MULTISTAGE TRIAXIAL TESTING OF ACTUAL RESERVOIR CORES UNDER SIMULATED RESERVOIR CONDITIONS

by

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Abstract

Non linear stress-strain behavior and failure envelopes are the main petroleum related rock mechanical data of interest to the research program briefly summarized in this paper. A series of multistage triaxial compression tests were conducted to determine the rock mechanical properties of actual reservoir cores under simulated reservoir conditions of temperature, fluid saturation, pore, overburden and confining pressures. The multistage triaxial testing option is extremely viable mainly because of the scarcity of actual reservoir rocks. More often than not the multistage approach is the only workable option. It is well known that actual cores and even more so preserved ones are only available under limited conditions. Multistage triaxial testing can generate a full failure envelope using a single core plug compared with a set of at least three core samples in case of the single stage testing procedure. The primary objective of these tests is to determine the mechanical properties of the reservoir rock formations. For every test stage the core sample is unloaded to its previous confining pressure after it exhibits signs of approaching failure. Each test involves four confining pressures and hence three unloading paths are recorded for each sample. Description of the multistage triaxial testing approach, followed in this research program, along with the single stage-multistage comparative study are presented in details. From the experimental test results obtained so far, the following observations were made: 1) With increasing confining pressure, the sandstone reservoir rock exhibits a stiffer response in both the deviatoric stress-axial strain and deviatoric stress-radial strain regimes. 2) The failure load of the sandstone reservoir rock increases with an increase in confining pressure. 3) The failure envelope can be approximated by a straight line in the (J_1 - $\sqrt{J_{2D}}$) stress invariant space. 4) The multistage triaxial testing procedure appears to be an efficient alternative to determine the rock mechanical properties under reservoir conditions whenever core sample availability is limited.

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Introduction

Petroleum related rock mechanics triaxial testing provides valuable data to many aspects of petroleum engineering: Wellbore stability in drilling, sand strength and elastic properties along with stimulation design parameters in production engineering, infill drilling and pattern injection in improved hydrocarbon recovery. This paper describes a multistage triaxial testing approach based on the recommended procedure of the International Society of Rock Mechanics (ISRM)[1]. Actual reservoir cores saturated with actual fluids have been tested under reservoir conditions of pressures, fluids distribution and temperature. Preserved reservoir cores are representative of the formations from which they were cored despite the fact that they do have some serious limitations (shape and size) when compared to outcrops and/or synthetic cores. However, actual cores are rather rare especially adequately preserved ones. A stress-strain behavior determination to generate a failure envelope requires at least three single stage triaxial tests (i.e., three rock samples). On the other hand, a similar failure envelope may be obtained through, only one multistage triaxial test, on a single rock sample. A set of Berea sandstone cores were tested to compare the single stage-multistage triaxial results. A comparison of dynamic rock elastic properties derived from field and laboratory experiments and the corresponding static elastic properties obtained through multistage triaxial testing gives a good indication of the accuracy of the data generated through multistage triaxial testing. The procedure, described in this paper, appears to be an efficient alternative to generate petroleum related rock mechanics properties under reservoir conditions.

Experimental procedure

In multistage triaxial testing one single core plug can be used to generate a full failure envelope. The testing procedure includes sample preparation under ISRM[1] specifications, sample jacketing, mounting and saturation to meet the reservoir conditions under investigation and finally the actual multistage triaxial testing process.

Sample preparation

The consolidated and poorly consolidated preserved sandstone cores used in this study were obtained from different wells within the same field. Four by eight inches core plugs were cut from the poorly consolidated cores and two inches in diameter core plugs were overcored from the consolidated ones. All core samples were prepared in such a way that their length was at least twice their diameter to account for the difference in properties between the sample tested and the platens bounding it. The platens house the transmitter and receiver of the acoustic module which is discussed elsewhere[2]. All core samples tested were steam cleaned for two days and then dried in a vacuum oven at 180 °F for another two days. Their Helium porosity and air vertical permeability were then measured. The end faces of each sample were cut and made flat and parallel to within ISRM[1] specifications to avoid bending moments and ensure accurate axial and radial deformation measurements. The sample is then jacketed, fitted with axial linear variable differential transducers (LVDTs) and a radial extensometer to monitor axial and radial deformations. It is finally mounted in a triaxial cell which allows for pore, confining pressure, temperature and axial load control.

