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Viscous Rheology and State of Stress in Unconsolidated Sands

C.T. Chang and M.D. Zoback, SPE, Stanford University

Abstract

Observations of triaxial creep and stress relaxation of unconsolidated reservoir sands imply markedly different static and dynamic modulii and may explain observations of very low differential stresses found in the Wilmington Field, CA, the Gulf of Mexico, and elsewhere. Triaxial testing performed on 1 inch plugs of reservoir sands under both stress- and strain-controlled conditions show transient stresses and strains. All tests were performed under dry or drained conditions to eliminate poroelastic effects. We previously observed creep under hydrostatic stress conditions in these unconsolidated sands. The resulting strain vs. time curves could be fit with a standard linear solid viscoelastic model that had a relaxation time of about 10 hours. The data demonstrates the rock's ability to dissipate stress through relaxation and creep. The reservoir material shows viscoelastic rheological behavior in both creep and relaxation tests which appears to be related to the presence of intergranular clay. Measurements of the static Poisson's ratio under large strains yielded values ~ .29 which suggests that the particles in the matrix efficiently coupled the principle strains.

Introduction

Time dependent deformation of unconsolidated sediments is traditionally understood to arise from pore fluid expulsion in saturated earth materials[1,2]. Although many accounts have been published relating the viscous behavior of soils at shallow depth associated with dewatering, there have been few studies of time-dependent deformation of poorly consolidated rocks under drained or dry conditions at th
encountered in hydrocarbon reservoirs. W
unconsolidated sands can creep during com
at elevated pressures[3] and related this beha
dependent moduli. They do not necess
differential stresses, saturation, or high temp
This study examines time varying stres
viscoelastically deforming sediments unde
conditions and demonstrates how they can c
differential stress in unconsolidated reservoir

Highly variable and often very low differe
are commonly seen in poorly consolidated
(e.g. Finkbeiner and Zoback[4]). This results
estimates of principle stress magnitudes.
explained if poorly consolidated sands were
viscoelastic rheology.

There are numerous studies of streng
deformation of unconsolidated or weakly c
in the rock mechanics literature. These test
at pressures more relevant to those enc
hydrocarbon recovery[5,6,7,8]. However, ve
accounts report the existence of time depe
strain when dealing with the compressiv
sediments. Although time dependent def
observed in investigations (such as Karig[8],
flat plateaus on stress versus strain cur
addressed directly. As in the soil mechanics
dependent deformation is addressed, it is ass
fluid expulsion during consolidation. Such te
using partially drained conditions arisin
permeability such as Lo and Lee[9] wh
dependent deformation in saturated shales
poroelastic phenomena associated with low p
are not relevant when studying highly permea

Two investigations that examined
deformation in poorly consolidated rock a
under drained conditions are Dudley et al[10],
These investigations report time dependen
unconsolidated reservoir rocks at pressures
triaxial loading configurations. Their sampl
yet drained and highly permeable. The h
prevented the development of unrelaxed p
consolidation. These triaxial loading tests ex

creep strain that could be fit with a power law creep model. Their study observed the creeping behavior of sand at low temperatures. These observations of time dependent creep in Gulf of Mexico turbidites and river sands suggested that the rocks have a viscoelastic character. However, their boundary conditions were constant axial or hydrostatic load and zero pore pressure, which prevented the observation of stress relaxation or transient pore pressure, thus leaving the question of time dependent stress unanswered.

Poisson's ratio should give some indication of an unconsolidated sand's degree of fluidity. Poisson's ratio describes how well the principle strains in a material are coupled. Spencer[12] provided extensive experimental results showing that clean dry sands tested in the laboratory using ultrasonic techniques had Poisson's ratios between .15 and .20. These are much lower than one would expect from a matrix that "flows" as an incompressible fluid which has a theoretical value of 0.50. Karig[8] performed static experiments on sediments from the Nankai trench that gave values of approximately .20 to .25. To observe coupling between the principle strains requires deforming the material past its virgin consolidation state. This is not captured by ultrasonic measurement techniques that use smaller strain perturbations. Large strain perturbations would be a simple way to observe the degree of coupling between ε_{11} and ε_{22} thus determining the degree of fluidity. The static Poisson's ratio is as important as the ultrasonic information because it governs how unconsolidated reservoir rock behaves under large displacements and over long time periods.

