THE EFFECT OF PORE AND CONFINING PRESSURE ON THE FAILURE PROCESS IN SEDIMENTARY ROCK

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CONTENTS

ILLUSTRATIONS

TABLE

INTRODUCTION

The work reported here was performed to provide a foundation for possible future improvements in methods of drilling boreholes into the earth's crust. The implications of this work, as related to oil-well drilling, will be published in the *Transactions of the AIME*. However, since this research concerned the fundamentals of rock failure, the information contained in this report may find application in other industries also interested in rock properties. Some of the methods and interpretation of data are closely related to those well known in soil mechanics.

Early in the twentieth century it was observed that the principal factor affecting rock failure in the state of applied stress of the rock (Adams and Nicholson, 1901; von Karman, 1911; Boker, 1915). More recently, a number of investigators have explored the effects of stress on the strength of various types of rocks because of the geologic implications of rock strength (Griggs, 1936; Bredthauer, 1955). A summary of the strength and elastic properties of rocks was recently presented by Wuerker (1956). The possible applications of rock strength data to structural petrology, to structural geology and geophysics, to engineering and to the physics of solids was summarized by Handin (1957) at the Second Rock Mechanics Symposium.

The effects of pore pressure in soils were described by Terzaghi (1943) in 1943. He has also discussed (1945) the stress conditions for failure in water-saturated concrete and rocks. He states that until triaxial compression tests are made with controlled pore pressure conditions, the stress conditions for the failure of rocks at depth remain a matter of speculation.

It is surprising, perhaps, that so little has been published concerning the failure of rocks containing pore pressure when those working in the field of soil mechanics are cognizant of the important role of the liquid in the pores of unconsolidated masses. For example, the behavior of "quicksand" is the well-known effect of having a large vertical gradient in pore pressure. This gradient must be so large that the weight of the sand grains no longer produces an effective confining pressure. Since the shear strength of the soil is then zero, the state of the soil is said to be "quicksand." This example provides a clear illustration of the effect of pore pressure on the state of stress of materials.

Some of the early work in triaxial compression testing was done by Griggs (1938) in 1936 with unjacketed samples of rock. In these tests the pore pressure tended to become equal to the confining pressure. A brittle-type failure was observed at 4000 atm in Solenhofen limestone and in marble. With higher confining pressures, Griggs observed plastic flow. In subsequent work, Griggs and his co-workers (Griggs, 1940; Handin and Griggs, 1951), jacketed their samples, and most of the rocks were tested with pore pressure equal to zero. The results of this work demonstrated that the mode of failure and the strength of the rock are dependent on the confining pressure. Comparison of the two types of tests, unjacketed and jacketed, indicated that the application of pore pressure changed the properties of rocks.

Information on the behavior of concrete with nitrogen pressure in the pores was published by McHenry (1948). Three hundred thirty-seven jacketed and unjacketed concrete specimens were compressed while subjected to confining pressures up to 1800 psi. Three tests were reported in which the pore preessure was one-quarter, one-half, and three-quarters of the lateral confining pressure. In these three compression tests, the measured failure stresses are consistent with the experiments in which no pore pressure was applied if the concept of "effective" external pressure is introduced. This concept assumes that the pore pressure acts over the full area of the potential surface of failure. Consequently, the effective pressure between the grains contacting this area is the confining pressure reduced by the amount of the pore pressure.

One application of these studies of the rock failure process is to the drilling of deep boreholes in the earth's crust. When drilling with certain types of roller rock bits, the formation is removed by exceeding the "compressive" strength (or more exactly, the shearing resistance) of the material under the teeth of the bit. Since this compressure is strongly influenced by confining and pore pressure, it is a natural step in understanding the drilling process to resort to triaxial compression tests with the confining and pore pressures simulating conditions experienced while drilling.

All of the experiments which have been described produce the conclusion that in either consolidated or unconsolidated materials, the stress between the grains controls the failure properties. For this reason pore pressure is an important variable in the study of soil or rock properties. The research described in this paper was undertaken to obtain quantitative data on the yield strength and mode of failure of limestone, sandstone, and shale subjected to various confining and pore pressures.

EQUIPMENT

To test the failure characteristics of rocks under compressive loading while they are subjected to controlled stress conditions, it was necessary to design and fabricate a compression cell which both holds liquid pressure to surround a test specimen encased in a plastic sleeve, and admits liquid pressure directly to the pore volume of the specimen while it is compressed by a piston. A liquid pressure regulator was used to maintain a constant confining pressure around the test specimen while the compressive load is applied. The compression cell (positioned between the platens of a Tinius Olsen universal testing machine), the pressure regulator, and the associated pressure equipment are shown schematically in Figure 1.

The compression cell, shown in more detail in Figure 2, is a hollow cylinder 5 inches outside diameter, 2.5 inches inside diameter, and 8 inches long. It is made of AISI designation 304 stainless steel and designed for a working pressure of 15,000 psi. The top closure is fitted with a movable piston. To allow the transmission of pressure into the vessel, there are two

