ROUTINE DETERMINATION OF PORE COMPRESSIBILITY AT ANY PRESSURE BASED ON TWO POINT MEASUREMENTS

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ABSTRACT

During the production of reservoir fluids, the pore fluid pressure decreases as the overburden pressure remains constant. Consequently, pore compression occurs as the disparity between external and internal pressure increases. The technique developed in this study has a different approach to the conventional method resulting in a procedure which is both highly efficient and cost effective. This is achieved by neglecting the c_r, which is typically an order of ten less than the c_b, thus permitting the almost routine determination of c_p. A microcomputer controlled porosimeter has been utilized to carry out compressibility studies to obtain rapid reliable results in a highly cost effective manner. The compressibility characteristics of twelve samples, 2 inches in length and 1.5 inch in diameter, can be determined to a maximum frame stress of 10,000 psi in a matter of hours. The applied technique assumes that: (a) pore compressibility behavior depends only on the effective frame stress based on the theory of poroelasticity; (b) irreducible brine and rock matrix expansion due to reduction in pore pressure are negligible; (c) hydrostatic pore volume compressibility can be converted to uniaxial strain condition based on constant Poisson's ratio for all loading conditions.

Demonstrative studies were applied to core samples from limestone and sandstone reservoirs. A total of 714 carbonate plugs were tested at five different frame stresses between 500 and 3,500 psi. A further 32 sandstone samples were tested, primarily at four different pressures ranging from 500 psi to 3,500 psi. Of these six samples were tested at pressures from 4,000 psi to 9,500 psi at 500 psi increments. An exponential relationship in the form of:

$$C_P = -\frac{m}{P} \qquad \text{Eq. (1)}$$

was found to give excellent correlation with an $R^2 > 97\%$ for all cases. The slope of the exponential line allows one to determine the pore volume compressibility, porosity at stress, and relative porosity change of each core plug at any pressure corresponding to the relevant depth.

INTRODUCTION

The natural energy which exists in the reservoir overcomes the resistance to the hydrocarbon movement in the direction of the well bore. This energy is released during production by several drive mechanisms some of which are water, solution gas, gas cap expansion, and gravity drainage. The drive mechanism which will be discussed here is due to the external pressure on the reservoir rock resulting from the weight of the overlying strata. The internal pressure maintained by the fluids present in the pore space decreases as hydrocarbons are produced from that reservoir. This decline in the pore pressure allows the fluids to expand in the producing zone. The decrease in the pore pressure also results in the formation contracting due to the increase in the frame stress or more specifically, the net overburden pressure. This expulsive energy known as the reservoir compaction drive mechanism, is expressed in terms of bulk compressibility. The bulk compressibility is defined as;

$$c_b = \phi c_p + (1-\phi)c_r \text{....................Eq. (2)}$$

For samples with porosity exceeding 15%, the rock bulk compressibility, c_b, is much greater than the rock matrix compressibility, c_r [1]. In practical terms, the bulk compressibility can be neglected when routinely determining the pore volume compressibility.

Pore volume compressibility is not only used as an indication of potential production, it can also be used to calculate hydrocarbon storage capacity of the reservoir at various production phases.

Currently, the most commonly applied technique in the oil industry to measure Pore Volume Compressibility entails subjecting the fully saturated core sample to an overburden and pore pressure. The pore pressure is allowed to decrease in stages. The resulting expelled fluid is an indication of the pore volume reduction. The pore volume compressibility is calculated at any pressure based on the definition of [2]:

$$c_p = -\frac{1}{V_p} \cdot \frac{dV_p}{dP} \text{...................Eq. (3)}$$

This laboratory determined compressibility is the result of the hydrostatic load which differs from the actual reservoir loading. In the hydrocarbon reservoir the contraction is only in the vertical direction which is referred to as unilateral or uniaxial stress. Therefore, the laboratory measured hydrostatic strain condition should be converted to the uniaxial strain condition[3,4].

EXPERIMENTAL TECHNIQUE

The application of the subject technique differs from the conventional procedure by keeping the pore pressure constant at near atmospheric pressure, as the overburden pressure is increased. This results in a comparable stress on the rock matrix causing an equivalent reduction in the pore volume. However, since there is no liquid present in the pore space there is no hydrostatic compression of the rock matrix, only that due to the hydrostatic stress transmitted through the matrix itself. The basic assumptions behind this approach are: (a) pore compressibility behavior depends only on the effective frame stress based on the theory of poroelasticity [1,5,6]; (b) grain expansion due to reduction in pore pressure is negligible and consequently, the reduction in the pore volume is equal to reduction in the bulk volume.

