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Laboratory Determination of Effective Stress Laws for Deformation and Permeability of Chalk

Lawrence W. Teufel and Norman R. Warpinski

Sandia National Laboratories
Albuquerque, New Mexico 87185

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ABSTRACT

Laboratory deformation and permeability measurements have been made on chalk samples from Ekofisk area fields as a function of confining stress and pore pressure to determine the effective stress laws for chalk. An understanding of the effective stress law is essential to obtain correct reservoir-property data from core analysis and is critical for reservoir management studies and reservoir compaction models. There has been limited previous work on effective stress laws and some question about the validity of theoretical form of these laws. A powerful statistical technique known as the response surface method has been used to analyze our laboratory data and determine the form of the effective stress law for deformation and permeability. Experiments were conducted on chalk samples that had a range of porosities from 15% to 36%, because porosity is the dominant intrinsic property that affects deformation and permeability behavior of chalk. Deformation of a 36% porosity chalk was highly nonlinear, but the effective stress law was linear (of the form σ - αP), with α equal to about unity. Lower-porosity samples showed linear strain behavior and a linear effective stress law with α as low as 0.74. Analysis of the effective stress law for permeability is presented only for the lowest porosity chalk sample because changes in permeability in the higher-porosity chalk samples due to increasing confining stress or pore pressure were not large enough, relative to the error in the measurement itself, to deduce meaningful effective stress relationships. For the low porosity chalk the effective stress law for permeability is nonlinear, with pore pressure having a greater effect than confining stress at low confining stress. It is thought that the nonlinearity is due to the nature of the pore structure and a significant amount of non-interconnected porosity.

INTRODUCTION

Effective stress laws and the behavior of porous and permeable rocks under poroelastic stresses are important parameters for completion, development, and management of hydrocarbon reservoirs. It is necessary to invoke an effective stress law for the material and process in order to perform many core and log analyses, reservoir simulations, stress analyses, and

many other laboratory and computational studies of reservoir rocks. This law gives the relationship between confining stress and pore pressure on specific stress-sensitive properties of the rock.

Terzaghi (1923) orginally proposed a simple effective-stress-law relationship, that of the stress minus the pore pressure, which was sufficient for most applications of the time. However, more recent research has shown that a more complex effective stress law is appropriate. Biot (1941) developed the form of the equations of poroelasticity and Rice and Cleary (1976) clarified and expanded some of the theoretical concepts of deformation behavior. Robin (1973) showed that effective stress laws may be different for different processes and properties. Accordingly, this relationship generally takes the form

$$property = f(\sigma - \alpha P)$$

where f is some generalized function determining the value of a specific property, σ is the confining stress, P is the pore pressure, and α is a poroelastic constant defining the interplay between stress and pore pressure. For soils, α is found to be unity for most processes and properties, such as deformation, failure, and permeability (Skempton, 1960). However, some rocks exhibit complicated pressure and stress dependencies because of relaxation microcracks, slot pores, and unconnected porosity. A consequence of this behavior is that the effective stress law may not be linear (as suggested by Robin, 1973; Garg and Nur, 1973; and implied by Nur and Byerlee, 1971) and the values of α are often uncertain.

Some previous work on effective stress in sedimentary rocks includes the Nur and Byerlee (1971) measurements on volumetric strain in Weber sandstone and the Zoback and Byerlee (1975) measurements of permeability in Berea sandstone. A set of very careful measurements on the effective stress law for permeability was made by Bernabe (1986, 1987, 1988) on crystalline rocks. Bernabe's work shows the importance of cycling the sample several times (seasoning) before reproducible measurements can be made. This is a critical factor since comparisons of the effects of stress and pore pressure cannot be made unless the rock yields consistent, reproducible behavior. It is not clear if other studies have also properly seasoned the rock samples.

The purpose of this paper is to present an analysis of effective stress laws for chalk. Laboratory deformation and permeability measurements on chalk samples were conducted as a function of confining stress and pore pressure. Experiments were conducted on chalk samples with a range of porosities from 15% to 36%, because porosity is the dominant intrinsic property that affects deformation and permeability behavior of chalk. All of the chalk samples were from Ekofisk-area fields, which are located in the Central Graben of the Norwegian sector of the North Sea. A powerful statistical technique known as the response surface method (Box and Draper, 1987) has been used to analyze our laboratory data and to determine if the effective stress law is linear for the different processes.

EXPERIMENTAL PROCEDURE

The experimental procedure consists of measuring the volumetric strain (ϵ_V) and permeability (k) of a core sample as a function of confining stress and pore pressure. Core plugs, nominally 2.5 cm in diameter and 5.6 cm in length, are instrumented with axial and circumferential strain gages, jacketed, and inserted into a hydrostatic pressure vessel (Figure 1). Endcaps slip inside the rubber jackets and provide entry for the pore-fluid pressure. Confining stress is provided through hydraulic fluid pressure applied to the outer side of the jacket; pore pressure is supplied by the test fluid (nitrogen) within the core. Permeability was determined using a steady state measurement technique.

We have used a modified factorial structure for our test matrix and measurement procedure for obtaining α for deformation and permeability (Figure 2). Permeability and volumetric strain data were taken as a function of confining stress for at least four pore pressures during loading and unloading cycles. Minimum pore pressure for permeability was 6.9 MPa in order to avoid Klinkenberg corrections (API, 1956). Since the pore pressure cannot be higher than the confining stress, the factorial structure of the test matrix is cut on one corner. Test cycles were performed at constant pore pressure while varying the confining stress; this reduced the equilibration time of the fluid within the sample.