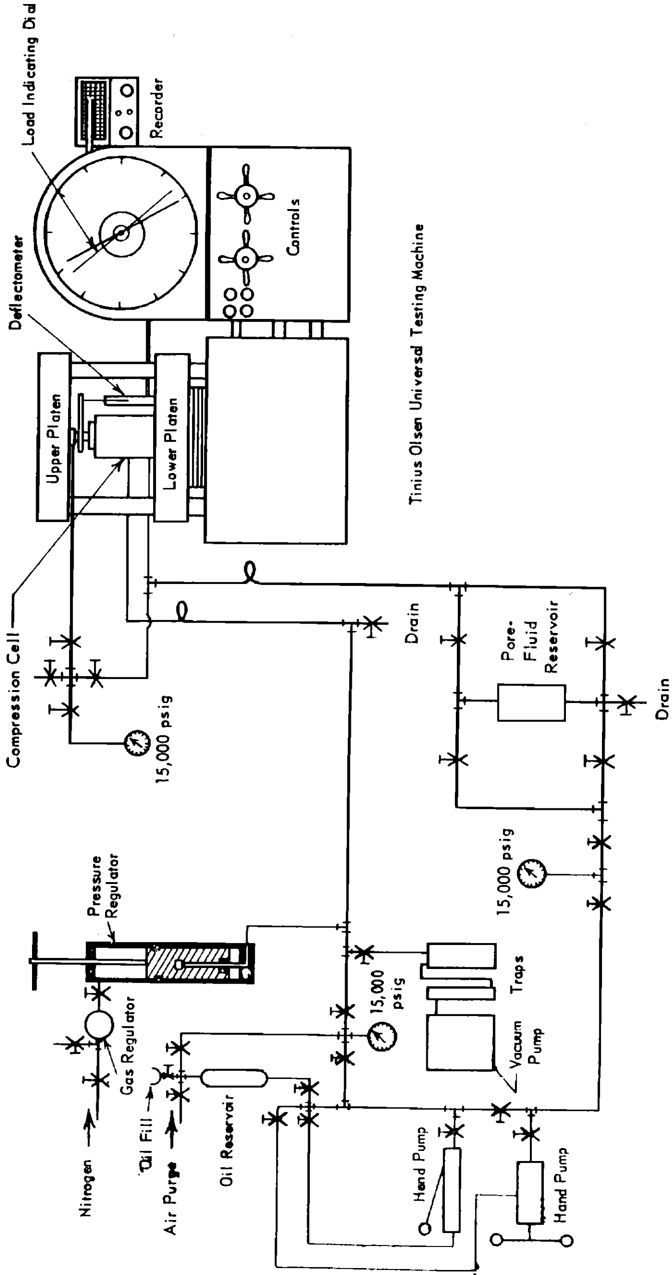

FIGURE 1. Schematic diagram of fluid supply system and compression cell positioned in testing machine.

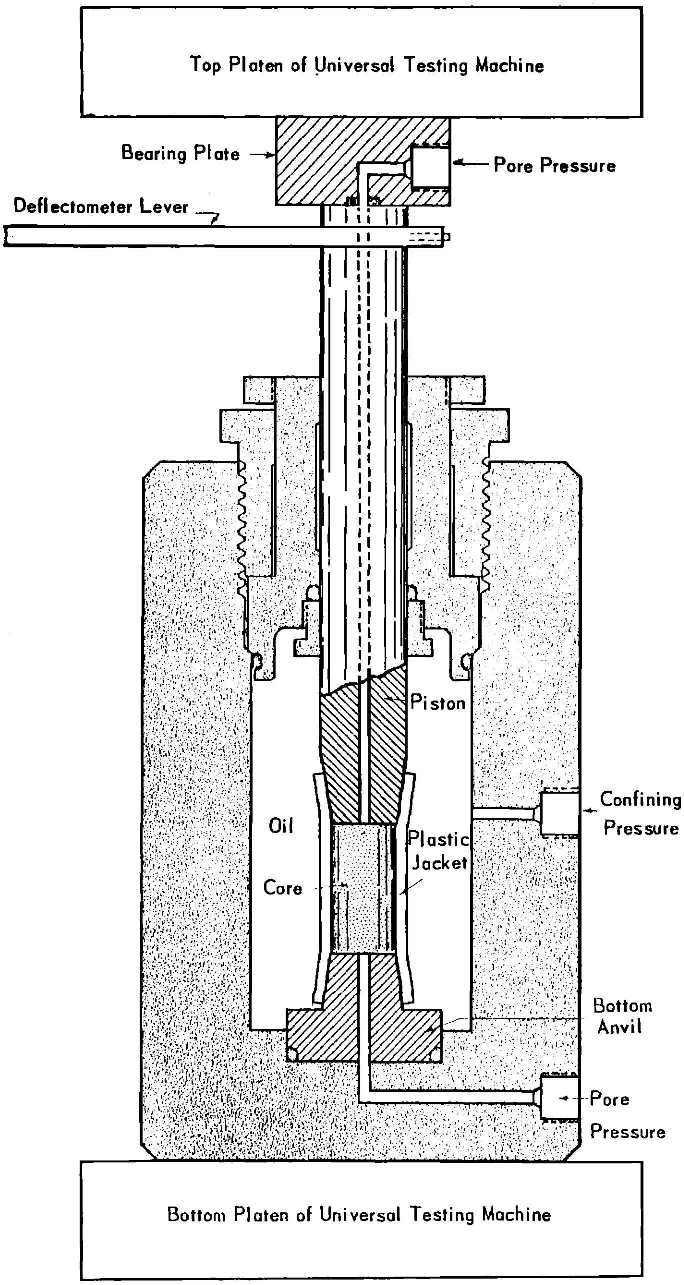

FIGURE 2. Compression cell.

entry ports. The uppermost opening permits a confining pressure to be applied around the test sample, and the lower opening permits a pore pressure to be applied directly to the interstices of the core. One other opening (not shown) in the pressure vessel facilitates draining and cleaning of the vessel.

The piston is made with a hole bored axially through its center. The top bearing plate permits the pore pressure fluids to enter into the top of the core.

The liquid system used for filling and pressuring the compression cell is designed for a working pressure of 15,000 psi. A vacuum pump is used to remove air trapped inside the system after the top closure has been placed on the compression cell. White mineral oil, National Formulary grade 65, is used to transmit the pressure that surrounds the specimen. Pore pressure is applied by pumping the mineral oil against water contained in a 150-cc reservoir. Two hand pumps are used to apply the desired confining and pore pressure.

The piston which causes the anvils to compress the specimen is loaded by the Tinius Olsen universal testing machine. This machine also records a force-deformation curve which relates to force applied to the piston and the movement of the piston. The movement of the piston is detected with a deflectometer activated by the deflectometer lever illustrated in Figure 2.

When the piston moves into the compression cell during the test, the pressure regulator maintains a constant pressure in the liquid-filled system that surrounds the encased specimen. The liquid pressure admitted directly to the pores of the test specimen is controlled satisfactorily with one of the hand pumps.

Since a considerable length of time is required to saturate very low permeability rocks, a yoke system has been provided for the compression cell so that the piston remains in place while 5000-psig pore and confining pressures are applied to the rock which is being saturated.

EXPERIMENTAL PROCEDURE

The rock specimens were prepared as cylinders 0.750 inch in diameter and 1.50 inches in length. All triaxial tests were performed with specimens saturated either with distilled water (limestones and sandstones) or with brine (shale). Saturation was accomplished by evacuating the air from the specimen and then flooding the liquid into the core.

After the specimen was mounted in the compression cell and saturated with liquid, an appropriate confining pressure was applied to the outside of the plastic sleeve and the pressure in the pores of the rock was adjusted to the desired value. The specimen was then made to fail in compression by moving the platens of the compression machine at a constant rate of 0.0015 inch per second.