In-situ fluid saturation

As soon as the sample is jacketed, the triaxial cell is closed firmly to prevent leaks and filled with the confining fluid. Vacuum is then pulled from the top of the cell and the sample at a confining pressure of 2000 psi. Once the desired level of vacuum, approximately 0.15 millibar, is achieved a multistage triaxial test is carried out primarily to determine the Biot elastic constant as described in details in reference 3. However, in this case the unloading during each of the four stages is done well before the sample shows any sign of approaching failure. The filtered and deaerated actual reservoir fluid is introduced into the sample from the bottom of the triaxial cell while vacuum is still being pulled to speed up the saturation process. It may take from few minutes to hours and in some cases days to saturate one sample depending on its permeability. After break through, the vacuuming process is stopped and one to several more pore volumes of the saturating fluid are injected to ensure a complete good saturation.

Multistage test

The core sample already jacketed, mounted and saturated is brought to reservoir pore pressure, temperature, and initial confining pressure. The axial load is automatically raised at a constant selected rate while the confining pressure is kept constant until the sample exhibits signs of approaching failure. ISRM recommends to maintain the loading rate between 70 and 140 psi/sec. To complete the first stage, the axial load is lowered manually to the original starting load and the downloading is recorded. This process is repeated by increasing the confining pressure to the second required value. The axial load is raised again at the same specified rate as in the case of the initial confining pressure until the sample shows signs of approaching failure. Four different stages of confining pressures: 3150, 3650, 4150 and 4650 psi are employed in each multistage failure compression experiment. The sample is allowed to fail under the fourth and last confining pressure.

Single stage-multistage comparative study

Several Berea sandstone core samples were tested to compare the failure envelopes generated through single and multistage testing. Berea sandstone core plugs were prepared from the same block of rock. Single stage triaxial tests were conducted till failure on four samples at confining pressures of 500, 3500, 5000, and 7000 psi respectively. The failure curve obtained from these tests is shown in Figure 1 and in the J_1 - $\sqrt{J_{2D}}$ stress invariant space. The invariants J_1 and J_{2D} are defined in terms of the principal stresses $\sigma_1, \sigma_2, and\ \sigma_3$ as:

$$J_1 = \sigma_1 + \sigma_2 + \sigma_3 ;$$
$$J_{2D} = 1/6 [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]$$

A multistage triaxial test on a Berea sandstone sample cored from the same block was performed in four different stages and with the same four confining pressure values, i.e., 500, 3500, 5000, and 7000 psi. The maximum stress values reached during the first three stages and the failure value obtained from the fourth stage, in the J_1 - $\sqrt{J_{2D}}$ stress invariant space, are shown in Figure 1. The stress values representing the first three stages were extrapolated to indicate the approximate failure stresses. The extrapolated values are also shown in Figure 1. It can be inferred (from Figure 1) that the multistage triaxial compression testing yields a failure envelope which is sufficiently close to the one obtained from many single stage triaxial compression tests. Moreover, it is clear that even the failure envelope obtained without extrapolation is close to the actual failure envelope. Similar observations can be made for the case of the rock Young's modulus at different confining pressures.

Experimental results

A series of multistage triaxial compression tests were conducted to determine the rock mechanical properties of actual reservoir sandstone cores. Each core sample was tested under both dry and saturated state. For each of the states, the sample was subjected to multistage loading conditions. In total, a sample was subjected to four confining pressures while under vacuum and dry state, and four confining pressures while saturated. One of the main reasons for running the experiment under both dry and saturated state was to determine the Biot elastic constant. It should be noted here that, while evaluating the Biot elastic constant, the sample was not allowed to approach anywhere near failure. The sample previously tested under dry condition is in-situ saturated with the reservoir fluid and is used for the next (under saturated condition) phase of the multistage triaxial test.

The four different confining pressures applied during each multistage triaxial test on dry samples were 500(C_{d1}), 1000(C_{d2}), 1500(C_{d3}), and 2000(C_{d4}) psi respectively. Typical responses of multistage tests on two dry reservoir samples corresponding to these four different confining pressures are shown in Figures 2 and 3. These curves show clearly that the stiffness or the modulus of elasticity of the reservoir rock increases with an increase in confining pressure.