Prior to starting our test matrix, all samples were seasoned through several loading and unloading cycles to the maximum confining stress until reproducible deformation and permeability behavior was obtained. While seasoning may induce a small amount of damage in the rock sample, it is imperative that uniform rock behavior can be obtained through all data cycles if accurate effective-stress-law measurements are to be made. In these tests, nitrogen was chosen as the test fluid to eliminate any chemical effects (such as interactions with clays) that are likely to occur with water.

ANALYSIS PROCEDURE

In developing an analysis technique for these data, it first assumed that we knew nothing about the mechanistic or constitutive form of either permeability or deformation (volumetric strain) behavior in response to confining stress or pore pressure. We then used a statistical technique called empirical model building (Box and Draper, 1987), whereby an approximate surface (response surface) is fit to the data. The parameters describing the response surface were then examined to deduce information about material behavior. Using this approach, we felt that we could avoid biasing the results by defining *a priori* a form for the effective stress law. This is especially important when one recognizes that relaxation microcracks or non-interconnected porosity may induce highly nonlinear material behavior, effectively invalidating the theoretical forms for the effective stress laws, the development of which assumes constant material properties.

The procedure is relatively straight forward and ends up providing a linear regression from which goodness of fit and confidence limits can be extracted. The procedure has three steps, as given below.

1. Transform the data. The purpose of this step is two-fold. First a judicious choice of a transformation can smooth the data into a simple linear or quadratic surface so that a linear regression can be applied to the transformed data. Second, a properly constructed transformation can weight the variance in known ways. Box and Draper (1987) give a

technique to determine appropriate transformations. Generally, transformations of the form $(k', \epsilon_V')^\lambda$ were used, where λ varies from -3 to +3, with $\lambda = 0$ being the natural log transformation.

2. Perform the regression with a full linear or quadratic surface. In this case we used

$$k' \ or \ \epsilon_V' = x_1 + x_2\sigma + x_3P + x_4\sigma^2 + x_5\sigma P + x_6P^2,$$

where k' and ϵ_V' are the transformed permeability and volumetric strain. The x_i are then determined from the least-squares fit of the data. The response surface of interest is in the $k' - \sigma - P$ or $\epsilon_V' - \sigma - P$ space, as this surface describes the effects of confining stress and pore pressure on material behavior.

3. From the fit deduce the behavior of the surface and obtain statistical properties, confidence limits, etc.

In this case, the confidence limits can be obtained for all of the x_i given above and F-test values, and correlation coefficients can be obtained for the regression as a whole. These provide important information on the quality of the data and the resultant fit. A first order value of α can be obtained from the ratio, $-x_3/x_2$. Confidence limits for ratios can be found, assuming a normal distribution for the ratios (Williams, 1959); the normal distribution hypothesis could not be rejected for any of our data using several goodness-of-fit techniques. Two second order values of α can be determined from x_4, x_5, and x_6. These values provide information on the linearity of the effective stress law. As will be seen in the results, however, the easiest test of linearity of the effective stress law is a visual look at the 3-space plots that can be generated as a result of this analysis. More details of this procedure can be found in Warpinski and Teufel (1990).

RESULTS

Deformation and permeability measurements have been made on chalk samples as a function of confining stress to 55.2 MPa and pore pressures to 27.6 MPa. Samples were unfractured chalk from fields in the Ekofisk area. Analysis of the effective stress law for deformation is presented for three samples with different porosities, 15%, 24%, and 36%. Analysis of the effective stress law for permeability is presented only for the lowest porosity chalk sample because an insufficient change in permeability was observed in the higher porosity chalk samples with increasing confining stress or pore pressure.

Effective Stress Law for Deformation

In order to determine an effective stress law for deformation, volumetric strain data were taken as a function of confining stress with no pore pressure and for four pore pressures during loading and unloading cycles. A response surface was constructed from these data using the analysis procedure previously described. Figures 3 - 6 show the inverted response surface (transformed back into ϵ_V space) for deformation during loading and unloading cycles of different porosity chalk samples. Each plot in these figures shows a three-dimensional surface in ϵ_V - σ - P space, where ϵ_V is the volumetric strain, σ is the confining stress, and P is the pore pressure, along with lines of constant volumetric strain and constant pore pressure. The constant pore pressure lines are the same ones on which the data were obtained. If there is an effective stress law in which α is relatively constant (linear effective stress law), then the constant volumetric strain lines should be straight and parallel, since ϵ_V must be constant along lines given by $\sigma - \alpha P$ = constant.

Figure 3 shows the inverted response surfaces for deformation of a 36% porosity chalk during loading and unloading cycles to confining pressure of 27.6 MPa and to pore pressure of 13.8 MPa. This material is highly non-linear, as can be seen by the curvature of the farthest left curves (for zero pore pressure). Although deformation is highly nonlinear, the effective stress law is linear, because the lines of constant volumetric strain are straight and parallel. For the loading cycle the first order α is 0.96 and for unloading it is 1.03.

The power of the response-surface technique is that it allows conventional statistical analyses to be performed, since the regression is linear. Table 1 gives some important results that were derived from the statistics, including confidence limits, F-test values, and an estimate of the nonplanarity of the surface at average stress and pore pressure conditions. For this sample, the 95% confidence limits on the first order α are 0.93 - 0.99 for loading and 0.99 - 1.07 for unloading. The data are accurately fit by the surface, as evidenced by the huge F-test values (F-test values greater than about 30 would be required for confidence in the fit (Box and Draper, 1987)). The nonplanarity parameters are the ratio of the second order terms to the first order term, taken separately for stress and pore pressure, at average stress (13.8 MPa here) and pore pressure (6.9 MPa). If the response surface is nearly planar (small nonplanarity parameters), then the first-order α is the true α. Note, however, that the effective stress law can be linear even with a nonplanar response surface; this requires that the second order α, deduced from x_4, x_5, and x_6, is the same as the first order α. For this high-porosity chalk, the nonplanarity is 1% in loading and 4% in unloading, validating the linear effective stress law hypothesis and confirming that the first order α is the true α. Values of x_i and the transformations of all samples are given in Table 2. We caution, however, that the response surface should not be extrapolated outside the data domain.