THE ROCK FAILURE PROCESS

The manner in which stresses affect the failure of a typical sedimentary rock was examined in detail. Indiana limestone was selected for this study because it is relatively homogeneous, is readily available in quantity, and can be saturated quickly and easily.

Experimentally, the factor which controlled the mode of rock failure was found to be the *difference* between confining and pore pressure. As this difference increases from zero to about 10,000 psi, the mode of failure gradually changes from brittle to malleable. The gradual transition can be observed from the force-deformation curves.

FORCE-DEFORMATION CURVES

The force-deformation curves produced as the piston compresses the test specimen are shown in Figure 3. These curves represent cores which have been compressed while subjected to a 10,000-psig confining pressure. Each of the lines represents a core which has been compressed at a different pore pressure. One obvious feature of these curves is the linear section during the early stages of the deformation. This is commonly interpreted as indicating elastic behavior.

When the pore pressure is the same as the confining pressure, the core fails by brittle fracture. The curve marked A is a force-deformation curve typical of a brittle material. A typical plastic-type deformation is illustrated

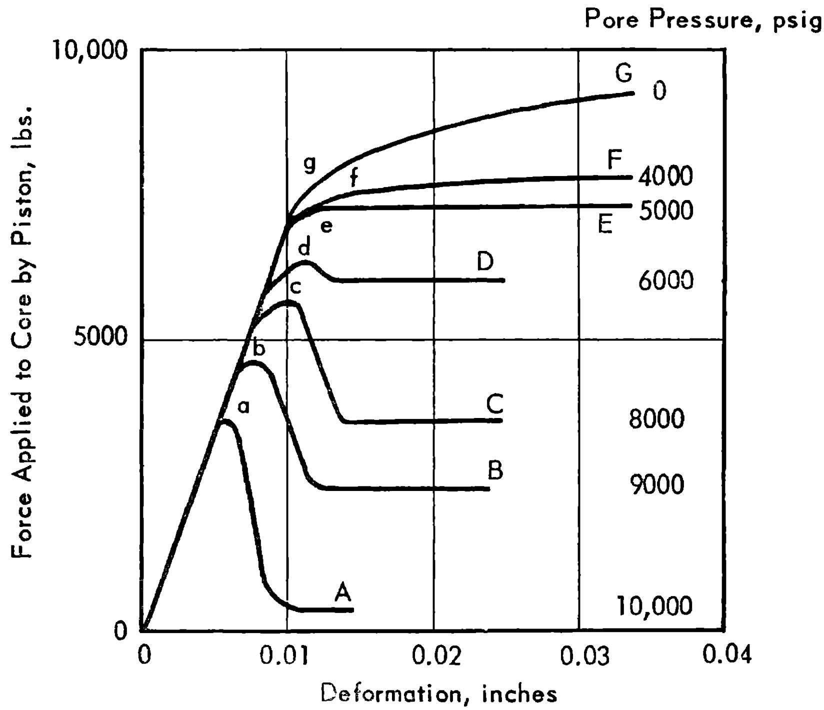

FIGURE 3. Force-deformation curves for Indiana limestone at a confining pressure of 10,000 psig.

by curve G, which was produced at zero pore pressure. The force increases rapidly at first and then becomes almost constant in the latter stages of the deformation.

It is interesting to note that Orowan (von Karman, 1911) states that if a load maximum is observed in compression, it must be due to a true softening, or loosening of the material with increasing deformation. If this is true, the maximum peaks (a, b, c, and d) represent points at which the material becomes strain-softened* (corresponding to thixotrophy) because a load maximum is observed. When the pressure differential reaches about 5000 psi, the strain-softening disappears and there is evidence (by the gradual increase of the force) of strain-hardening.

YIELD STRENGTH

The points marked a, b, c, d, and e in Figure 3 are normally defined as yield points. The data clearly show that for constant confining pressure, the yield strength increases as the pore pressure decreases. The yield strength represents the stress at which an increase in strain does not produce an accompanying increase in stress.

No well-defined yield points appear at f and g in Figure 3 because the applied piston force is never constant with increasing deformation at pore pressures of zero and 4000 psig. It is desirable to adopt a standard method for determining yield strength, even in malleable deformation; and, therefore, an arbitrary convention was adopted. The yield strength has been chosen as the stress necessary to deform the specimen 0.2 percent beyond the proportional limit.

The effect of the pore pressure on the yield strength of Indiana limestone is shown in Figure 4. One of the most interesting features of Figure 4 is the fact that when the confining and pore pressures are almost equal, a slight decrease in pore pressure results in a relatively large increase in the yield strength. In the section a-a of curve A, for example, a decrease of only 500 psi pore pressure results in an increase of approximately 25 percent in the yield strength.

Superimposed upon this primary effect is a secondary effect caused by the absolute magnitude of the two pressures. Curve B in Figure 4 shows that the yield strength increases about 25 percent as the pore and confining pressures are simultaneously increased from zero to 3000 psig. Above this pressure, little additional increase in yield strength occurs.

THIN-SECTION ANALYSIS

The force-deformation curves give a good macroscopic description of the way in which triaxial test specimens fail. However, it is also of interest to determine microscopically the manner and sequence in which malleable rock failure proceeds. To do this, a number of specimens were compressed to various deformations, and thin sections were made of a central slab of each specimen. The results illustrate, step by step, the process of malleable failure.

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*In metals, strain-hardening is common. After an initial yielding, re-application of the load finds the apparent yield stress is greater.