After completion of the multistage triaxial test (dry condition), the sample is brought to neutral loading condition and is saturated with the filtered and deaerated synthetic formation brine. The confining pressure values were 3150 (C_1), 3650 (C_2), 4150 (C_3), and 4650 (C_4) psi respectively. The actual reservoir pore pressure of 2650 psi is maintained in every stage. Figures 4 and 5 show the typical deviatoric stress-axial strain and deviatoric stress-radial strain responses for the same but saturated samples subjected to the above mentioned four confining pressures. Figure 6 shows the corresponding failure envelopes.

The values of Young's modulus obtained from these tests are listed in Table 1. They, as expected, increase as the confining pressure increases. They, also, differ from one rock sample to another indicating the layering of the reservoir. Therefore, in any analytical or numerical simulation run, the variation in these properties has to be appropriately incorporated in order to achieve reasonable predictions.

Table 1. Young's modulus and other properties of the tested reservoir rock samples.

Sample Number	Length (in)	Diameter (in)	Helium Porosity (%)	Vertical Permeability (md)	Confining pressure (psi)	Young's Modulus, E (ksi)
1	3.98	1.99	17.89	52.8	3150	35.2
					3650	39.8
					4150	41.7
					4650	42.3
2	4.00	2.00	14.00	1.98	3150	27.7
					3650	28.0
					4150	29.1
					4650	28.0

Discussion and conclusions

The use of multistage triaxial testing to obtain the rock mechanical properties, especially the failure envelope, was shown to be a viable option. The multistage approach discussed in this paper is based on the recommended procedure of the International Society of Rock Mechanics (ISRM)[1]. The failure envelopes for the Berea and actual reservoir samples were plotted in the J_1 - $\sqrt{J_{2D}}$ stress invariant space. The equation of the failure envelope for the rock samples can be written as:

$$\sqrt{J_{2D}} = \alpha\ J_1 + k$$

The equation of the failure envelope can also be written in Mohr-Coulomb space, represented by the shear stress, τ, and the normal stress, σ, as:

$$\tau = c + \sigma \tan \phi$$

where c is the "apparent" cohesion and ϕ is the angle of internal friction. The relation between the parameters used in the above two equations is given as:

$$Sin\phi = \frac{3\alpha\sqrt{3}}{2 + \alpha\sqrt{3}}\ ;\ c = \frac{k\sqrt{3}(3 - Sin\phi)}{6Cos\phi}$$

However, the results of the present study are plotted in the J_1 - $\sqrt{J_{2D}}$ stress invariant space in a form similar to the Drucker-Prager failure criterion. The intermediate stress effect is accounted for in this criterion which should be more appropriate for the description of failure envelopes when compared to the Mohr-Coulomb failure criterion.

The conclusions drawn from this experimental program can be summarized as follows:

1. With increasing confining pressure, the sandstone reservoir rock exhibits a stiffer response in both the deviatoric stress-axial strain and deviatoric stress-radial strain regimes.
2. The failure load of the sandstone reservoir rock increases as the confining pressure increases.
3. The failure envelope can be approximated by a straight line in the (J_1 - $\sqrt{J_{2D}}$) stress invariant space.
4. The multistage triaxial testing procedure appears to be an efficient alternative to determine the rock mechanical properties under reservoir conditions whenever core sample availability is limited.