Similar deformation behavior is observed for this chalk sample over a greater range of confining stress (to 55.2 MPa) and pore pressure (to 27.6 MPa) (Figure 4). The value of the first order α is essentially the same over this range of pressures as at the lower pressures, with α equal to 0.96 during loading and 1.00 during unloading.

Figures 5 and 6 show the inverted response surfaces for deformation of 24% and 15% porosity chalk samples during loading cycles. For each of these samples deformation cycles were to confining stress of 55.2 MPa and to pore pressure of 27.6 MPa. Both of these lower porosity samples show a linear strain behavior (the response surface is a plane) and a linear effective stress law. The 24% porosity chalk has a first order α of 0.90 and the 15% porosity chalk has a lower value of 0.74. Confidence limits, as shown in Table 1, are 0.87 - 0.93 for the 24% porosity chalk and 0.72 - 0.76 for the 15% porosity sample. Also given in Table 1 are the unloading data, with slightly different values in loading compared to unloading. In both samples the F-test values are very large and nonplanarity ratios are low, implying that the effective stress law is linear and the first order α is an accurate representation of the true value.

Effective Stress Law for Permeability

Permeability of chalk shows a dramatic decrease with decreasing porosity, from 1 md at 36% porosity, to 100 μd at 24% porosity, to 5 μd at 15% porosity. For chalk samples with porosities of 36% and 24% the decrease in permeability with increasing confining stress from 6.9 MPa to 55.2 MPa was less than 15% of the initial value (Figure 7). Differences in permeabilities between incremental steps in confining stress or pore pressure were less than the errors of the measurements. Accordingly, it was impossible to establish reasonable confidence limits on trends in the data, and therefore we could not determine an effective stress law for permeability of these chalks. The relatively small decrease in permeability with increasing confining stress, compared to the large reduction in volumetric strain with increasing confining pressure, is attributed to the fact the most chalks have a high percentage of non-interconnected porosity and permeability is controlled mainly by the smaller pores and pore throats.

For the chalk sample with the lowest porosity (15%) and the lowest permeability, differences in permeabilities between incremental steps in confining pressure and pore pressure were significant relative to the errors of the measurements. A response surface was constructed from permeability measurements made as a function of confining stress for four pore pressures during loading (Figure 8) and unloading cycles. In sharp contrast to the effective stress law for deformation of this low-porosity sample, the effective stress for permeability is nonlinear, with α varying as a function of confining stress and pore pressure. It is thought that the nonlinearity is due to the nature of the pore structure and a significant amount of non-interconnected porosity.

For this sample, the F-test value was only 100, indicating the large errors associated with permeability measurements compared to strain measurements. Note, however, that this is still an an adequate F-test value for this regression. The nonplanarity ratios, as defined earlier, were 12% for stress and 36% for pore pressure at midrange (stress equal to 27.6 MPa and pore pressure equal to 13.8 MPa). The functional relationships for the effective stress law include a first order term $\sigma - 1.82P$, and a second order term, $\sigma^2 - 1.04\sigma P - 3.44P^2$. The second order term is not factorable into a perfect square; perfect factorability would be advantageous as it would yield a second order value of α. In this case, the effective stress law is highly nonlinear.

DISCUSSION and SUMMARY

Laboratory deformation and permeability measurements have been made on chalk samples from Ekofisk area fields as a function of confining stress and pore pressure to determine the effective stress law for chalk. A powerful statistical technique known as the response surface method has been used to analyze our laboratory data and to determine if the effective stress law is linear for the different processes. The results of our laboratory study indicate that the effective stress law for deformation is linear. Over a wide range of porosities (36% to 15%) there was a decrease in α from 1.0 to around 0.8, respectively.

Our study also found that most reservoir chalks do not show a large decrease in permeability with increasing confining stress or decreasing pore pressure. Moreover, differences in permeabilities between incremental steps in confining stress or pore pressure were less than the errors of the measurements for these chalks. Therefore, it was not possible to determine an effective stress law for permeability, except for the lowest porosity and permeability sample. For this low porosity chalk the effective stress for permeability is nonlinear, with pore pressure having a greater effect than confining stress at low confining stress.

The lack of a significant change in permeability of high-porosity reservoir chalks suggests that during reservoir depletion there will be no significant decline in matrix permeability. However, most North Sea chalk reservoirs are fractured reservoirs, with the fracture system forming the primary conduction path for produced hydrocarbons. At present there is no information on the deformation and permeability behavior of fractured chalk during changes in poroelastic stresses, as would occur during reservoir depletion and compaction. We plan to conduct a series of laboratory experiments to determine effective stress laws for fractured chalk.

These initial tests for determining the effective stress laws for permeability and deformation of chalk have been made on dry samples. Tests on dry samples with nitrogen test fluid were chosen in order to eliminate complexities associated with possible chemical effects (as with water or brine test fluid) in a liquid saturated rock and capillary pressure effects in a partially saturated sample. These types of experiments are being considered for the future.

In the course of these tests, we found that seasoning of the samples was critical for obtaining accurate, reproducible results, as previously shown by Bernabe (1986, 1987, 1988). We do not believe that the damage caused by seasoning is significant; similar results have been obtained using samples that have been seasoned through different maximum stress levels (Figures 3-4).