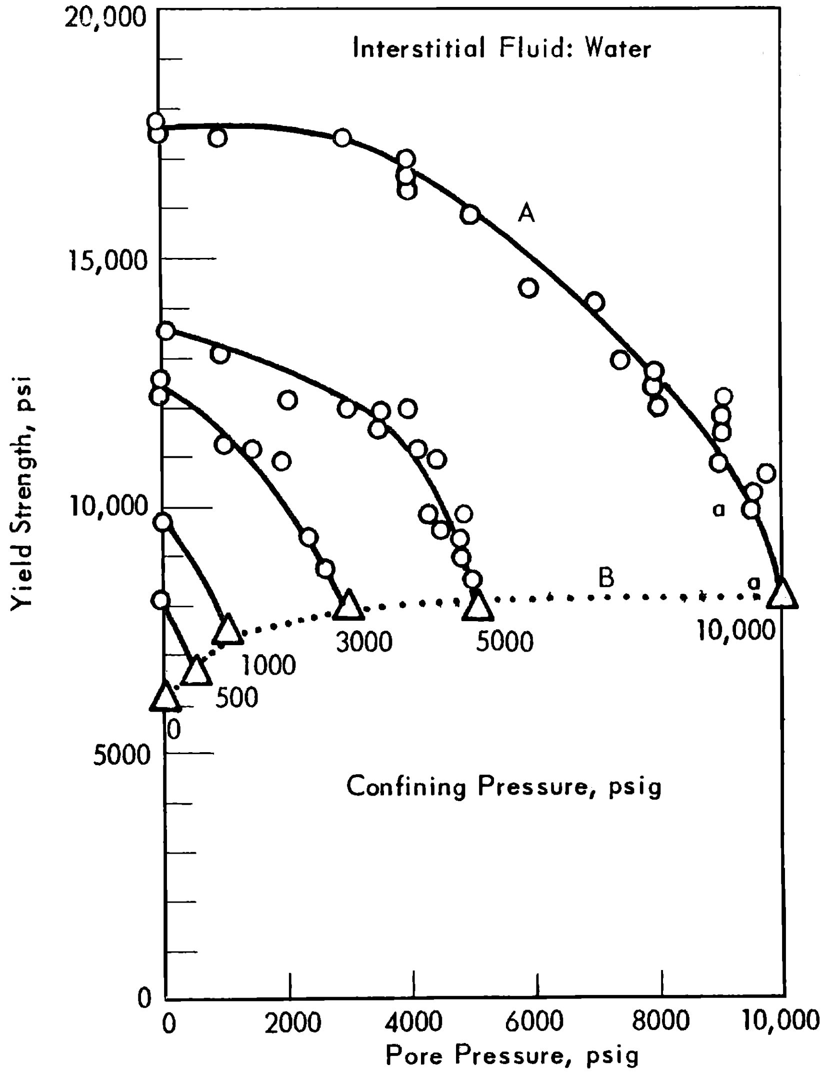


FIGURE 4. Effect of pore pressure on the yield strength of Indiana limestone.

Figures 5 and 6 are typical of the suite of thin sections obtained. An undeformed. Indiana limestone thin section is shown in Figure 5 to demonstrate the grain size and shape before deformation. Figure 6 shows cores compressed with 10,000 psi difference between pore and confining pressure.

As the piston compresses a core, the regions adjacent to the piston at the top and to the anvil at the bottom do not yield. These two conically shaped regions are called cones of fracture. After yielding, plastic deformation occurs for a short while outside the cones of fracture. When the crystals can no longer plastically deform, they begin to shear apart. Simultaneously, a concentration of broken crystals appears at the boundaries of the cones of fracture.

Figure 6A shows a rock sample which has been compressed to about 83 percent of its original length. The cones of fracture are well developed, and both plastic and minor shear deformation are evident.

As compression continues, the cones of fracture meet and then become distorted. Finally, a condition is reached where although major shear planes still outline the cones of fracture, the only recognizable crystals are those immediately adjacent to the piston and anvil. Figure 6B is a thin section of a core which has been deformed in this manner.

During this phase of the compression, more and more crystals are sheared apart until the crystal structure in some areas of the rock is unrecognizable at the magnification used in Figure 6B. Some X-ray analyses, which are not presented here, revealed that these areas are not amorphous but are still crystalline, as shown by the presence of characteristic principal lattice spacings.

Change in Pore Volume After Yielding

An interesting feature of many of the deformation experiments was the tendency of the pore pressure to change in a regular manner. The equipment used to maintain constant pore pressure compensated for this by supplying or removing measured amounts of liquid from the rock pores.

Generally, a small amount of liquid was removed during the initial deformation (linear portion of the force-deformation diagram) indicating a decrease in pore volume. At the point of yielding and thereafter, liquid was supplied to the rock interstices, indicating an increase in pore volume.

The amount of change in pore volume was found to be related to the state of applied stress of the rock. In Table I the state of applied stress of five cores is presented with the volume of fluid input required during the first, second, and third arbitrary increments of deformation after yielding. The pore volume change per unit deformation along the axis of the core has also been computed, and this is given in the last column of Table I.

As indicated in Table I, the pore volume change per unit deformation is dependent upon the differential pressure. When the differential pressure is about 4000 psi, relatively little increase (about 45 percent per unit deformation) in pore volume occurs. On the other hand, when the differential pressure is less than 4000 psi, very large increases in porosity occur.

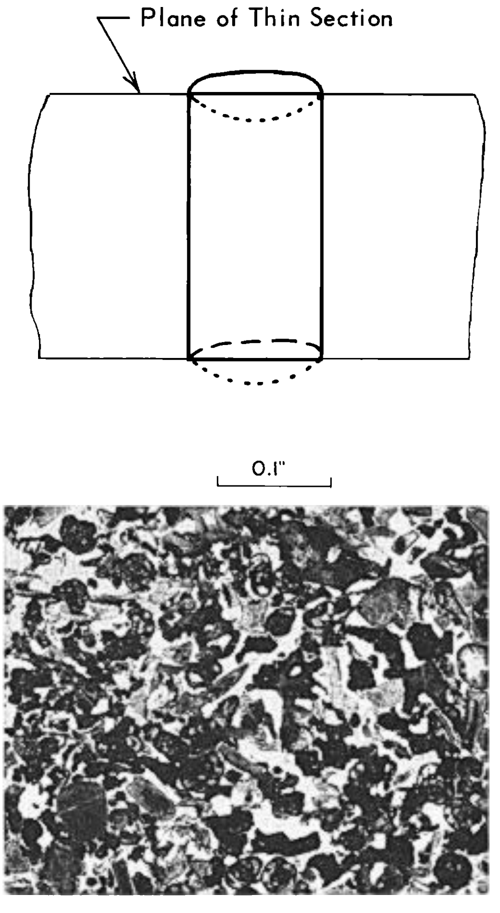
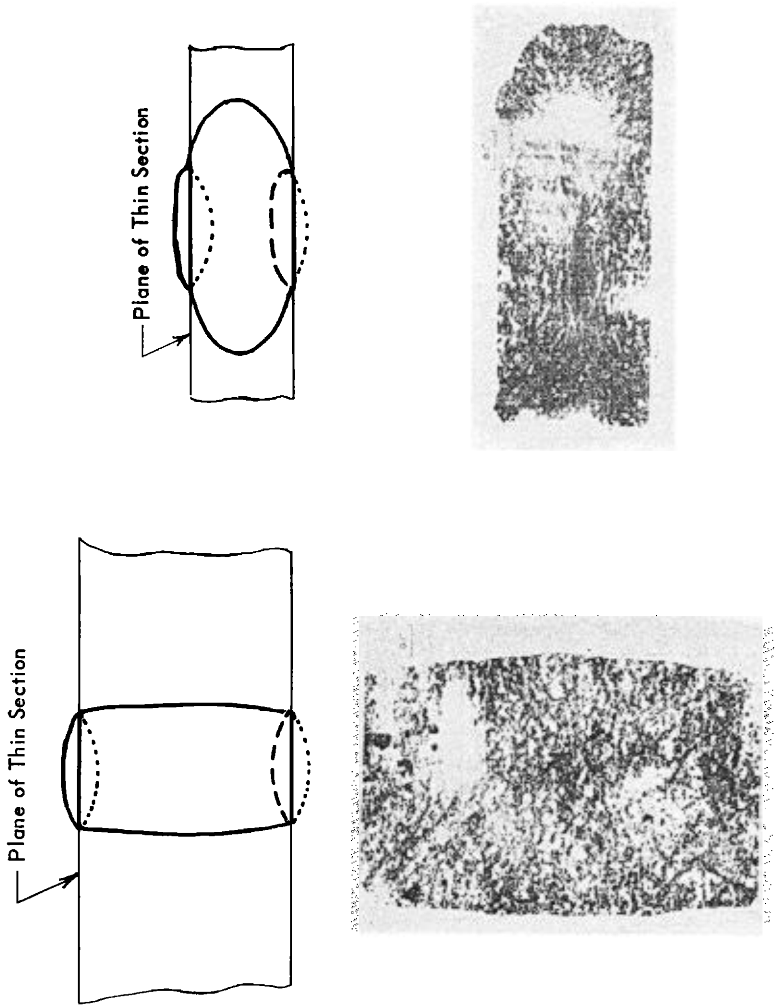