Viscoelastic theory states that if a material creeps, then it should relax given the proper boundary conditions[13,14]. Creep is time dependent deformation under constant stress while relaxation is stress decay under constant strain. Viscoelastic theory states that if a material creeps viscoelastically, the relaxation stress can be derived mathematically (See Appendix). This means that if our sample is viscoelastic, then we should observe time varying stresses under constant strain boundary conditions. To illustrate the relationship between creep and relaxation, consider the creep strain in **Fig. 1**. By fitting the data with a standard linear solid model **(Fig. 1 inset)**, we can get a creep function for the material. Using viscoelastic theory (e.g. Tchoegel[15] and Appendix) we can use the creep data to calculate the expected time dependent stress as seen in **Fig. 2**.

In the following study, we present our observations of time dependent deformation under triaxial loads. This presents compelling evidence of viscoelasticity. Viscoelastic creep (but not stress relaxation) under hydrostatic pressures in unconsolidated sands has already been documented in Chang et al[2]. To demonstrate the phenomena under triaxial loads, we extended our study to tests with both constant stress and constant strain boundary conditions. Data from a variety of different triaxial tests demonstrate the different phenomena arising from a viscous rheology. The resulting data presents clear evidence for rock viscoelasticity under

Experimental Procedure

The samples used in this study were all unco
described in the **Table 1**. All samples we
quartz sands with mean grain of 300 µ
porosities were between 30 and 40%. The
containing less than 10% clay.

The core samples of unconsolidated
obtained from two hydrocarbon reservoirs.
samples were obtained from the Wilmin
Beach, California from a depth of approxim
wells UP941B and 169W. The Lentic samp
South Eugene Island field in the Gulf of Mex
of 7883 feet in well SEI-613/A12. Ottawa s
prepared in the laboratory. The cores from
were jacketed in PVC at the wellsite and
testing to preserve the natural state of the r
The Lentic samples came from a refrigerated

The samples were extracted from the
coring at room temperature with steel tub
extruding the sand into soft polyolefin jacket
specimen was 1 inch in diameter and 2 inc
samples to be tested "dry", residual heavy
from the samples by flushing first with m
then with air to dry the porespace. The sa
wired to a transducer stack and placed in a p
testing under room-dry conditions and room t

The Ottawa sand Montmorillonite cla
prepared by mixing Ottawa sand with 5%
clay by volume. The laboratory grade cla
then allowed to dry with air circulation fo
testing. The absence of viscous effects with
clay motivated this procedure. The residual v
below 5% by gravimetric analysis estima
jacketing enclosed the mixtures while the san
the loading endcaps.

The loading system was a triaxial
instrumented with axial strain and radial stra
A PC based data acquisition system cons
stress, strain, temperature, and pore pressur
internal load cell measured the differential lo
was maintained at room conditions. H
controllers allowed for precise stress ramps
Feedback circuitry connected to the
measurement system allowed experiments to
constant stress boundary conditions as well.

(I) Creep Testing.

Constant load creep tests were performe
the axial load at 10 MPa/minute and then
constant while maintaining a constant co

Maintaining a constant axial load resulted in axial creep. PC data acquisition monitored he transient creep response for up to 10 hours.

Uniaxial creep strain experiments were performed similarly but rather than maintaining a constant confining pressure, the radial strain gauge adjusted the confining pressure to maintain constant radial strain while holding the differential load constant.

(II) Relaxation Testing.

The analog of creep can be achieved by holding the axial strain boundary condition constant following a step displacement of the axial piston. Relaxation tests were performed under triaxial conditions by step loading the stress and allowing the axial piston to advance to a predetermined position. A closed loop feedback controller maintained that position by adjusting the axial stress. An internal load cell directly measured the vertical load on the sample. PC data acquisition performed prior to and following loading recorded both the impulse and transient response of the displacement and load. These tests are run dry and drained. The Ottawa sand/5% Montmorillonite clay sample was run "room dry" with pre-wetted laboratory grade Montmorillonite (see description in Chang et al[2]).

(III) Pore Pressure Transient Tests.

The pore pressure transient testing was performed in a manner similar to (II). The major difference was that the samples were saturated. The pore pressure control system was shut in to maintain constant pore volume. These were essentially undrained triaxial and uniaxial tests. The differential load was stepped and held at a nominal value and the axial displacement was allowed to creep at constant confining pressure in the triaxial case, or constant radial strain in the uniaxial case. The PC acquisition system monitored the time history of the pore pressure prior to and following the stress perturbation. These tests were run saturated with denatured alcohol to avoid chemical interactions with the rock fabric.