There are several possible methods of analyzing the data, but most methods have drawbacks that make them unsuitable for these results. Bernabe (1986, 1987) describes a method using differentials that can be easily applied. Differentials of permeability (or volume strain) with respect to confining stress and pore pressure can be determined, with α being the negative ratio of the pressu. differential to the stress differential. While this technique is simple, it is difficult to apply in many of these cases because the error in the permeability measurement is on the same order as the differential. Large uncertainties resulted when this procedure was used.

A second procedure is to fit the data to either a polynomial or mechanistic models in effective stress space, for example,

$$k \ or \ \epsilon_V = f(\sigma - \alpha P).$$

In this procedure, the effect of measurement errors can be reduced, but there is a tacit assumption that the effective stress law is linear and a constant value for α can be obtained. Since these regressions are nonlinear, it is also not easy to determine the confidence limits and other statistical properties to characterize the accuracy of the analysis.

After first applying the response surface analysis to permeability data, we found that this technique offers the most flexibility and provides the most information on the accuracy of any type of effective stress law. The transformation process allows much flexibility in weighting the variances and smoothing the data prior to regressing. For example, where the measurement errors are proportional to the value of the measured property (as in our permeability data), a log transformation can bring all variances to equal weight. Since the regression is linear in parameters, standard statistical analyses and tables can be used to obtain F-test statistics, multiple correlation coefficients, and most importantly confidence limits. Finally, the empirical-model-building/response-surface technique allows us to examine the stress and pressure effects on material behavior without biasing the results by assuming an effective stress law or constitutive form *a priori*. This is particularly important for rocks exhibiting nonlinear behavior, as the nonlinearity invalidates most theoretical and mechanistic models that have been developed assuming linear elastic strain behavior.

ACKNOWLEDGMENTS

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Table 1.
Statistical Results of Deformation Experiments

Sample	Alpha	Confidence Limits*	F-Test Values	Nonplanarity Ratio σ	Nonplanarity Ratio P
36% loading†	0.96	0.93 - 0.99	21281	1.3%	1.0%
36% unloading†	1.03	0.99 - 1.07	18833	3.7%	3.8%
36% loading	0.96	0.94 - 0.98	19418	1.7%	3.8%
36% unloading	1.00	0.98 -1.02	19450	3.4%	6.5%
24% loading	0.90	0.87 - 0.93	40379	1.2%	1.6%
24% unloading	0.86	0.84 - 0.89	39679	4.7%	8.2%
15% loading	0.74	0.72 - 0.76	67413	1.0%	9.7%
15% unloading	0.86	0.84 - 0.88	79091	1.6%	4.4%

* Confidence limits at the 95% level.

† Deformation cycle had confining stress to 27.6 MPa and pore pressure to 13.8 MPa. For remaining tests the deformation cycle had confining stress to 55.2 MPa and pore pressure to 27.6 MPa.

Table 2.
Response Surface Parameters

Sample	Transformation	x_1	x_2	x_3	x_4	x_5	x_6
				Deformation			
36% loading[†]	$\epsilon^{1.90}$	7.69E-3	2.82E-4	-2.71E-4	-2.13E-10	4.06E-9	-5.54E-9
36% unloading[†]	$\epsilon^{2.60}$	7.59E-3	3.17E-4	-3.26E-4	-1.01E-9	3.18E-9	6.15E-9
36% loading	$\epsilon^{1.90}$	3.78E-3	2.86E-4	-2.75E-4	-1.15E-9	4.71E-9	4.25E-9
36% unloading	$\epsilon^{2.60}$	-8.14E-2	3.22E-4	-3.23E-4	-2.09E-9	6.52E-9	-2.54E-9
24% loading	$\epsilon^{1.00}$	2.72E-2	6.97E-5	-6.27E-5	1.32E-10	1.66E-10	1.83E-10
24% unloading	$\epsilon^{1.35}$	2.16E-2	6.28E-5	-5.42E-4	2.20E-10	-1.90E-10	1.58E-9
15% loading	$\epsilon^{1.00}$	5.21E-3	4.88E-5	-3.62E-5	3.71E-10	-8.87E-10	1.03E-10
15% unloading	$\epsilon^{1.00}$	5.45E-3	5.51E-5	-4.75E-5	-4.12E-10	3.89E-10	2.71E-10
				Permeability			
15% loading	$ln(\frac{k}{k_{max}})^*$	5.36E-3	-7.69E-5	1.40E-4	4.60E-9	-4.78E-9	-1.58E-8
15% unloading	$ln(\frac{k}{k_{max}})^{**}$	-1.07E-1	-7.56E-5	1.96E-4	5.56E-9	-1.16E-9	-1.65E-8

[†] Deformation cycle had confining stress to 27.6 MPa and pore pressure to 13.8 MPa. For remaining tests the deformation cycle had confining stress to 55.2 MPa and pore pressure to 27.6 MPa.