FIGURE 5. Thin section of undeformed Indiana limestone.



A B

FIGURE 6. Thin sections of malleably-deformed Indiana limestone.

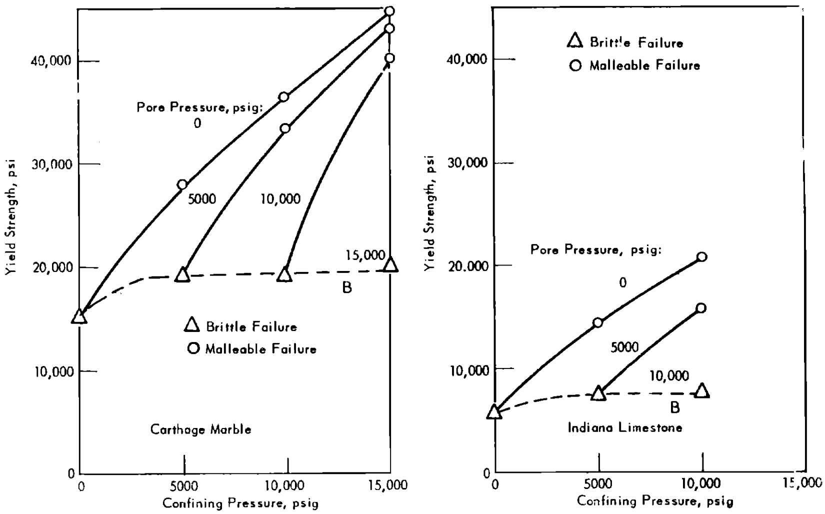


FIGURE 7. Effect of confining pressure on the yield strength of limestone.

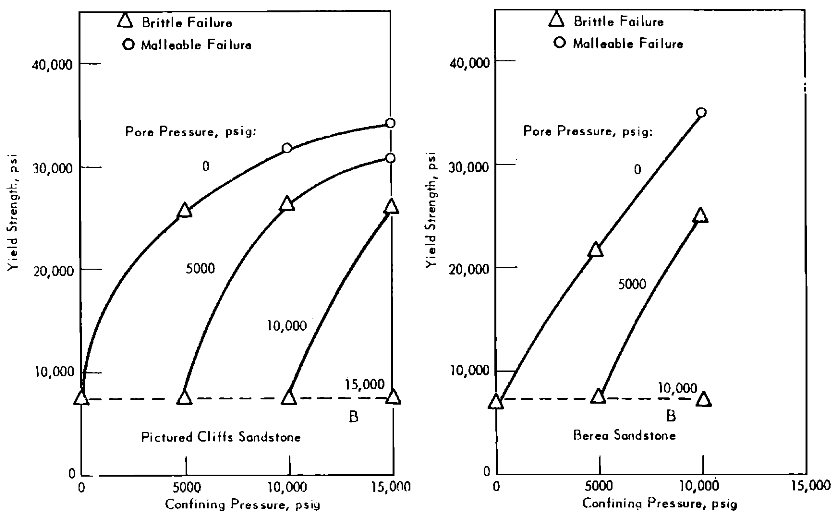


FIGURE 8. Effect of confining pressure on the yield strength of sandstone.

The data from core No. 1 illustrate this effect. Here, a unit deformation of only 0.013 inch/inch increased the pore volume approximately 22 percent. (The original pore volume of this Indiana limestone core was 1.53 cc; the incremental increase in pore volume was 0.33 cc; thus, the final pore volume was 1.86 cc.)

FAILURE CHARACTERISTICS OF VARIOUS TYPES OF ROCKS

The experimental results described above provided a clear picture of the manner in which a single sedimentary rock, Indiana limestone, failed under stress. The question of whether other sedimentary rocks exhibit similar behavior was next investigated. Accordingly, additional specimens of different types were subjected to triaxial loading tests identical to those previously described. Strength and mode-of-failure data were obtained for one other limestone, two sandstones, and one shale.

Limestones

Carthage "marble" was the second limestone tested. Both the Indiana limestone and the Carthage marble are believed to be true limestones (not marbles), and both are obtained from commercial quarries.

Figure 7 shows the relationships between yield strength and confining pressure for various pore pressures. The Carthage marble is obviously inherently stronger, but both limestones have similar modes of failure and show increasing strengths with higher differential pressures.

Sandstones

The two sandstones tested were (1) Pictured Cliffs sandstone cored from a well in the Otero field, New Mexico, and (2) Berea sandstone obtained from a quarry. As is shown in Figure 8, the failure characteristics of the two rocks are very similar.