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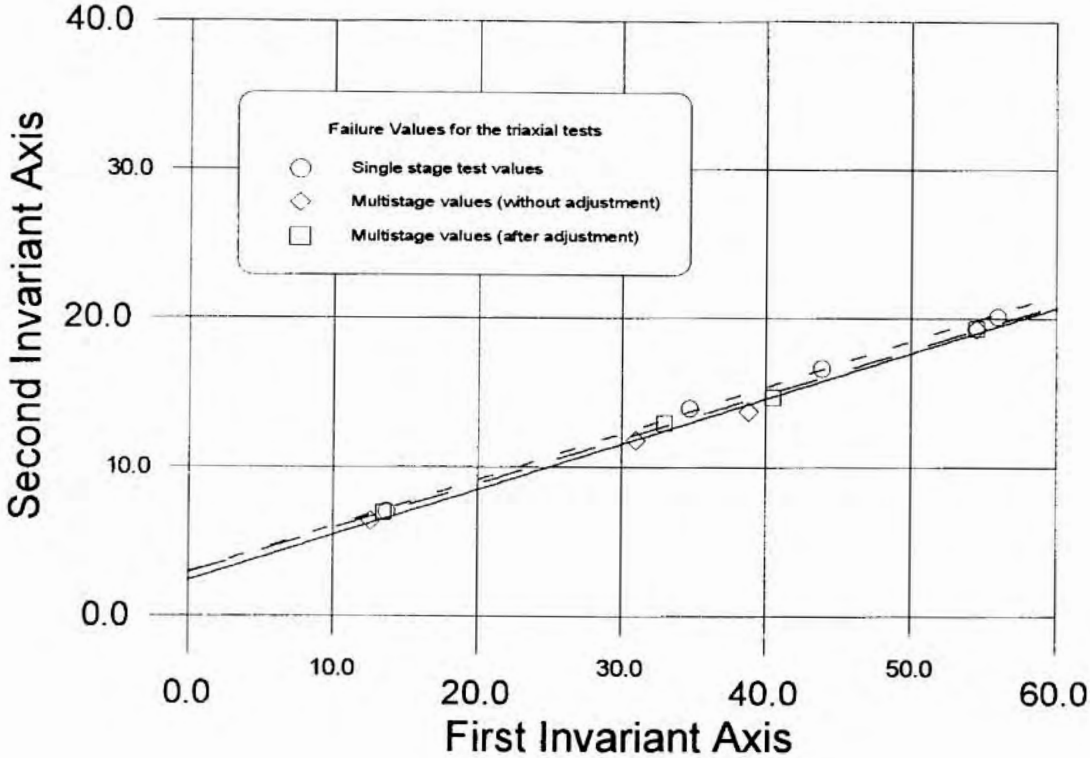

Figure 1. Failure envelopes drawn from single stage and multistage triaxial compression tests (Berea sandstone samples)