[*] $k_{max} = 5.87\ \mu$d

[**] $k_{max} = 6.09\ \mu$d

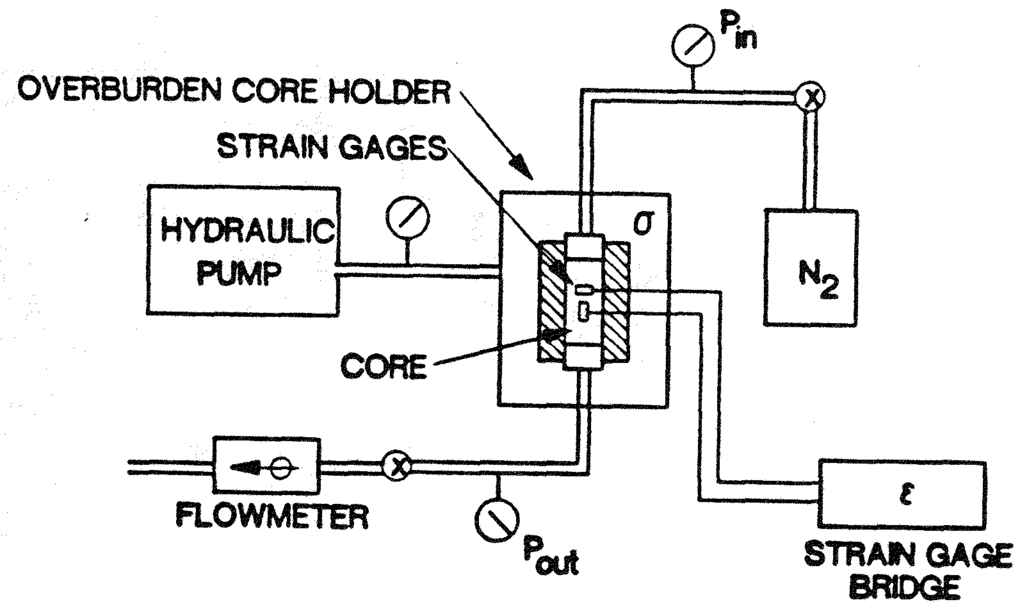


Figure 1. Schematic of experimental set-up.

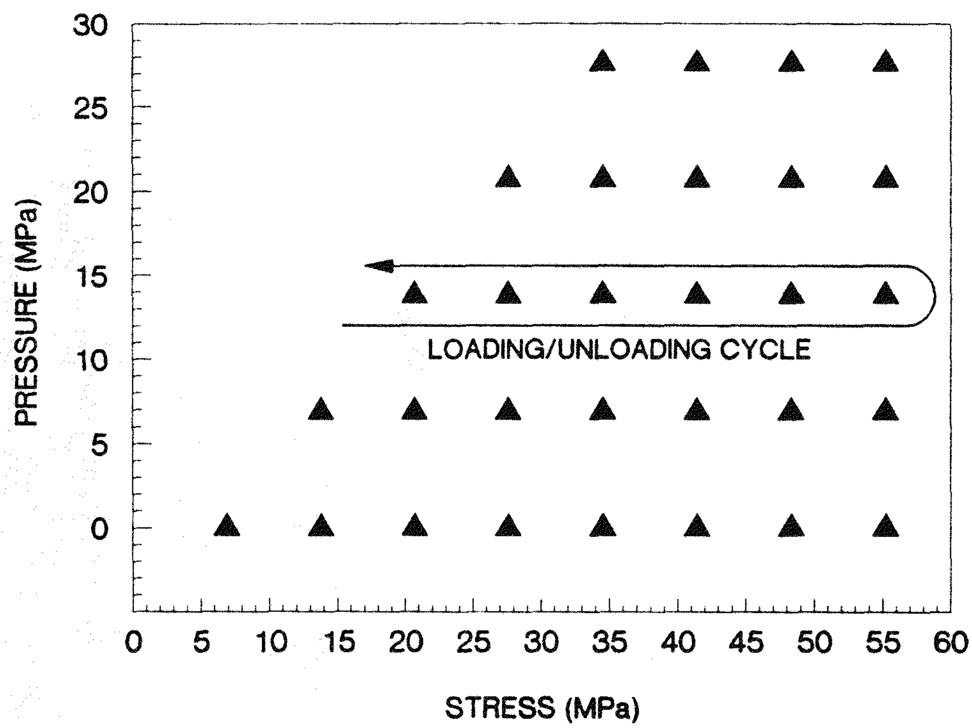


Figure 2. Modified factorial test matrix for determining effective-stress law.