(IV) Poisson's Ratio by stress and strain.

To determine Poisson's ratio at large displacements, a direct measurement of principle strains (axial and radial) is required during triaxial loading. By measuring the stress ratio under uniaxial strain, we can also estimate the Poisson's ratio assuming linear elasticity of the sample. Under uniaxial strain loading, the sample was monitored while increasing the confining pressure to determine the stress ratio up to 27 MPa of vertical stress. Both measurements are large strain observations of the degree of coupling between the principle strains under large displacements.

Results of Laboratory Testing

As in the hydrostatic loading cases, the rock
creep deformation in uniaxial and tr
configurations while pausing loading ramps
constant pressures. All of the samples cre
constant loads in both triaxial stress and
configurations.

The creep response under triaxial lo
resembles that measured under hydros
conditions[2]. **Table 1** summarizes the relaxatio
and loading conditions. For the triaxial case
the Lentic sand time constants are shorter t
Wilmington.

When testing the Wilmington sample und
(**Fig. 4**), the radial strain gauge and pre
controller had a tendency to give a step like re
sample creeped. Since all strain changes
perturbations in the sample, controlling st
measurement (as in the uniaxial strain case) l
of minor instability observed in **Fig. 4**. Al
contains more irregularity than the other re
compression, it is evident that the sample cr
boundary conditions as well.

In the Lentic sand tests, the triaxial and un
strikingly similar to triaxial stress, unia
hydrostatic stress tests in the Wilmington sa
triaxial compression experiment (**Fig. 5**) fits
creep function of a standard linear solid and
measured triaxially and hydrostaticly[3] on Wil

The uniaxial compression of the Lentic sa
much lower time constant than the other
equilibrated much faster. Evidently the tim
simply a function of the boundary condi
Wilmington uniaxial strain test, the difficult
the confining pressure using a strain feedback
the data. However, the signal is suffic
demonstrate the effects of creep under
compaction.

Although there isn't a clear connection b
condition and relaxation time, it appears tha
sample deforms with a longer time constant t
the more stable triaxial cases. All tests have
under 13 hours as in the hydrostatic cases.
between the uniaxial creep time constants a
time constants may reflect the instability of t
tests. Still, the Lentic sand appears to be a so
equilibrates quickly under triaxial loading.

Triaxial stress relaxation experiments

Under constant strain steps, stress relax
both the Wilmington sand samples a
sand/Montmorillonite samples. In the Ottawa
transient stress peaked at 36 MPa differentia

to equilibrium (**Fig. 7**) after 5 hours following the step displacement of the axial piston.

The stress, monitored using an internal load cell mounted directly to the sample, decayed exponentially as a function of time and resembled the theoretical predictions made for viscoelastic media (**Fig. 2**). The sample was under dry and drained conditions. Although the sample displayed some degree of fluidity under compression, the shear stress did not decay to 0 MPa suggesting that the sample does not reach the isotropic stress state. The residual stress after equilibration is suggests that there is a static modulus of this material that maintains a finite differential load over time. This indicates that the rock material isn't totally fluid-like.

A similar response is seen in the Wilmington turbidite sample as well (**Fig. 8**). In this case, the sample stress increased to a transient peak following the step strain axial displacement and then decayed away over a period of several hours. In this case, the hydrostatic stress was held at a constant pressure of 20 MPa. This sample required more strain to obtain the peak stress observed in the Wilmington sample. The Ottawa sand/Montmorillonite sample lost 58% of it's initial strain by the time it reached equilibrium. The sample cannot maintain the initial 36 MPa of differential stress indefinitely, however did maintain a finite load over time.

Pore fluid compression experiments

The objective of the pore fluid compression experiments was to observe the transient increase of pore pressure associated with creep compaction under polyaxial stresses. Under polyaxial compression, sealing the pore fluid system maintained constant pore volume minus the effects of fluid compressibility. Following step axial loads in both triaxial stress and uniaxial strain boundary conditions, the acquisition system collected data of axial creep, volumetric strain, and pore pressure.

