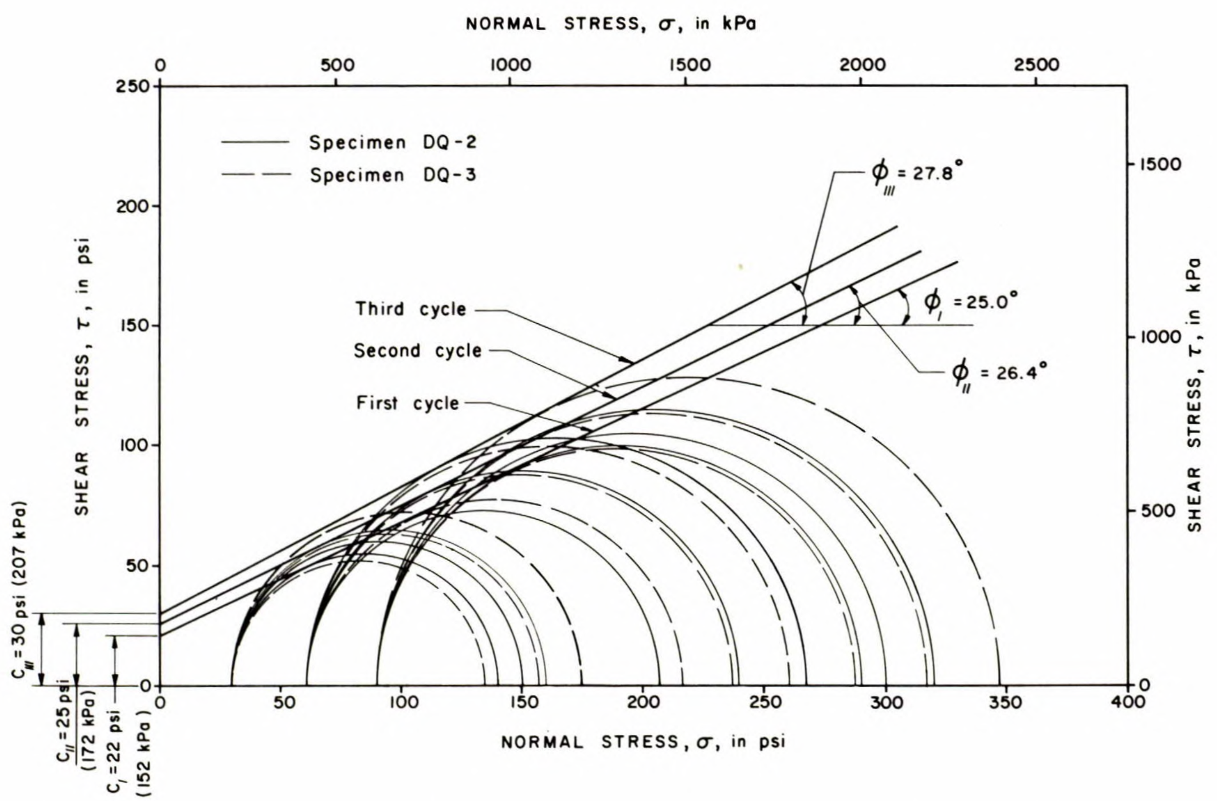


Fig 56 - Mohr's circles and Mohr's envelopes of the various loading cycles.

tion and cohesion intercept and their variation due to change in density if load cycling is performed

j. storage and environmental history of the sample
k. method of specimen preparation and information indicating the applied compaction energy
l. information on testing such as: date, type of testing apparatus, test rate, duration and method of saturation, if applicable
m. any other observation or available physical data.

89. In addition, the report should include in convenient tabulated form, the following information for each specimen:

a. specimen identification (specimen's number within the sample)
b. specimen diameter, height and cross-sectional area
c. initial water content (compaction water content) and tested water content (water content of failed specimen)
d. degree of saturation and porosity
e. unit weight
f. test duration, ie, elapsed time corresponding to the actual loading phase of the test procedure
g. confining pressure or pressures and the corresponding peak stress-differences
h. stress-strain curve of the test in the case of constant lateral cell pressure or of the test phase specified in paragraph 85 (Fig 53), and the established deformation modulus
i. any other observation related to the specimen.