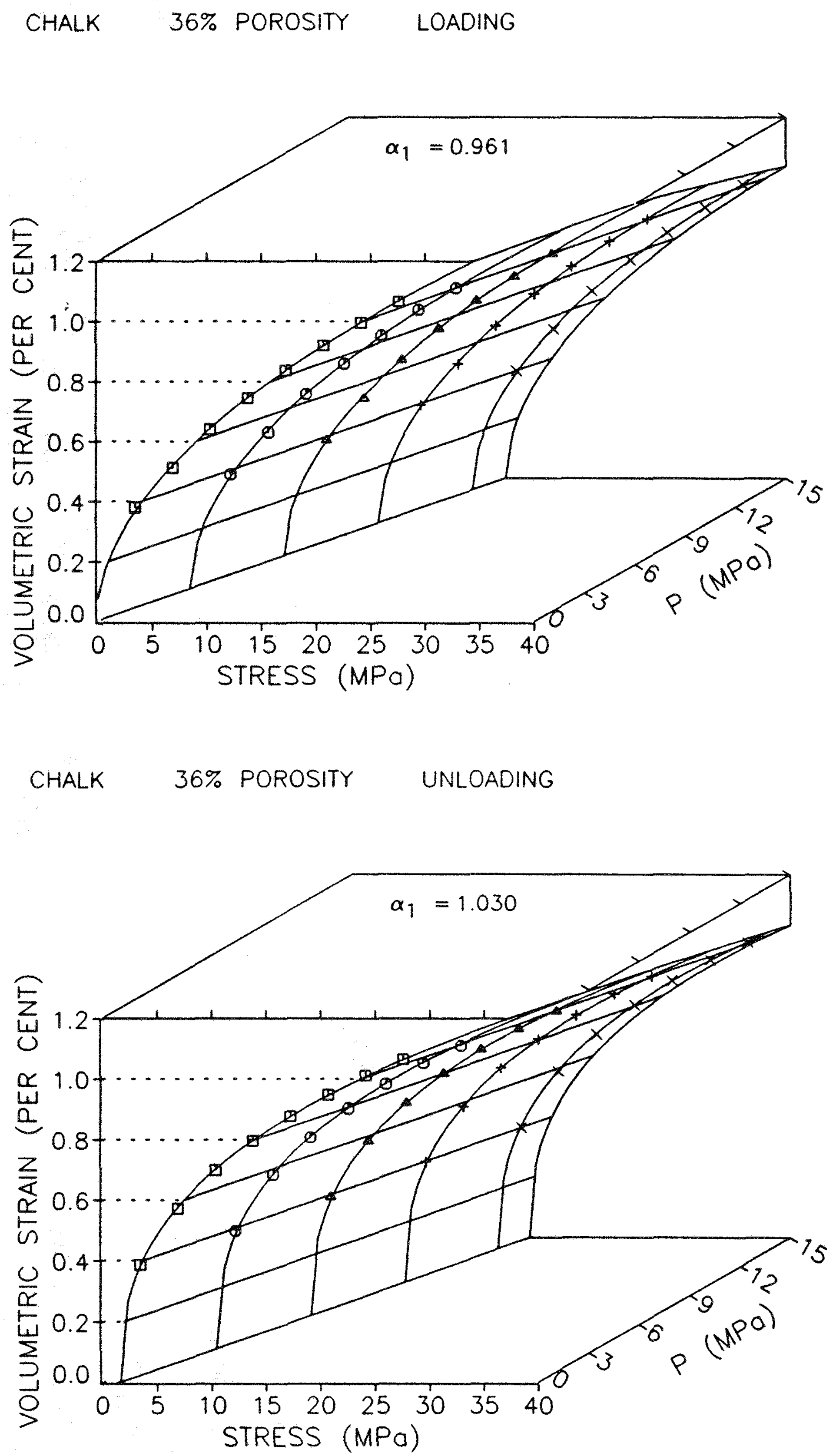


Figure 3. Inverse response-surface result for deformation of a 36% porosity chalk for loading and unloading cycles to confining stress of 27.6 MPa and to pore pressure of 13.8 MPa.

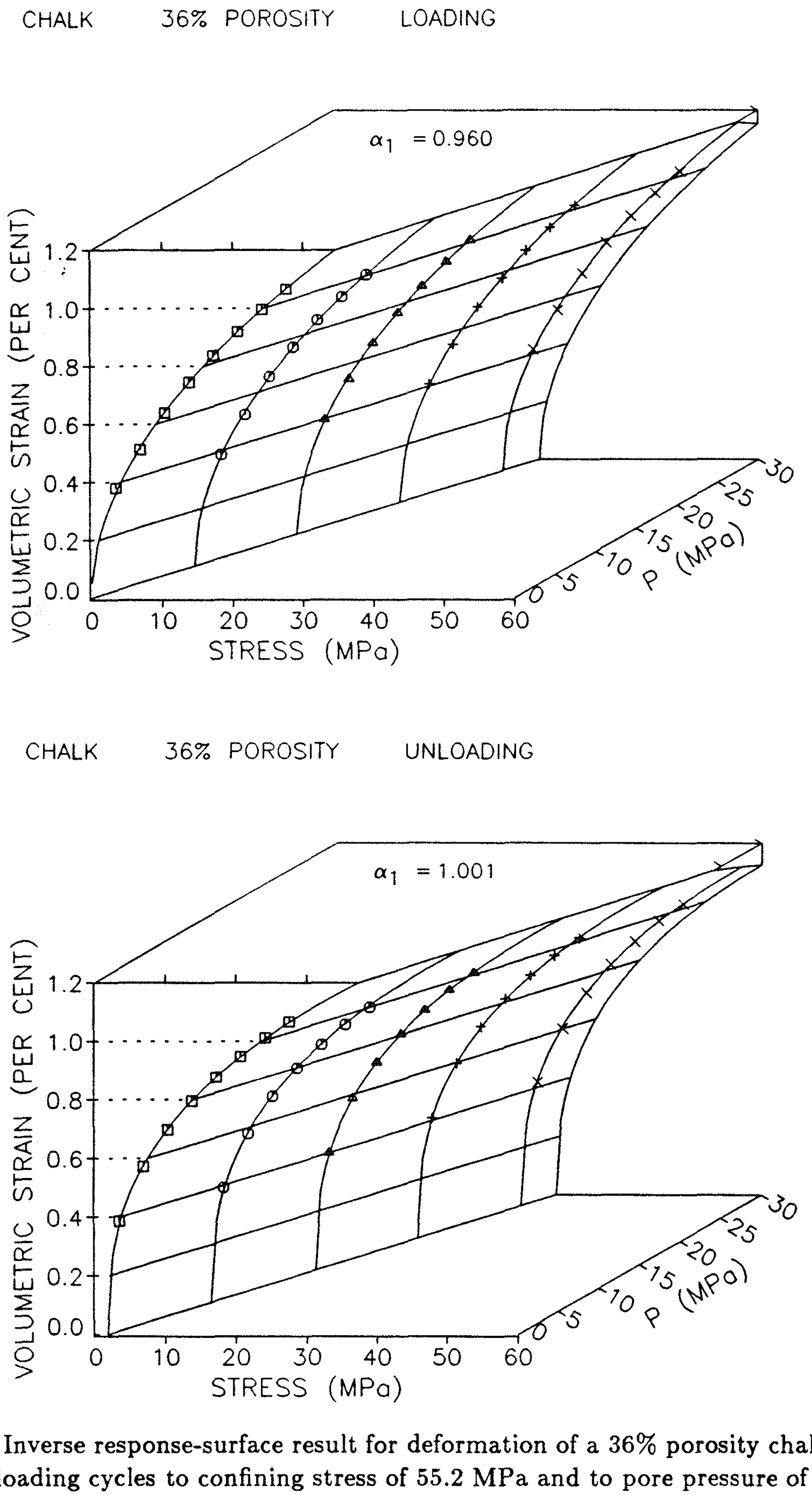


Figure 4. Inverse response-surface result for deformation of a 36% porosity chalk for loading and unloading cycles to confining stress of 55.2 MPa and to pore pressure of 27.6 MPa.