TABLE I

Effect of State of Stress on Pore Volume Change During Sample Deformation

Core Number	Confining Pressure, 10^3 psig	Pore Pressure, 10^3 psig	Volume of Fluid Input, cc	Increase in Pore Volume, percent	Unit Deformation along Axis of Sample, inch/inch	Pore Volume Change per Unit Deformation, percent
1	10	9.5	0.33	22	0.013 *	1650
			0.32	21	0.015 **	1390
			0.30	19	0.027 ***	735
2	10	8.0	0.036	2.4	0.0033*	705
			0.036	2.4	0.0033**	705
3	10	7	0.10	6.5	0.033 *	195
			0.22	14.4	0.060 **	256
4	10	6	0.05	3.3	0.079	45
5	10	0.1	0	0	....	0

*First increment of deformation after yielding.
**Second increment of deformation after yielding.
***Third increment of deformation after yielding.

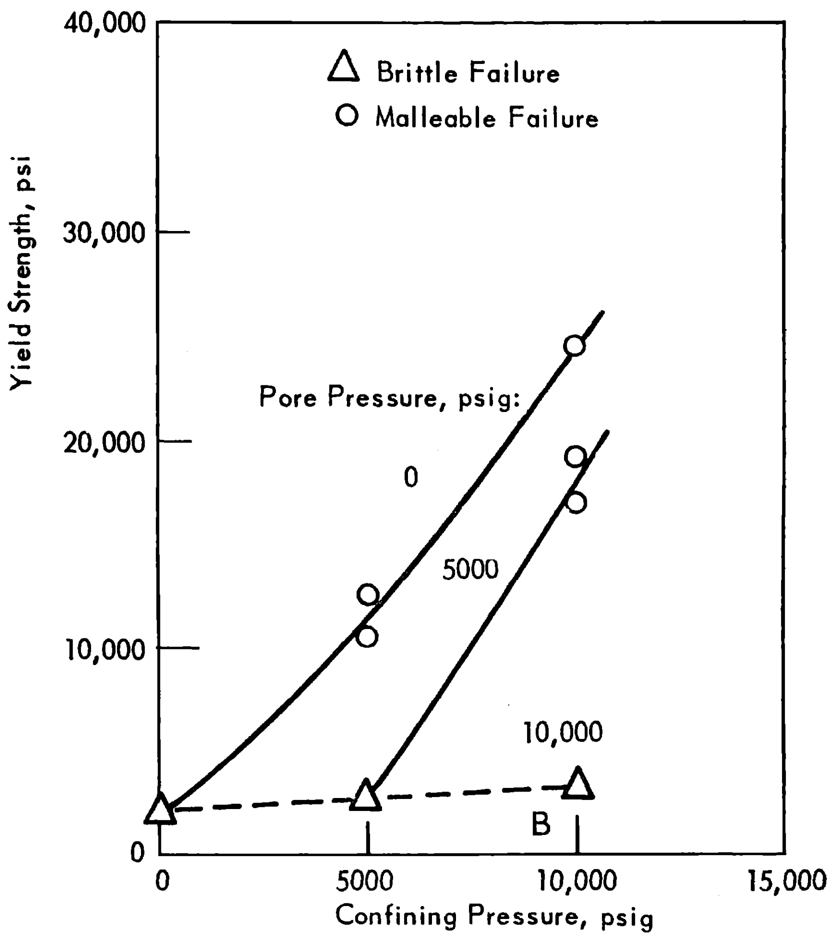


FIGURE 9. Effect of confining pressure on the yield strength of Belly River shale.

These failure curves for sandstone differ from the limestone results in three aspects. First, the yield strength of sandstone increases more rapidly with increased differential between confining and pore pressures, especially at low confining pressures. Second, a higher differential pressure is required before the sandstones fail malleably. Whereas the two limestones undergo malleable failure at a pressure differential of 5000 psi, the two sandstones require about 10,000 psi. Third, as long as the pore and confining pressures are equal, the magnitudes of these pressures have no effect upon rock strengths. This third difference between limestone and sandstone is evident from curves B in Figures 4, 7, and 8.

SHALE

Samples of Belly River shale were obtained from cores taken from Canadian oil wells. These relatively pure shale samples had a permeability of the order of 0.0001 millidarcy, and five to eight days were required to saturate them with brine. Saturation of lower permeability shales was not attempted because of the extremely long times required, even with the high pressures available in the laboratory.

The results of a limited number of compression tests on shale are shown in Figure 9. They conform in most respects to the curves of limestone and sandstone. These data reveal that the Belly River shale has a relatively low yield strength at zero differential pressure, but that the strength increases very rapidly as a pressure differential is applied.

FAILURE THEORY

Mohr's circles and envelopes have been used extensively to describe the failure characteristics of rocks and soils. At the last Rock Mechanics Symposium, Silverman (1957) discussed the various failure theories with considerable attention given to Mohr's General Theory of Failure. Because of his excellent discussion as well as explanations available in textbooks on failure of materials, there is no necessity of explaining Mohr's theory here. R. R. Philippe and F. M. Mellinger (1957) presented some results of triaxial compression tests of limestone in the form of a Mohr's diagram. They found that the angle of the linear envelope of the stress semi-circles was 37° with the abscissa for a series of tests with confining pressures up to 4000 psi.

In the early applications (Adams and Nicholson, 1901; von Karman, 1911) of Mohr's theory of failure to rocks, pore pressure was not mentioned. The effect of the interstitial pore pressure on the location of the Mohr's stress circles was discussed by McCutchen (1949) in 1949. He surmises that the normal compressive stresses along the plane of failure (*i.e,* normal stress between the grains) is counteracted by the hydrostatic pressure of the fluids in the pore spaces of the rock; therefore, the apparent shear strength of the rock is lowered. This, of course, changes the location of the Mohr's circles. Thus, McCutchen suggests that there would be no justification in drawing an envelope to the semi-circles constructed using the pore pressure as a parameter instead of part of the normal stress.