90. Alternatively the working sheets of the tests (Fig 54, 55) accompanied by the recorded graphs of axial deformation versus axial load (Fig 52) or the test data sheets could be substituted for the report requirements specified under paragraph 88.

DETERMINATION OF TIME-DEPENDENT PROPERTIES OF THE ROCK SUBSTANCE

SCOPE

91. The purpose of this test is to assess the time-dependent deformation and long-term strength of cylindrical rock specimens when subjected to uniaxial compressive loads (5).

APPARATUS

92. a. Loading equipment, with sufficient capacity, capable of maintaining a constant load over long periods - weeks, months or even a year. The equipment should be capable of exerting the desired load on the specimen or of unloading the specimen within a few seconds.

b. A time-measuring device for recording the elapsed time, capable of registering the final elapsed time in the case of specimen failure.

c. A suitable device to measure the axial deformation. This device should be stable and free from drift during the long test periods.

PREPARATION OF THE TEST SPECIMEN

93. a. The test specimen should be a straight circular cylinder, with a length-to-diameter ratio of 2.5 to 3.0 and a diameter preferably not less than NX core size, approximately 2 1/8 in. (54 mm). The ends of the specimen should be parallel to each other and at right angle to the longitudinal axis.

b. Guidance for sample and specimen handling and storage, as well as the method of specimen preparation together with allowable tolerance specifications, is given in Supplement 3-5.

c. The diameter of the test specimen is measured to the nearest 0.005 in. (0.1 mm) by averaging two diameters measured at right angle to each other at about the upper height, mid height and lower height of the specimen. The average diameter is used for calculating the cross-sectional area. The height of the specimen is determined to the nearest 0.05 in. (1.0 mm).

d. The inclination of bedding or foliation with respect to the specimen axis is recorded, together with the lithological description of the rock.

e. The number of specimens tested is determined by practical considerations, however, at least three specimens are preferred at each load level.

PROCEDURE

94. a. The tests should be performed in a controlled climate where both the temperature and humidity can be monitored. An environment of 20° ± 1C and 50% ± 5% humidity is recommended.

b. Specimens are tested at the following load levels: $0.2Q_u$, $0.4Q_u$, $0.6Q_u$, $0.8Q_u$, and $0.9Q_u$, where Q_u is the average uniaxial compressive strength of the rock substance established by the method described in Supplement 3-1.

c. The axial deformation is measured continuously during the test. The following measurement frequency is recommended: every 10 minutes for the first hour, every 30 minutes for the next seven hours, every hour for the rest of the first day, then daily until the test is completed.

d. The completion of the test is defined by any one of the following criteria: (i) no further deformation during a seven-day period, (ii) a constant strain rate has been achieved for seven days, (iii) the total axial strain has exceeded the failure strain (which is obtained by the uniaxial compressive test).

e. The temperature and humidity readings are also recorded during the test.

CALCULATIONS

95. a. The axial strain, corresponding to any particular elapsed time, is calculated as follows:

$$\varepsilon = \delta/L_o$$

where δ = axial deformation corresponding to the elapsed time of interest and

L_o = the specimen length.

b. The curves of axial strain versus elapsed time are drawn corresponding to the applied load levels, as shown in Fig 57.

c. The time of failure, corresponding to each load level, is established by one of the following criteria: (i) the time of failure is the one when the total axial strain equals the failure strain which was obtained by the uniaxial compressive tests and (ii) the time of failure is the one when actual specimen failure occurred.

d. The curve is drawn showing time of failure versus applied load (in ratios of Q_u) as in Fig 58. The long-term strength of the rock substance can be predicted from this curve.