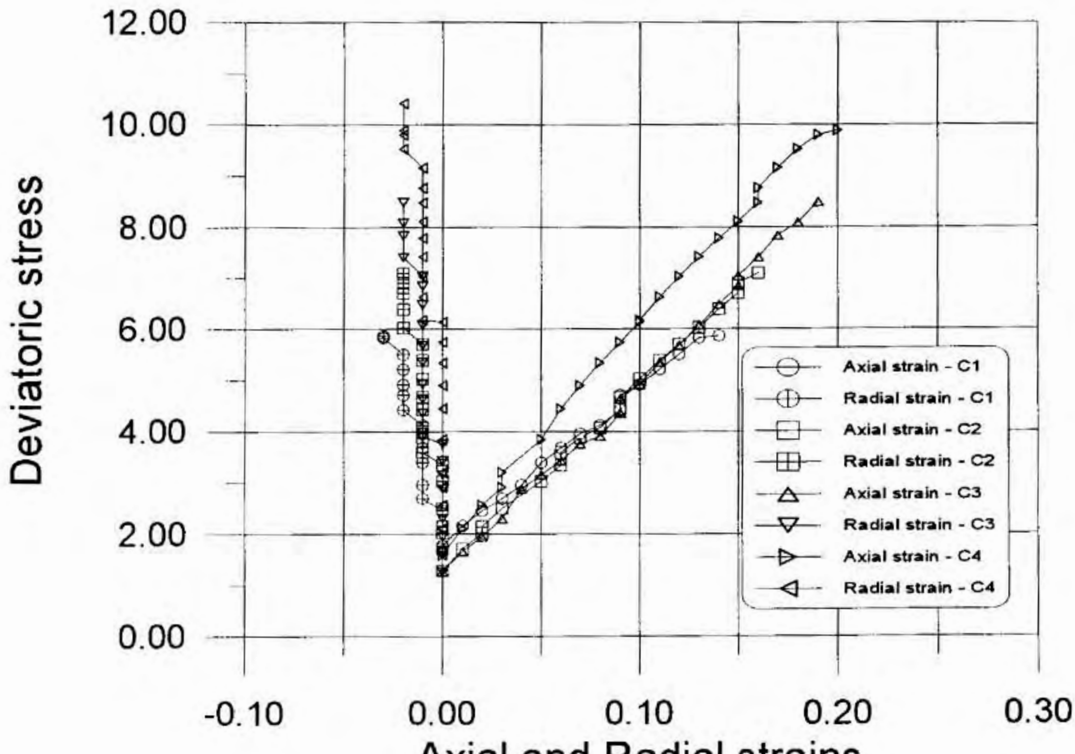

Figure 2. Stress-strain response at four confining pressures C_{d1}, C_{d2}, C_{d3}, and C_{d4} for Sample - 1 (Dry Condition).

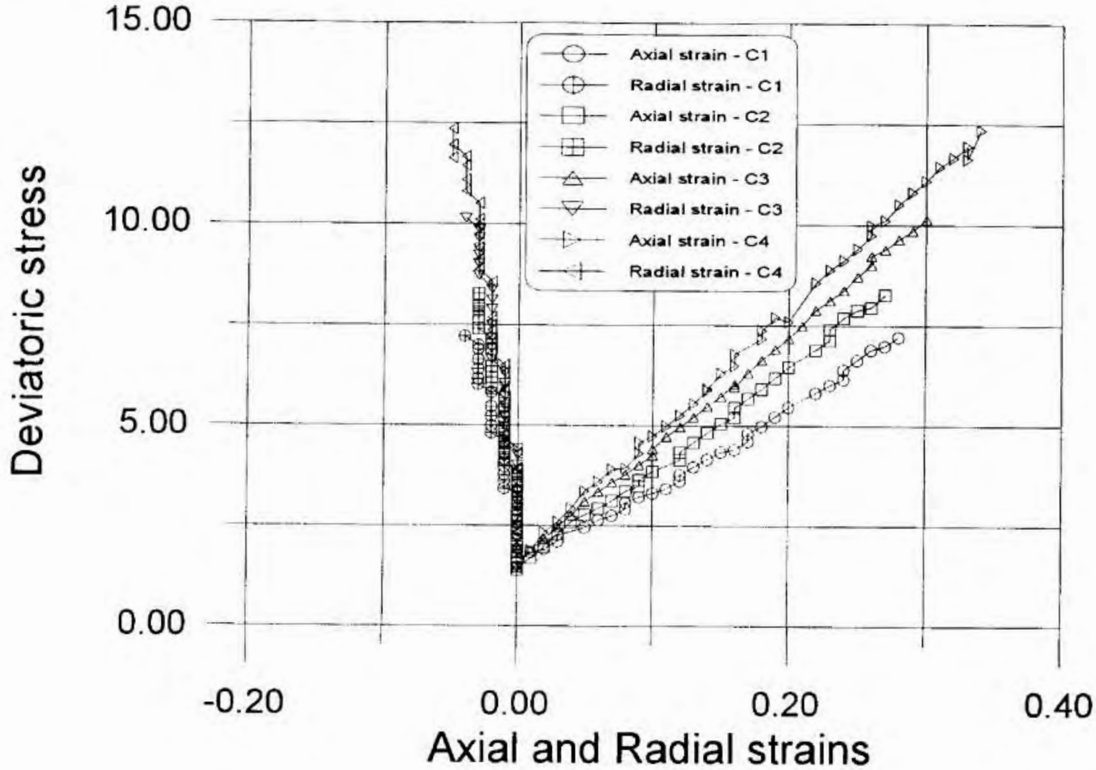

Figure 3. Stress-strain response at four confining pressures C_{d1}, C_{d2}, C_{d3}, and C_{d4} for Sample -2 (Dry Condition).