The pertinent technique demonstrates a development of the Exponential Relationship between measured pore volume and corresponding sleeve pressure based on two simulated net overburden pressures. This relationship is expressed as:

$$V_p = b \cdot P^{-m} \text{..................Eq. (4)}$$

The derivative of Eq. (4) with respect to pressure is:

$$\frac{dV_p}{dP} = -m \cdot b \cdot P^{-(m+1)} \text{.................Eq. (5)}$$

By substituting Eq. (4) & (5) into Eq. (3) we get:

$$C_P = -\frac{m}{P} \text{...................Eq. (1)}$$

This gives a direct easily determined relationship between Compressibility and Net Overburden Pressure. Furthermore, porosity at stress and relative porosity change can be calculated at the corresponding simulated pressures as follows:

$$\phi_s = \frac{V_{ps}}{V_{bs}} \text{...................Eq. (6)}$$

By writing stress pore volume in terms of Equation (4), and expressing bulk volume as a summation of grain and stress pore volume:

$$\phi_s = \frac{b \cdot P_s^{-m}}{b \cdot P_s^{-m} + V_g} \text{....................Eq. (7)}$$

By definition, the relative porosity change is:

$$\frac{\Delta\phi}{\phi_i} = \frac{(\phi_i - \phi_s)}{\phi_i} \text{...................Eq. (8)}$$

By expressing stress and initial porosity in terms of Eq. (6) and initial pore and grain volume respectively:

$$\frac{\Delta\phi}{\phi_i} = 1 - \frac{b \cdot P_s^{-m}}{b \cdot P_s^{-m} + V_g} \cdot \frac{V_g + V_p}{V_{pi}} \text{..................Eq. (9)}$$

The hypothesis formulated in Equation (1), (6) and (8) is supported by performing subject approach on 714 carbonate core samples 32 sandstone samples from Saudi Arabia Reservoirs. The relevant porosity/permeability cross plots of the tested samples are given in Figures 1 & 2.

Both limestone and sandstone samples were cut parallel to the bedding plane, perpendicular to the whole core, resulting in a sample 1.5 in. diameter and 2 in. in length. Following the hot solvent extraction and salt leaching, the samples were tested at ambient conditions for their grain volume in a matrix cup by the Helium-Injection-Boyle's Law technique. Tests were carried out in a microcomputer controlled helium injection-Boyle's Law porosimeter to define pore volumes and unsteady-state air permeabilities at increasing sleeve pressures.The simulated net overburden pressures for carbonate core study start from 500 psi, which represents the ambient condition pressure, and rising through 1,500; 2,500; 3,000; to 3,500 psi.

The study for sandstone samples was designed slightly different. The samples were tested primarily at pressures of 1,000; 2,000; 3,500 psi. To further investigate the effect of stress on the rock matrix and to in an attempt to define the yield stress. Six samples were further tested from 4,000 psi to 9,500 psi at 500 psi increments.

An exponential relationship was developed for each sample of the two subject studies, by constructing bi-logarithmic plot of the measured pore volume versus corresponding applied confining pressures.

RESULTS AND DISCUSSION

The relationship stated in Eq. (4), was found valid for all 714 samples with the $R^2>99\%$ for the limestone samples. Sandstone samples demonstrated similar strong validity with $R^2>99\%$. The samples totalling six, tested up to 9,500 psi showed that $R^2>99\%$ for three of them; $R^2>98\%$; 97%; and 89% for the remaining samples. This high correlation is presented in Figure 3 for the selected samples from the carbonate reservoir. In order to attain a representative population, selection was made at various depths based on diverse porosity/permeabilities for each different rock type. Figure 4 presents exponential relationship in the pressure range of 500 to 9,500 psi for selected samples of the sandstone reservoir. In all cases the pore volume change at 500 psi deviates from the regression line simply due to the boundary effect during the pore volume measurement[7].