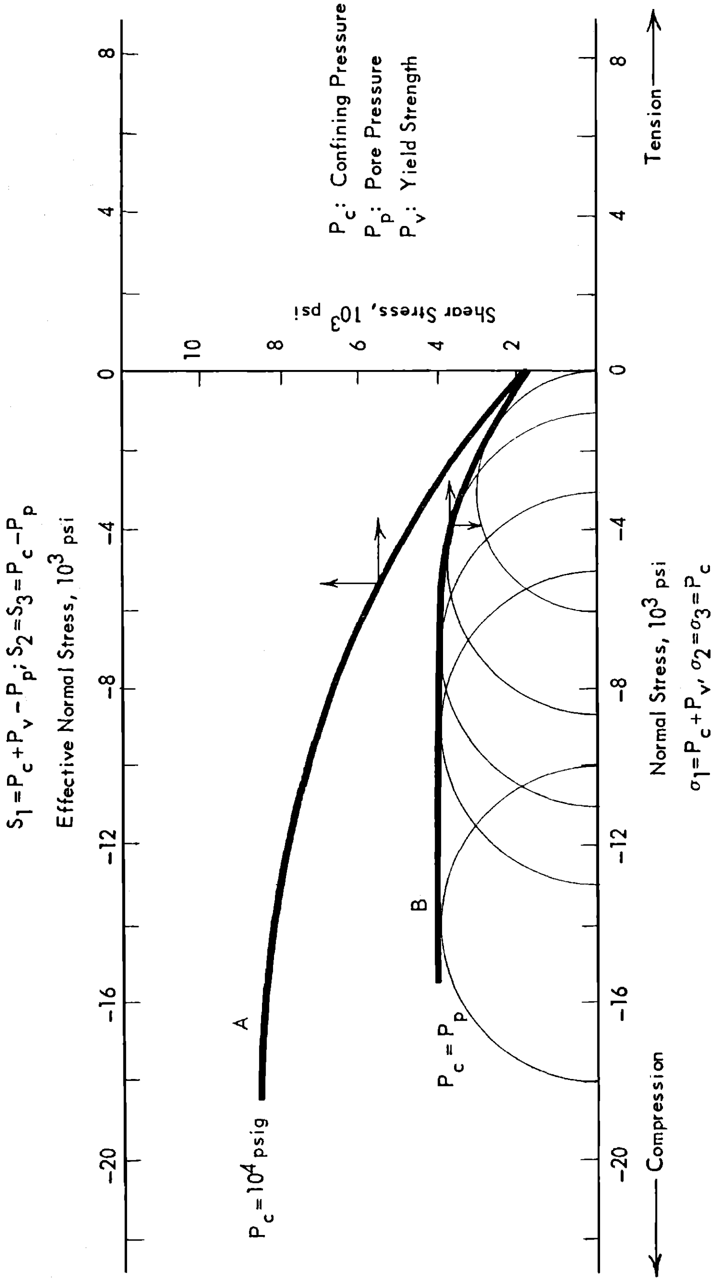


FIGURE 10. Mohr's Envelopes for Indiana limestone.

MOHR'S ENVELOPES

In Figure 10 two possible methods of interpretation of the normal stresses are used to construct the Mohr's envelopes. The top curve (marked A) has been constructed using the effective stresses and the bottom curve (marked B) has been constructed using the pore pressure as a parameter for the case of pore and confining pressure equal. Normally, a constant shearing stress in a Mohr's diagram is interpreted to be related to plastic yielding; however, all of the failures which are represented by curve B were brittle failures. Therefore, as McCutchen suggests, there can be no justification for drawing an envelope to this series of semi-circles. All of the Mohr's semi-circles shown under curve B should be constructed using the effective stresses and should have the right periphery of the circle on the origin.

In Figure 11 the Mohr's envelope has been drawn for the Pictured Cliffs sandstone. The lower section of the envelope is linear and makes an angle of about 46° with the abscissa. The conditions of applied stresses make the sandstone brittle in this region, a conclusion which is in agreement with the interpretation of a linear envelope.

In Figure 12 the Mohr's envelope has been drawn for the Carthage marble. The strength of this rock corresponds to strength of the limestone described by Philippe (Philippe and Mellinger, 1957). The lower linear part of this envelope makes an angle of 34° with the abscissa. This compares favorably with the 37° reported by Philippe.

DISCUSSION OF THE FAILURE MECHANISM

The transition of the rocks from brittle to malleable material as observed in the experiments presented in this paper agrees quite well with the behavior of materials described by P. W. Bridgman (1952). He points out that the term "brittle" properly does not refer to the process of fracture, but to the events occurring before the fracture. For example, if very little permanent deformation can occur before a material fractures, then the material is brittle; however, if it fractures after receiving a permanent set or a permanent deformation, then the material is plastic, *i.e.*, ductile or malleable. Bridgman emphasizes that all fractures might be spoken of as brittle, because a plastic substance which has been work-hardened to the limit fails by brittle fracture.

Returning to the cases which have been presented in this report, the thin section analyses of the Indiana limestone revealed that the crystals twin and then fail by a shear fracture. In other words, even when a large differential pressure is applied to the rock, the force-deformation diagram indicates a material which is truly plastic in nature. Although the crystals do exhibit a plastic deformation by twinning, there is also brittle fracture occurring through the grains. It is conceivable that, as the pore pressure is decreased from the confining pressure, a greater number of shear planes traverse the core, and the shear planes become shorter.