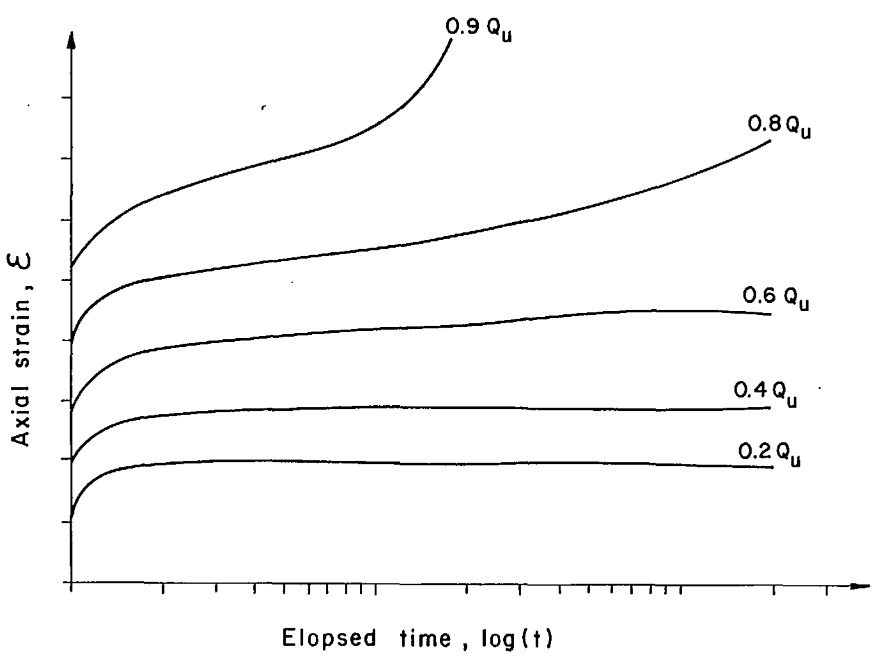


Fig 57 - Curves of axial strain vs elapsed time.

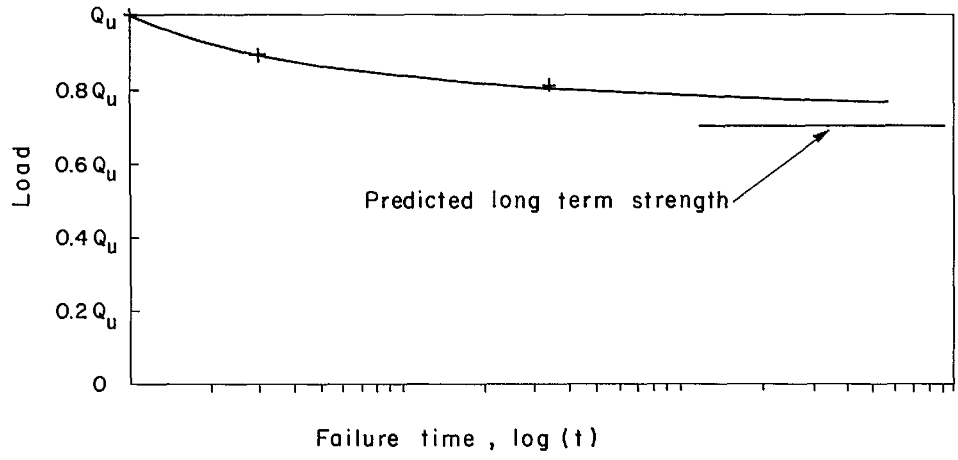


Fig 58 - Curve of applied load vs time of failure.

REPORTING OF RESULTS

96. The report should include the following information:

a. sample identification (rock type, origin)
b. a graph showing the curves of axial strain versus elapsed time (Fig 57)
c. the time of failure versus load curve (Fig 58)
d. predicted long-term strength of the rock substance
e. storage and environmental history of the sample
f. method and date of specimen preparation, storage history of specimens and number of specimens tested at various load levels
g. average short-term uniaxial compressive strength of the rock substance
h. average short-term uniaxial failure strain of the rock substance
i. information on testing such as: date, type of testing apparatus, type of deformation measuring device and environmental conditions
j. average water content of the sample
k. any other observations or available physical data.