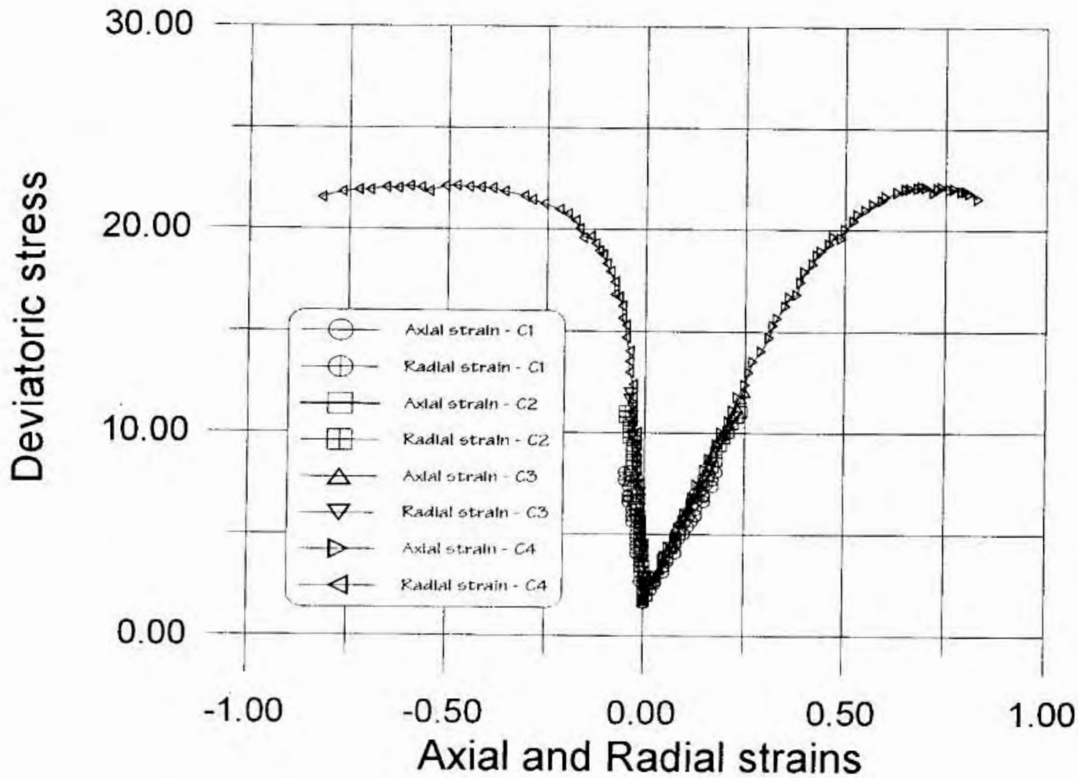

Figure 4. Stress-strain response at four confining pressures C1, C2, C3 and C4 for Sample - 1 (Saturated Condition).