The pore volume compressibility of the limestone samples are calculated at a reference pressure of 3,000 psi of simulated net overburden pressure based on the relationship developed (Eq. 1). The compressibility of the sandstone samples are calculated at two different NOB pressures of 3,650 and 4,800 psi. The comparisons between basic petrophysical data and compressibility showed that: (a) A good correlation exists between pore volume compressibility and porosity for both limestone and sandstone samples. Limestone samples with porosities less than 15% BV, displayed an inverse relationship between porosity and calculated compressibility (Fig. 5). For those samples with porosities greater than 15%, the compressibility increased with the increasing porosity (Fig. 6). The sandstone samples displayed an inverse relationship between porosity and compressibility. However, the slope of the regression line was seen to change at the 12% porosity point. The rate of change is higher in the lower porosity samples (Fig. 7 and 8). (b) A strong correlation is demonstrated between lithology of the limestone samples and reference pressure pore volume compressibility. Although this is due mainly to the reflection of the porosity/lithology relationship. (c) There is a slight correlation between unsteady-state air permeability and the calculated compressibility for limestone samples. The well sorted characteristics of the sandstone pore structure imparts a good correlation between the compressibility and permeability.

CONCLUSION

o Relationship of $c_p= -m/P$ is valid for the pressures over 700-800 psi where sleeve conformation is attained[7] .This relationship is maintained up to the matrix yield stress above which there is failure of the structure.

- o Because of the high correlation between log pore volume and corresponding log pressure, the pore volume compressibility can be determined by testing samples at only two pressures ordinarily 1,500 & 3,500 psi.

- o Pore volume compressibility; porosity under the simulated net overburden pressure; and relative porosity change can be determined routinely for individual samples at a particular pressure corresponding to its specific depth.

- o The test procedure is very cost effective resulting from the utilization of routine PK samples and associated sample preparation procedures and the rapid automated test procedure characteristics.

NOMENCLATURE

C_p	=	Pore volume compressibility, vol/vol/psi
C_b	=	Bulk volume compressibility, vol/vol/psi
C_r	=	Rock matrix compressibility, vol/vol/psi
V_p	=	Pore volume, cc.
V_{ps}	=	Pore volume at stress, cc.
V_b	=	Bulk volume, cc.
V_{bs}	=	Bulk volume at stress, cc.
V_g	=	Grain volume, cc.
P	=	Net overburden pressure, psi.
b	=	Intercept of log PV vs log P, cc.
m	=	Slope of log PV vs log P, cc/psi.
$\emptyset_i$	=	Initial porosity, %BV.
$\emptyset_s$	=	Porosity at stress, %BV.

ACKNOWLEDGEMENT

Appreciation is given to the Saudi Arabian Ministry of Petroleum and Mineral Resources and to the Saudi Aramco for permitting the publication of this paper.

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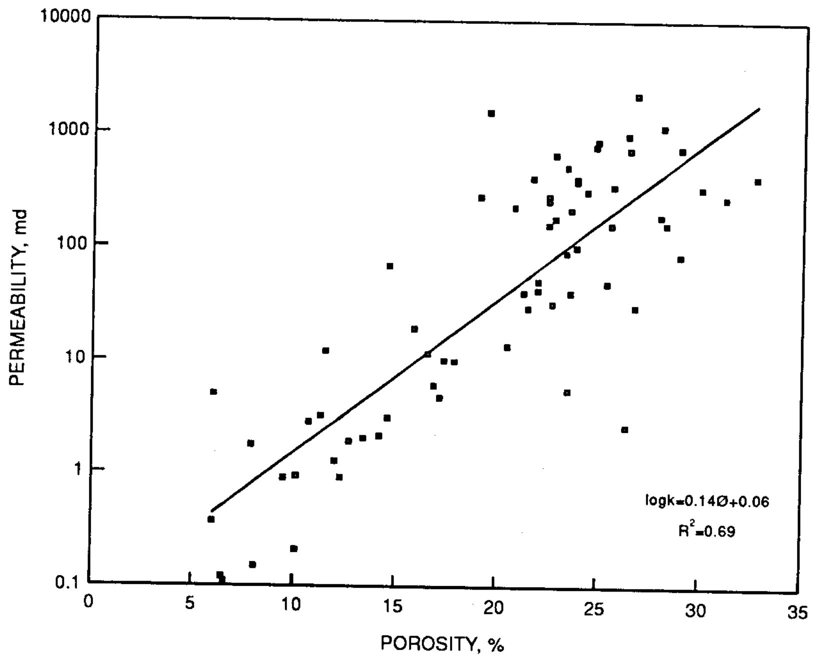

Figure 1.