The triaxial case showed a time dependent increase in pore pressure. This increase was accompanied by pore volume compaction (**Fig. 9a**) under constant loads as shown in below in **Fig. 9b**. The flat stress data demonstrates the system's ability to hold the principle stresses constant during the creep process. Pore pressure increased transiently and approached the confining pressure which is also the least principle stress. The experiment was terminated to prevent the sample jacket from rupturing in a "self hydrofracing" mechanism. The experiment demonstrated the possibility of transient pore pressure changes following deformation events that can change the effective stress state.

The second time dependent pore pressure experiment involved compacting the Lentic sand under uniaxial strain. From the strain history in **Fig. 10(a)**, the majority of the strain occurs during the step increase in differential stress. The axial creep strain follows the instantaneous step in stress for several hours. In this case there was no radial strain given the uniaxial strain boundary condition.

The stress history is shown in **Fig. 10(b)** creeped axially after a step load of 22 MPa vertical direction, the confining pressure balance the resulting change in horizon Poisson's effect. This resulted in a tran hydrostatic stress followed by a transient pressure. The pore pressure increase has the volume of fluid in the pore pressure plu

In these experiments the time dependent be connected to the viscous creep of an un under constant load. In both cases, after perturbed, a transient pore pressure respo undrained conditions. In both experimen changes in pore pressure following an ins perturbation lead to transient changes in th field.

Estimates of the Poisson's ratio

Poisson's ratio can be measured using e strain ratio. By definition, the Poisson's ratio principle strains under uniaxial stress. A se measurement of Poisson's ratio was deter stress ratio under the assumption that the ma a linear elastic material.

Compressing the Lentic sample under t with constant confining pressure gave a direc the principle strains. The results of radial a on the cylindrical plug sample are shown in of the curve gives the Poisson's ratio whi approximately 0.293. Aside from this bei experiment with plastic deformation, this definition of the Poisson's ratio. The curva **Fig. 11** suggests that the material disp behavior. Although the curvature suggests a Poisson's ratio, a linear fit was used on t attempt to capture the average value over t strains. The localized non-linearity of the c higher and lower estimates of the Poisson's fit attempts to capture the average value. T and 0.20 are superimposed on the plot to indi variability in the data associated with this mis

Fig. 12 is the strain history of the Lentic under uniaxial strain conditions. The strain r to approximately 1.55e-7/s. This is also the strain and approximately equal to the pore sample. The data shows some irregularity at the experiment because the hydraulic con trouble coming to equilibrium when the san poorly packed. As the material packed more deformation became more regular (Time>2.5

The relationship between vertical and ho summarized in **Fig. 13**. The change in verti the horizontal stress increase to maintain uniaxial strain. Assuming the material behaves as a linear elastic solid at times between 2.5 hours and 5 hours where the constitutive behavior is close to linear, we can relate the stress ratio and the Poisson's ratio by

$$\nu = \frac{\Delta P_c}{\Delta P_c + \Delta \sigma_1} \qquad \{1\}$$

Plotting the principle stresses (**Fig. 13**) and solving for the Poisson's ratio gives a value of approximately 0.272. There is localized nonlinearity on the curve suggesting that the Poisson's ratio isn't constant over the interval. Although the variation between small intervals is evident, a straight line captures the average behavior of the stress ratio well.

In summary, four different types of tests have demonstrated the physical manifestations associated with viscoelastic rheology. Creep tests at constant load exhibited time dependent deformation. Stress relaxation tests on dry samples showed exponentially decaying transient stresses and the tendency for unconsolidated materials to approach isotropic (low shear) stress states over time. Undrained compaction tests under triaxial loads developed transient pore pressure demonstrating the time dependence of effective stress in unconsolidated sediments. High Poisson's ratios are found when compressing the Lentic sand suggesting a flowing rheology.

Discussion

In all of the experiments presented here, unconsolidated reservoir sand and synthetic sand have a viscoelastic character. As predicted from viscoelastic theory and the hydrostatic creep data sets published previously[3], the creep can diminish differential stresses under constant strain boundary conditions, and pore pressure can increase due to time dependent pore volume compaction. Given this time dependent dynamic rheology, it appears that the rock matrix, with or without pore fluid, will deform viscously under the applied static loads. The Poisson's ratio measured under large scale strains indicates that this may be occuring by granular flow.