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1. Hardy, H.R. "Standardized procedures for determination of the physical properties of mine rock under short period uniaxial compression"; Unpublished Fuel Division report FRL-242; 1957.

2. "Standard method of test for elastic moduli of rock specimens in uniaxial compression"; Designation: D 3148-72; American Society for Testing and Materials; Annual book of ASTM standards; 1974.

3. "Standard method for laboratory determination of pulse velocities and ultrasonic elastic constants of rock"; Designation: D 2845-69; American Society for Testing and Materials; Annual book of ASTM standards; 1974.

4. "Standard method of test for triaxial compressive strength of undrained rock core specimens without pore pressure measurements"; Designation: D 2664-67; American Society for Testing and Materials; Annual book of ASTM standards; 1974.

5. Lama, R.D. "Suggested method for determination of time-dependent and plastic properties"; International Society for Rock Mechanics, Commission on Standardization of Laboratory and Field Tests, Committee on Laboratory Tests, Document no. 12; first draft; Aug. 1973.

APPENDIX A

DIFFERENTIAL TRANSFORMER COMPRESSOMETER

1. This device has been developed (1) to measure the axial strain of a cylindrical specimen loaded axially, thereby determining the elastic modulus of the rock substance. The principal features of the device are as follows:

a. high sensitivity (a strain of 2 micro in. per in. can be detected), consequently the instrument is suitable for rocks with low deformation characteristics
b. extended measuring range, (linear range over 30,000 micro in.), consequently the instrument is equally suitable for rocks of high and low deformation properties
c. simple design, consequently the instrument can be adapted to suit any core size (both diameter and length)
d. the strain recording unit is commercially available which means modest additional costs to suit specific requirements
e. easy installation and strain recording procedure and therefore no special experience required to use the instrument
f. relatively low-cost manufacturing
g. can be used for an indefinite number of non-destructive tests.

DESCRIPTION OF DEVICE

2. The compressometer (Fig A-1) consists of two aluminum rings secured to the specimen by four round-ended brass screws. The transformer units of two appropriately sized differential transformers (such as a Sanborn Model No. 595 DT-100) with their lead wires, are fitted into the lower ring. The magnetic-core units of the differential transformers are mounted on brass rods which are, in turn, threaded into the upper ring. Several holes are drilled into the rings to reduce their weight. Any two diametrically opposed pairs of holes are also used to align the rings while they are being installed on the specimen. In case of very soft rock material, the mounting screws are modified. Shorter screws are used and a firm grip is ensured by rubber-tipped spring-loaded pins, inserted between the specimen and the screws.

INSTALLATION OF DEVICE

3. The necessary steps for installing the compressometer (Fig A-2) are as follows:

a. the specimen is placed on the lower disc and centred on the loading platform
b. the lower ring is slipped over the specimen to rest on a pair of metal pedestal blocks of appropriate height
c. two guide rods are inserted into two conveniently located and diametrically opposed holes of the lower ring
d. the upper ring is slipped over the guide rods and over the specimen, care being taken that the magnetic cores are in proper alignment with

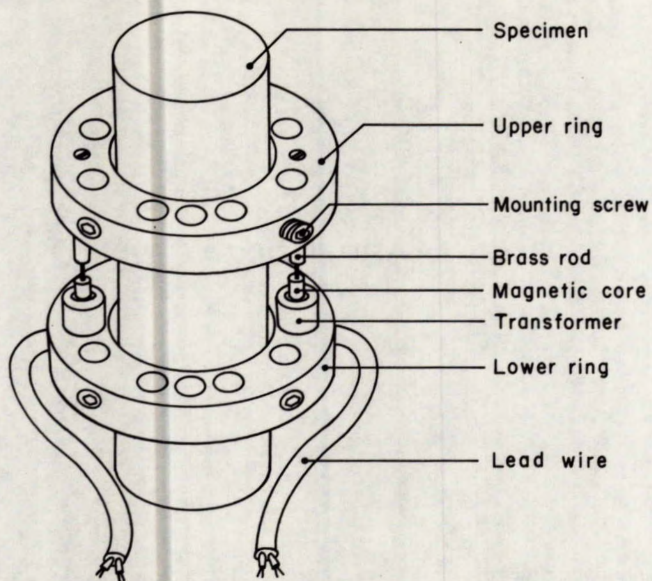

Fig A-1 - Compressometer installed on rock specimen.