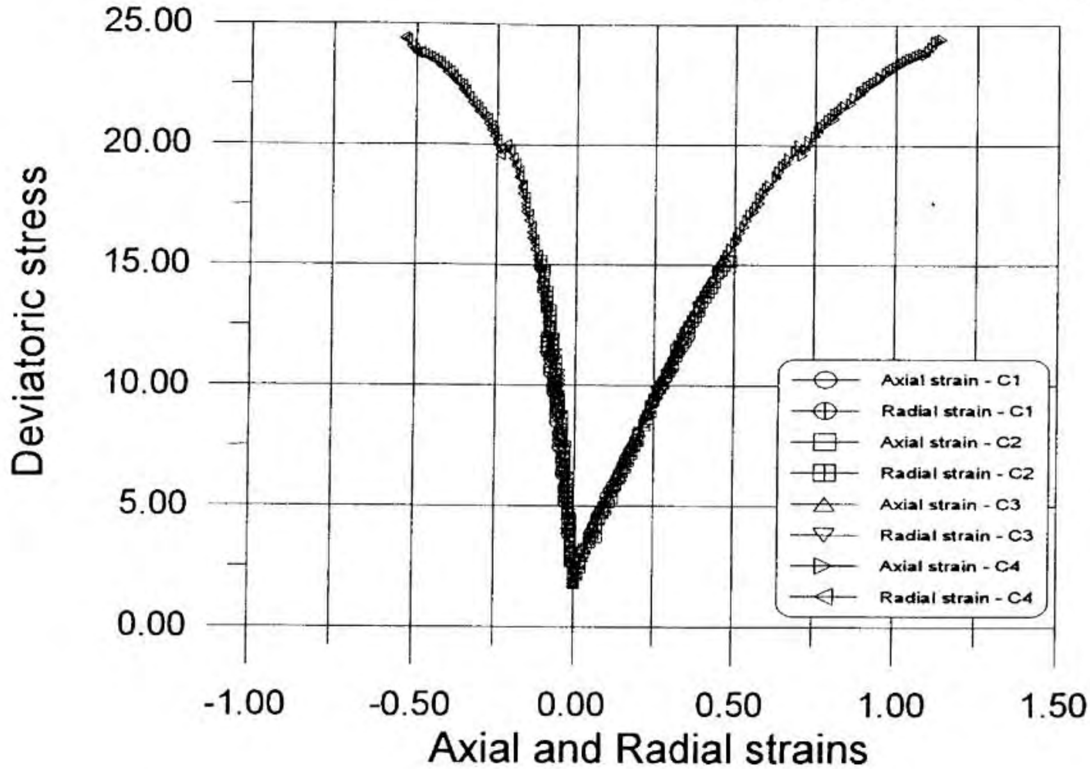

Figure 5. Stress-strain response at four confining pressures C1, C2, C3 and C4 for Sample - 2 (Saturated Condition).

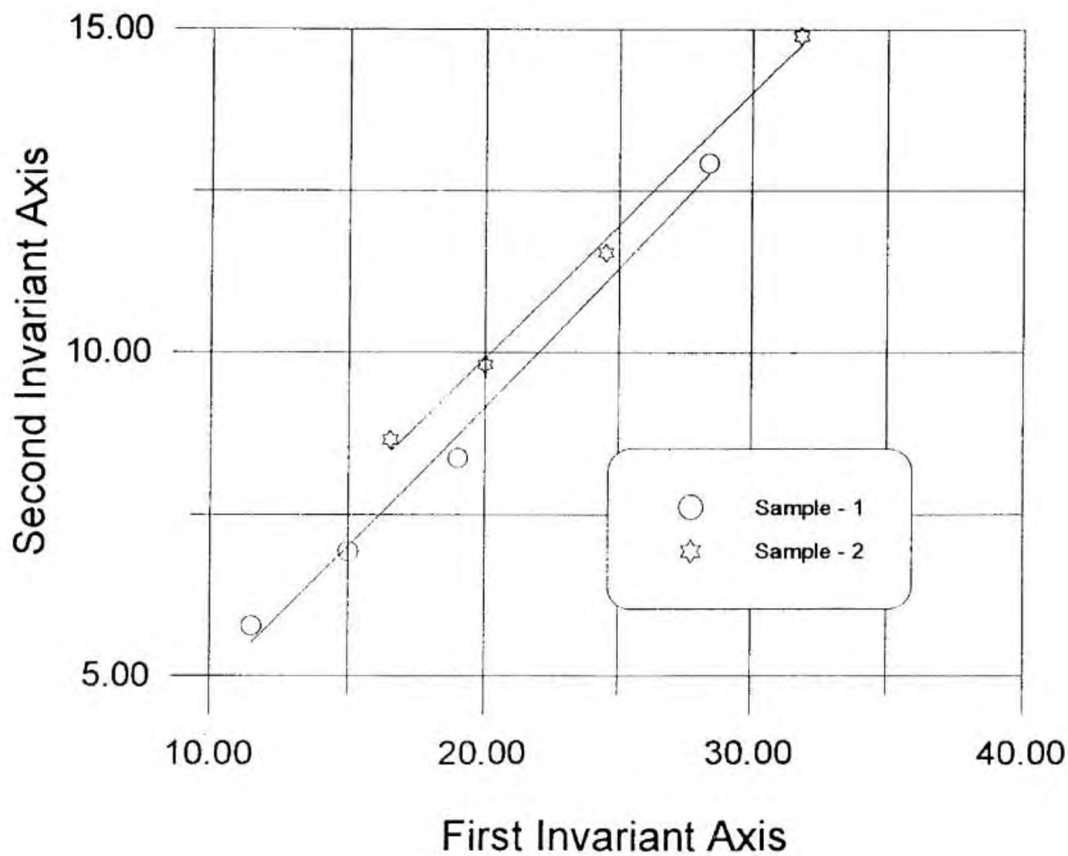

Figure 6. Failure points and failure envelopes for the reservoir rock samples 1 and 2.