The triaxial stress relaxation tests confirm that rock stresses can relax over time in the constant strain cases given the proper boundary conditions and rock materials. In **Figs. 7 and 8**, samples that begin with an instantaneous differential stress of around 30 MPa lose their ability to maintain shear stress over time. The steady state stresses in these cases do not approach zero (isotropic stress) because the rock is viscoelastic, not a viscous fluid. The stress decays to the steady state differential strength of the material which can be related to the static Young's modulus. Because the load bearing capacity of the media decays, it can be thought of as the time dependent strength. Although the sample is not in failure during these experiments, the relaxati
stress can be regarded as weakening. Over
sample loses its ability to carry load by appro
the Ottawa and Wilmington sands.

The Poisson's ratio was higher than that
elastic crystalline rock material (~0.25) but l
an ideal incompressible fluid (~0.5), and it is
ultrasonic measurements. Ultrasonic testi
higher values for the Poisson's ratio which a
for unconsolidated reservoir rock[12]. Ho
amplitude ultrasonic wave doesn't move the g
way as a static test. Because the large strain c
space, it increases the interaction between
grains. These increases intensify the deg
between the principle strains, hence increasin
the Poisson's ratio. Since the materials defor
at large strains, it may not be appropriate t
values to small strain ultrasonic measurement

Our tests on Ottawa sand samples have s
time dependent deformation comes from s
clay added to the matrix[2]. Although the
saturated, it is possible that minute amount
intergranular clay allowed the grains to repac
appeared to be a micro-poroelastic eff
poroelasticity at the grain boundaries dete
constant. Since this process is highly dep
amounts of residual moisture in the clay, this
the variation in relaxation time constants fo
creep experiments. To test this idea, v
compressed a thin piece of the same clay tha
the amount found in the 5% Ottawa san
mixture and observed creep displacemen
magnitude as those observed in the Ottawa s
samples (**Fig. 14**). This observation clearl
relationship between the semi-dry clay and th

Even with very low water content
viscoelastic behavior at high stresses. Our
premoistened then dried clay to generate cree
the experiments, the porosity often changed b
the clay's pore volume gets smaller, the mi
residual pore water will consume more of t
spaces in the clay clusters. This will re
increases in saturation. Since permeability
low at this scale, it is possible that these m
pore water are unrelaxed — regardless of st
the overall sand sample. This type of mech
as "domain compaction" in the clay mech
provides an explanation for creep in partially
this is true in our samples, the degree of
micro-porosity and hence micro-permeability
the relaxation time constant.

The viscoelastic mechanism controlled th
and strength of our rock samples over time
the time scale, the rock stress will vary. E

occurs after a sudden perturbation of the stress field, it is most relevant to engineering practices where loading rates and observation periods may last from hours to days. Without understanding this phenomena, it is difficult to make consistent strength estimates using log or seismic measurements alone. A combined analysis including a variety of data types at different frequencies better constrains the time dependent material properties. The stress relaxation experiments suggest that a high frequency measurement will never see the low frequency (long term) modulus or the residual stress. This results in a gross over prediction the sand's stiffness and load bearing capacity.

Conclusions

Deformation experiments performed on the Lentic sand, Wilmington sand, and Ottawa sand/Montmorillonite synthetic samples indicate viscoelastic behavior that is unrelated to pore fluid expulsion or dewatering. This type of mechanism may explain differential stresses of poorly consolidated sand. This mechanism may also explain the differences observed between static and dynamic modulii. The experiments successfully demonstrate viscoelastic behavior in unconsolidated sediments under various types of triaxial loads, and were able to identify that the viscoelastic nature of the sands is related to the presence of intergranular clays.

Nomenclature

P_c = confining pressure
ν = Poisson's ratio
σ_1 = axial stress
σ_d = differential stress
τ = relaxation time
ε_{11} = axial strain
ε_{22} = radial strain

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Appendix

The standard linear solid equations for cree relaxation are given by

$$\varepsilon = \left[\frac{1}{E_1} + \frac{1}{E_2}\left(1 - \varepsilon^{\frac{-\tau}{\tau}}\right)\right]\sigma_0$$

and

$$\sigma = \varepsilon_0 \cdot \left(\frac{E_1 E_2}{E_1 + E_2} + \frac{E_1^2}{E_1 + E_2} \cdot \varepsilon^{-\left(\frac{E_1 + E_2}{E_2}\right) \dots}\right.$$