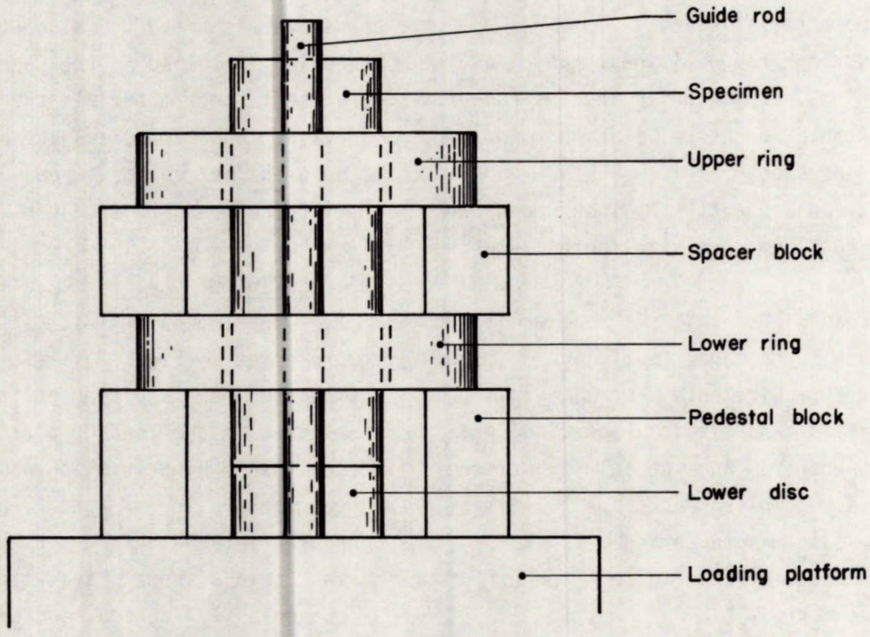

Fig A-2 - Installation of compressometer.

the centre holes of the transformers. Appropriately sized spacer blocks are then placed between the two rings

e. the mounting screws on both rings are tightened after checking alignments, especially that of the transformers and magnetic cores
f. the pedestal blocks, spacer blocks and guide rods are carefully removed before the electrical leads between the transformers and strain recording unit are connected.

STRAIN RECORDING UNIT

4. A standard "Baldwin" (Type N) strain indicator can be used for strain recording. As shown in the circuit diagram (Fig A-3), the transformers are reversed, ie, the input voltage is fed into the secondary windings of the transformers. A resistor (330 Ω) and a condenser (0.47 μF) is added to the circuit to obtain the highest possible sensitivity over the longest possible linear range. The gauge factor on the strain indicator is set at 2.00, and a full bridge is used (ie, the jumper at the post, R, of the indicator is removed).

CALIBRATION OF COMPRESSOMETER

5. The compressometer has to be calibrated for the predetermined gauge length to be used (ie, the distance measured between the planes defined by the mounting screws of the rings). The device is installed either on a rock specimen or on a metal cylinder (conveniently of brass). This specimen is compressed, by applying various loads in distinct steps, and the displacement of the rings is measured by dial gauges. Strain-indicator readings, corresponding to each load level, are also recorded. The strain indicator readings are plotted against the displacements of the rings, and the calibration constant is established. Fig A-4 shows the calibration curve for a 1.5 in. (3.81 cm) gauge length.