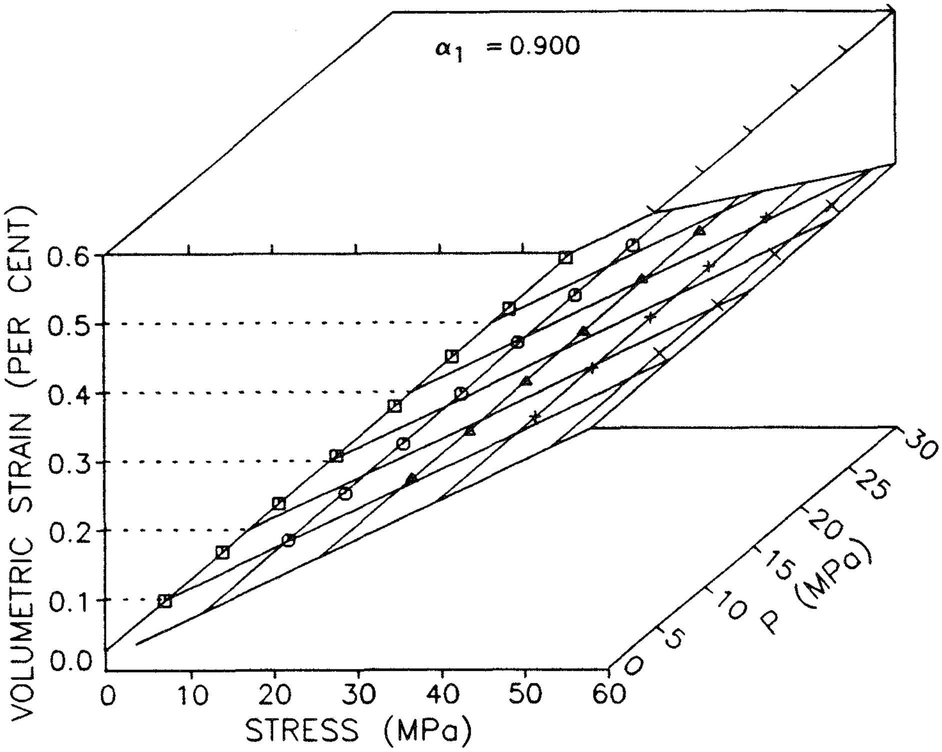


Figure 5. Inverse response-surface result for deformation of a 24% porosity chalk.

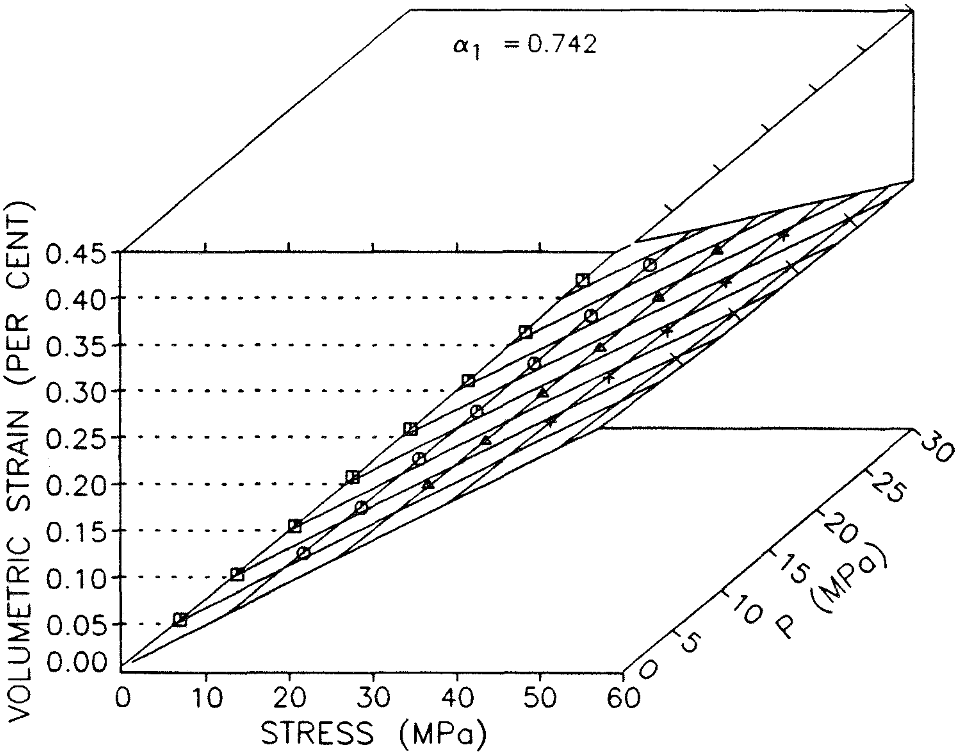
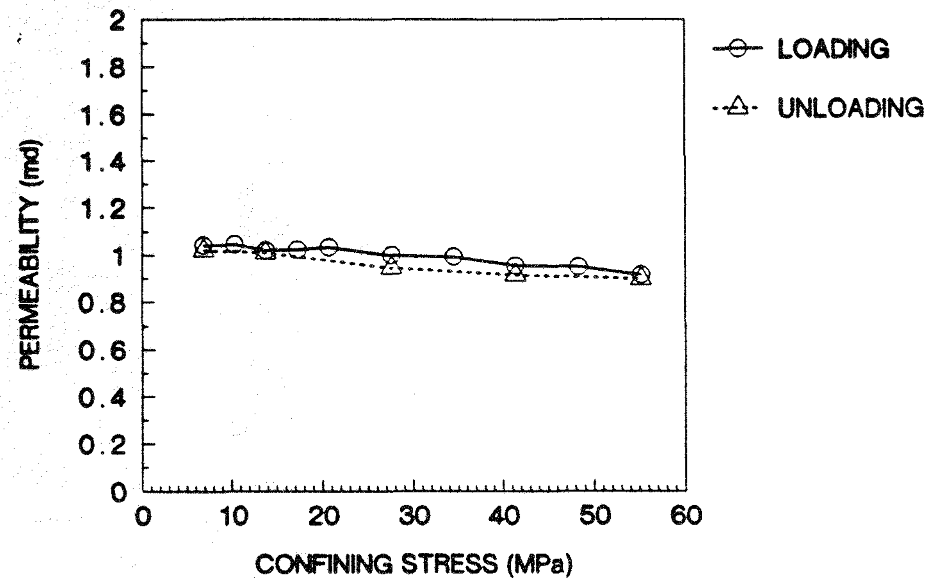
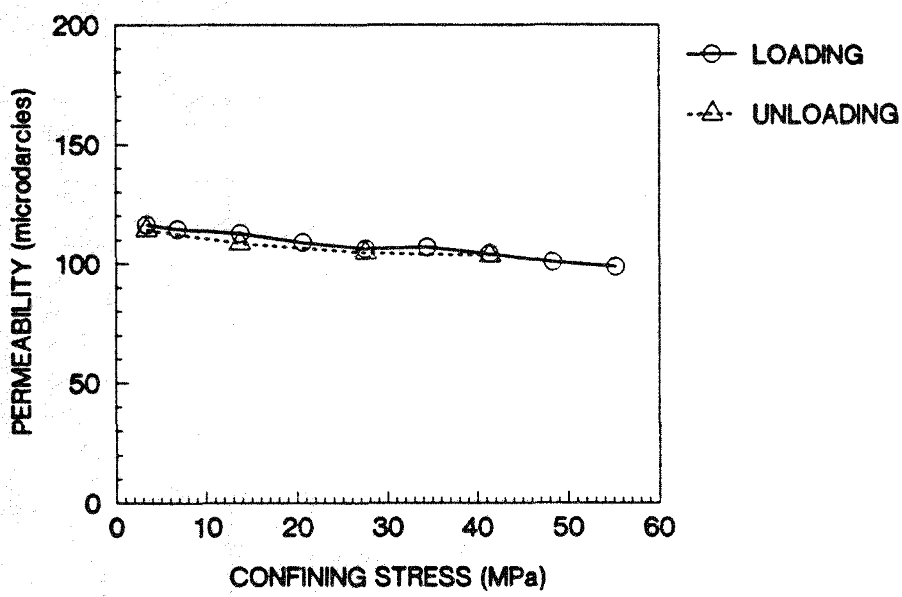