Carbonate Samples Porosity/Permeability Cross Plot

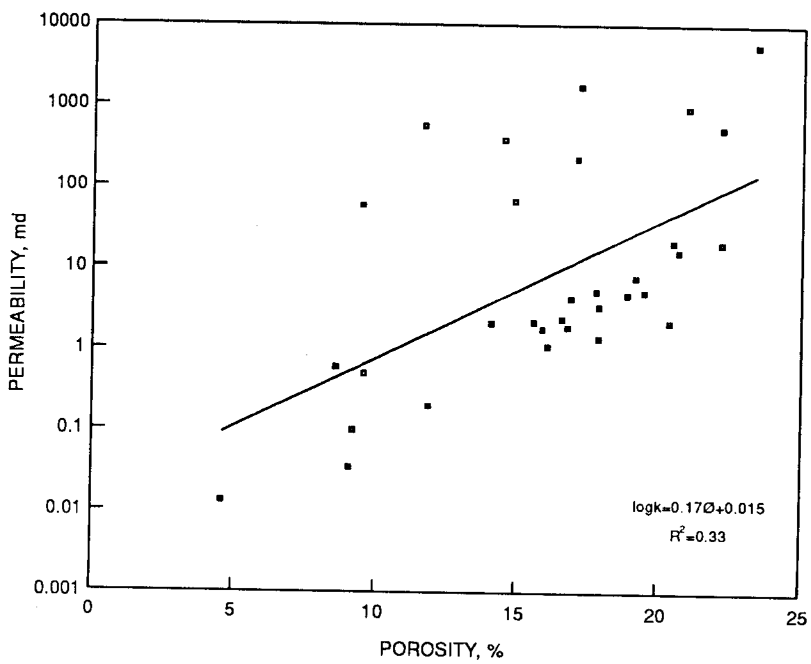

Figure 2.

Sandstone Samples Porosity/Permeability Cross Plot

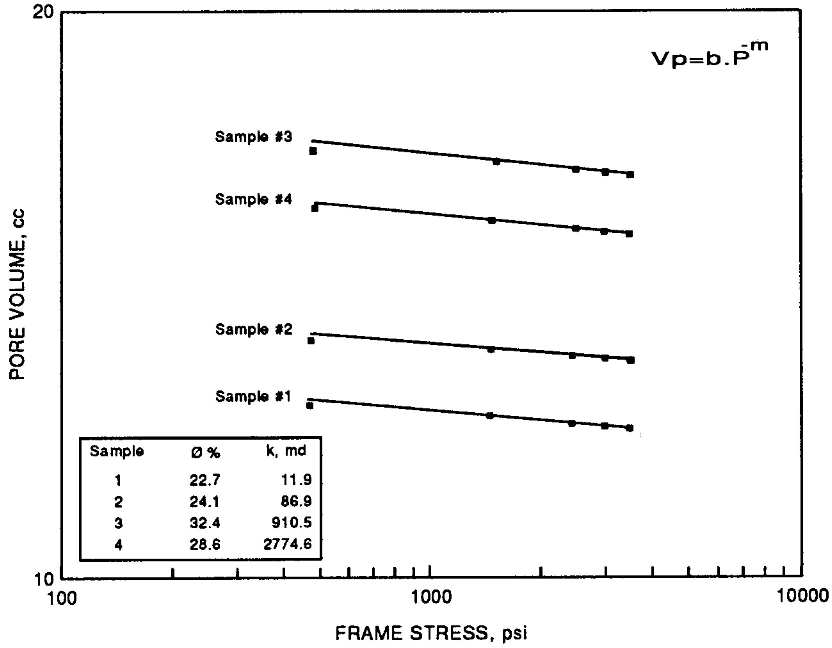

Figure 3.