6. Once the intended gauge length has been decided and the calibration has been performed,

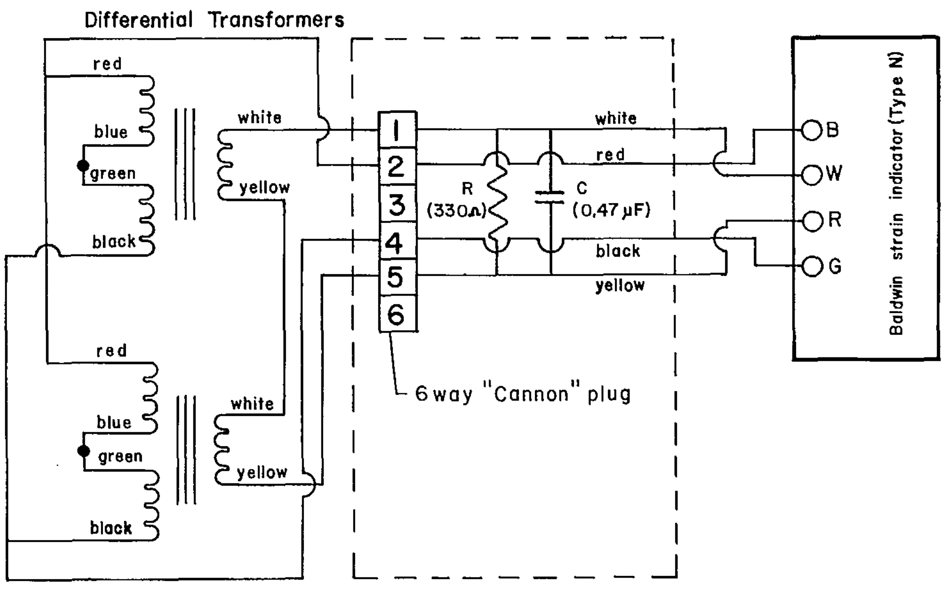

Fig A-3 - Circuit diagram for connecting the two differential transformers to a "Baldwin" strain indicator.

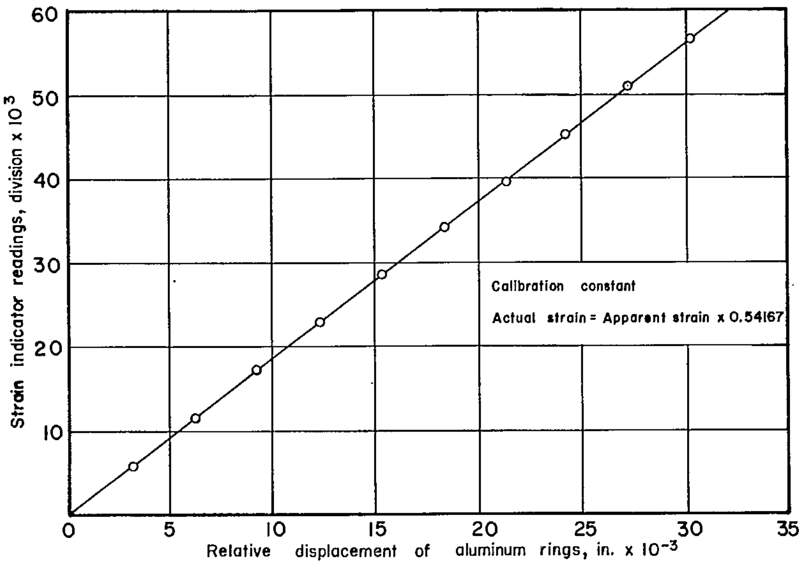

Fig A-4 - Calibration curve of compressometer (in this case Sanborn Model No 595 DT-100 differential transformers, with a 1.5 in. (3.81 cm) gauge length, were used).

spacer blocks corresponding to this gauge length are machined. Due to the physical dimension of the differential transformer, there is a given minimum gauge length for each transformer type. For example, if a Sanborn Model No. 595 DT-100 differential transformer is being used, the selected gauge length has to be more than 3/4 in. (1.905 cm).

REFERENCE

1. van Heerden, W.L. "A compressometer using differential transformers"; Divisional report EMR 65-175-MRL; 1965.