Figure 6. Inverse response-surface result for deformation of a 15% porosity chalk.



a.



b.

Figure 7. Plot of permeability versus confining stress for (a) 36% porosity chalk and (b) 24% porosity chalk.

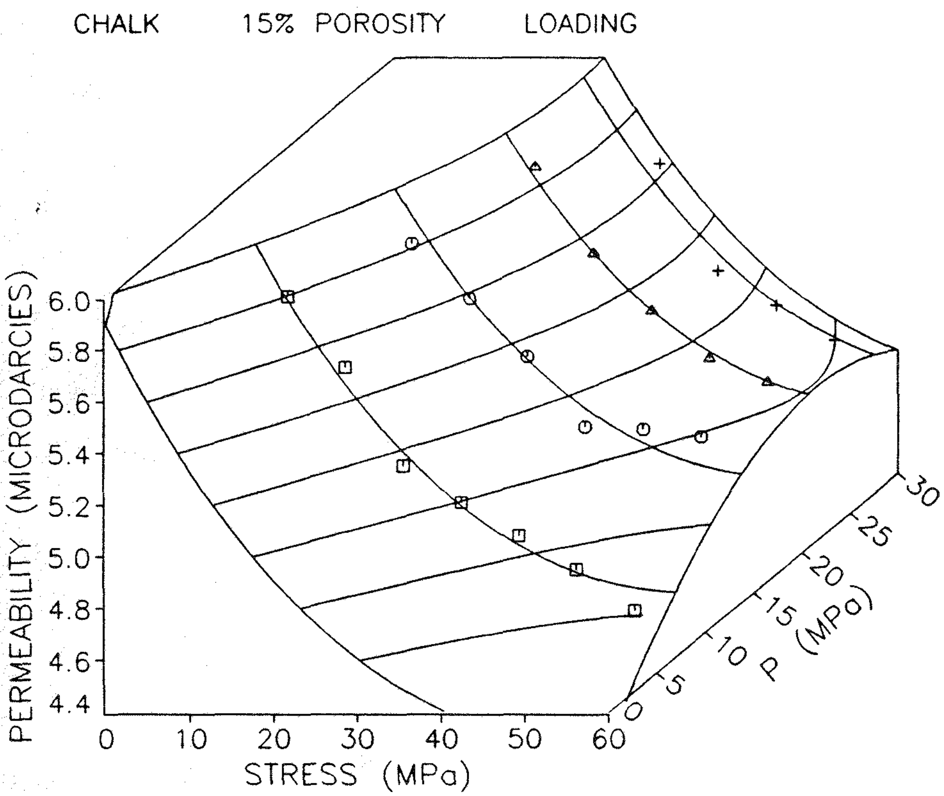


Figure 8. Inverse response-surface result for permeability of a 15% porosity chalk.