Carbonate Samples Pore Volume vs Frame Stress on bi-logarithmic plot

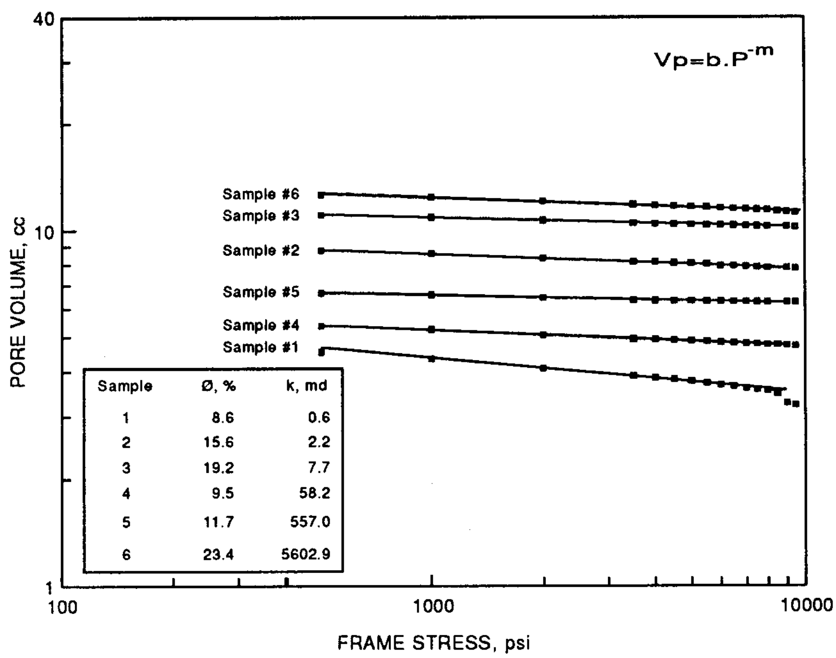

Figure 4.

Sandstone Samples Pore Volume vs Frame Stress on bi-logarithmic plot

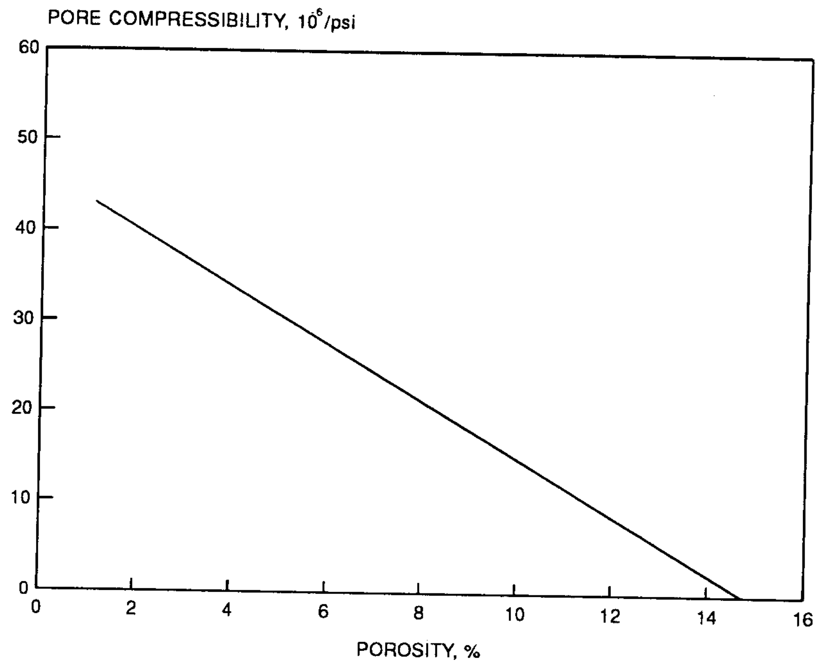

Figure 5.

Carbonate Samples Pore Compressibility vs Porosity Change for Lower Porosity Range at Reference Pressure 3000 psi

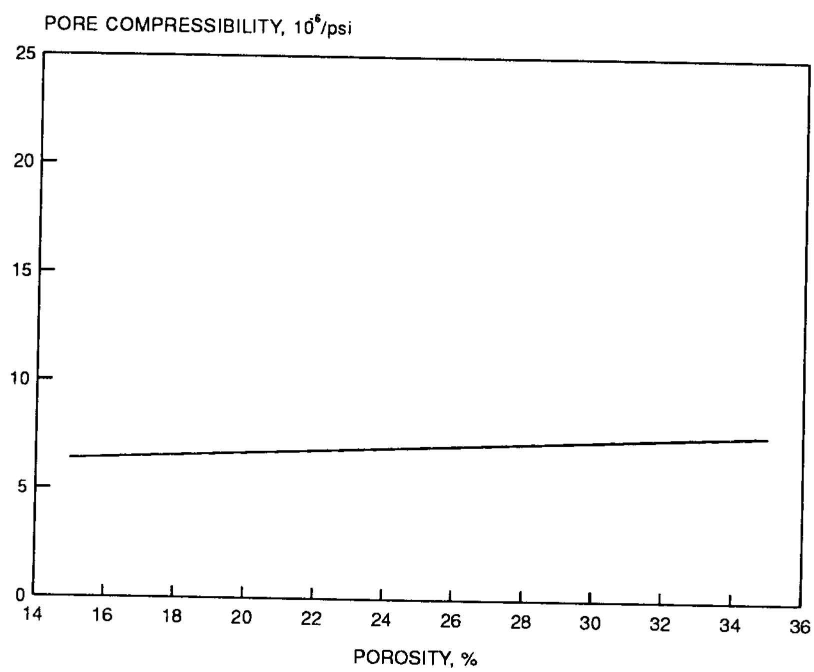

Figure 6.