For example, when the confining pressure is the same as the pore pres-

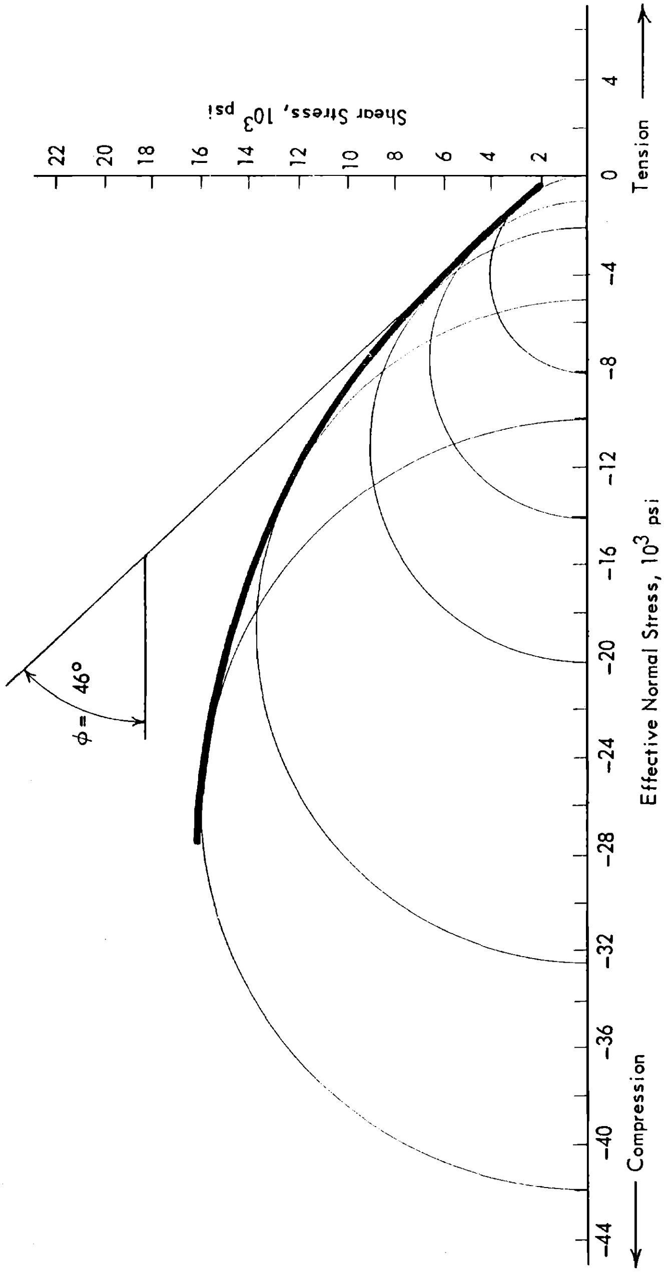


FIGURE 11. Mohr's Envelopes for pictured Cliffs sandstone confining pressure, 104 psig.

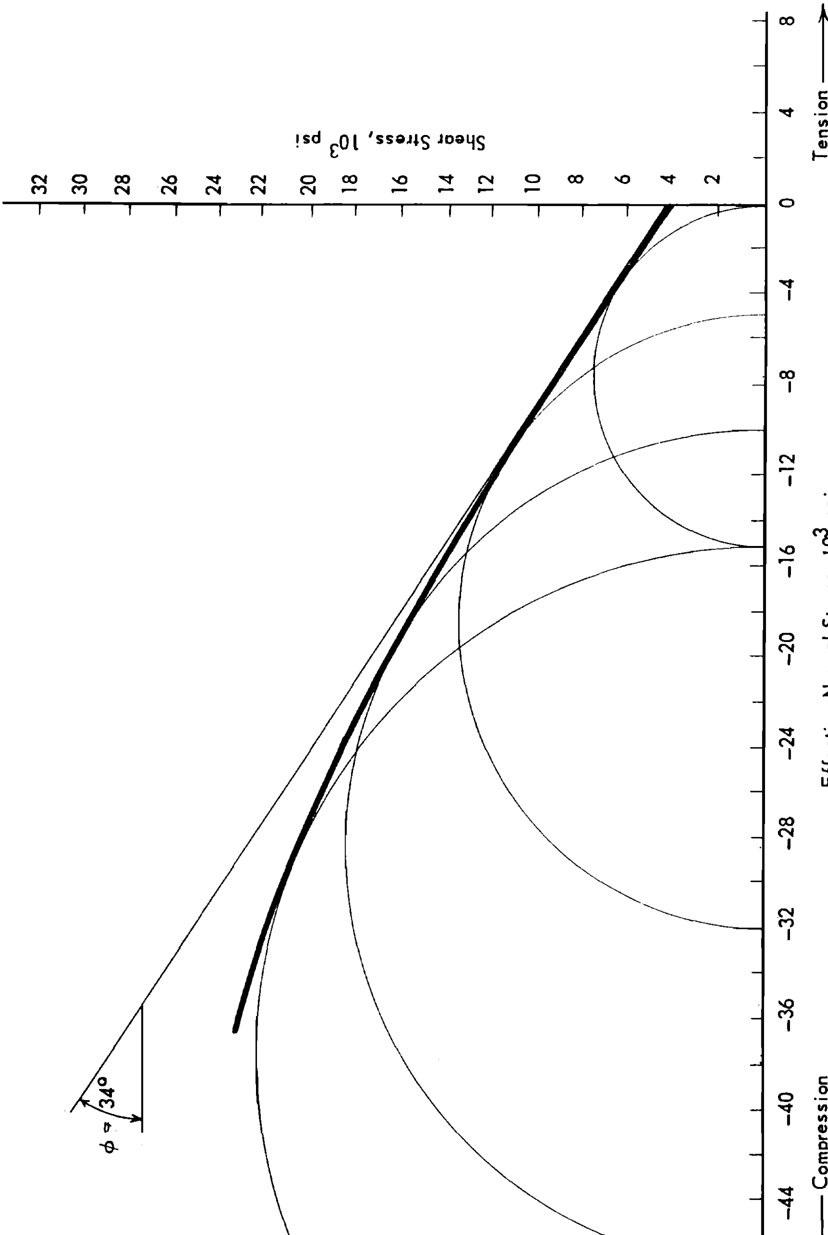


FIGURE 12. Mohr's Envelope for Carthage marble pore pressure, 0 psig.

sure, the cores of all of the specimens reported in this report exhibited one shear plane passing through the rock, and produced a dichotomy of the specimen. However, in Indiana limestone when the differential pressure is 500 psi and the confining pressure is 10,000 psi, two or three shear planes passed through the specimen and produced three or more sections. However, the appearance of the cores which have been compressed when the pore pressure is zero and the confining pressure is 10,000 psi (the case presented in the thin-section analysis) demonstrates that the shear planes are of a much shorter length than those which are exhibited in brittle failure. Indeed, even the appearance of the Luder's lines change as the differential pressure increases. When the differential pressure is 10,000 psi, the surface has a mottled appearance because of the great number of shear planes which have intersected the surface of the core.

CONCLUSIONS

Results of the investigation of the effects of pore and confining pressure on the failure characteristics of sedimentary rocks are summarized in the following conclusions:

1. Common sedimentary rocks will undergo either malleable or brittle failure, depending upon the difference which exists between confining pressure and internal pore pressure.
2. Although shales, limestones, and sandstones have inherently different strengths, it was observed
   (a) that brittle failure always occurs when the confining and pore pressures are equal, and
   (b) that the mode of failure changes gradually from brittle to malleable as the differential between the confining and pore pressures increases the transition pressure depending on the nature of the rock and the pressure level.
3. The yield strengths of rocks increase only slightly as the confining pressure increases if the confining and pore pressures are maintained equal.

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