Carbonate Samples Pore Compressibility vs Porosity Change for Higher Porosity Range at Reference Pressure 3000 psi

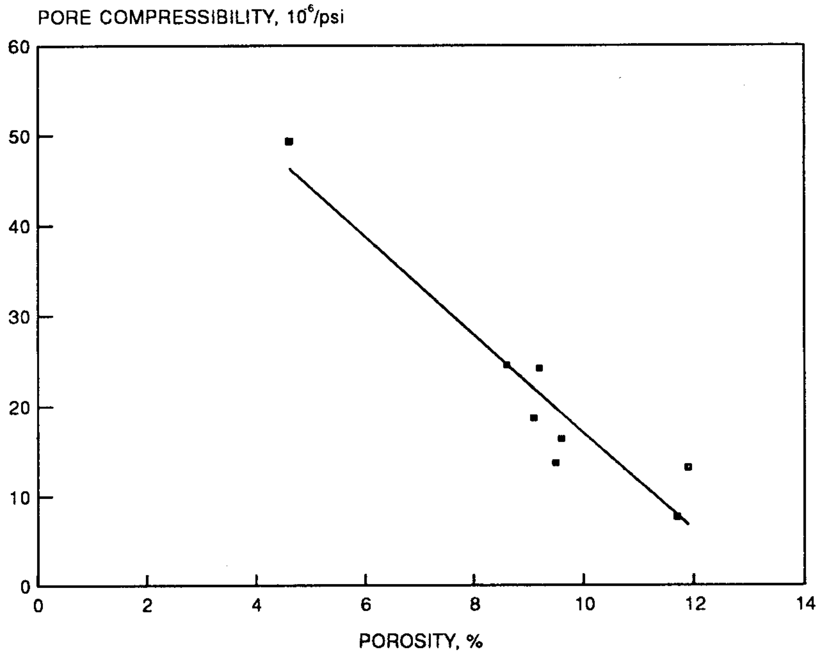

Figure 7.

Sandstone Samples Pore Compressibility vs Porosity Change for Lower Porosity Range at Reference Pressure 3000 psi

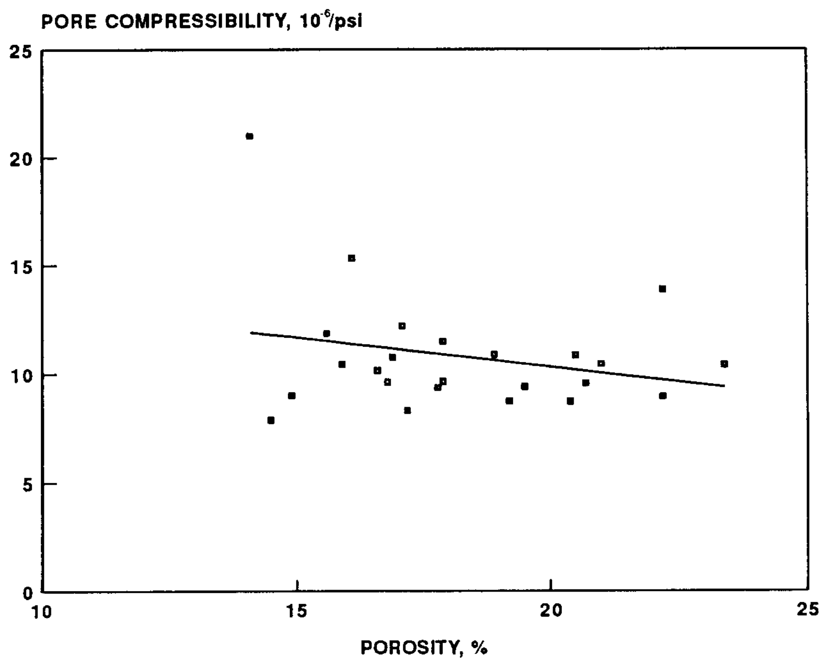

Figure 8.

Sandstone Samples Pore Compressibility vs Porosity Change for Higher Porosity Range at Reference Pressure 3000 psi