σ = 1-D stress
ε = 1-D strain
E_1 = outer spring (see **Fig. 1**)
E_2 = inner spring
σ_0 = stress perturbation
ε_0 = strain perturbation
t = time
τ = relaxation time constant

SI Metric Conversion Factors

in.x 2.54* E+00=cm

Tables

Table 1: The samples and their properties

Sample	Porosity	Mean grain size	Clay content	Grain morphology
Ottawa sand	34%	500 μm	5-10% (added by volume)	Rounded, well sorted
Wilm. sand	35-39%	300 μm	<10%	Angular, poorly sorted
Lentic sand	36%	100 μm	<5%	Angular, well sorted

Table 2: The creep parameters

Sample	Loading condition	Relaxation time (hours)	Pc (MPa)	σ_1(MPa)
Wilm.	uniaxial strain	13.0	30	40
Wilm.	triaxial stress	5.70	22	25
Lentic	uniaxial strain	0.37	15	18
Lentic	triaxial stress	1.88	10	18

Figures

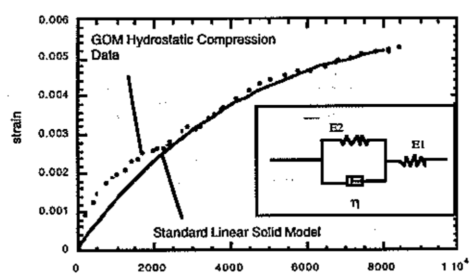


Fig 1.— A fit to hydrostatic creep data from an unconsolidated sand. This is a Gulf of Mexico sample fitted with a standard linear solid model. The fitting parameters give parameters necessary to predict the theoretical stress relaxation response[3].

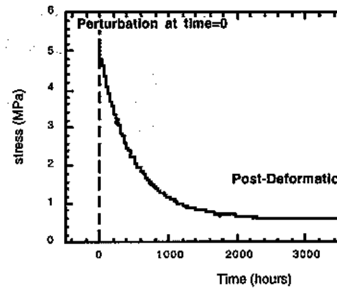


Fig 2.— Predicted theoretical stress relaxatio experiment shown in Figure 1 assumin Following a step increase in strain, the trans away with time.

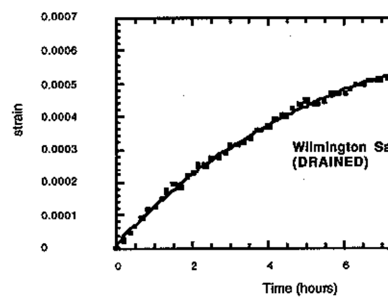


Fig 3.— Creep response of the Wilmington s loading conditions. The solid line is an expone Pc=22MPa,σ_1=25MPa.

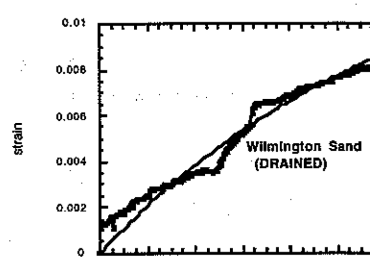


Fig 4.— Creep in the Wilmington sand un conditions. The solid line is an exponenti

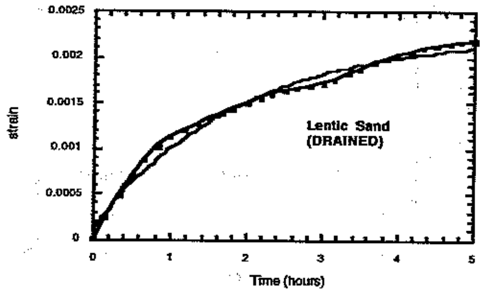


Fig 5.— Creep in the Lentic sand under triaxial loading conditions. The solid line is an exponential fit to the data.

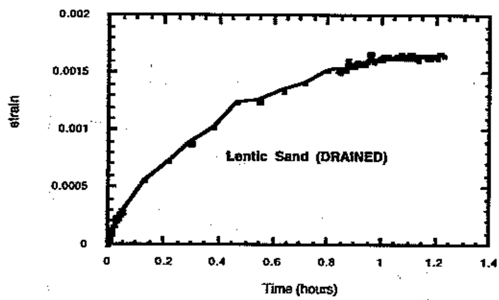


Figure 6.— Creep in the Lentic sand under uniaxial strain.

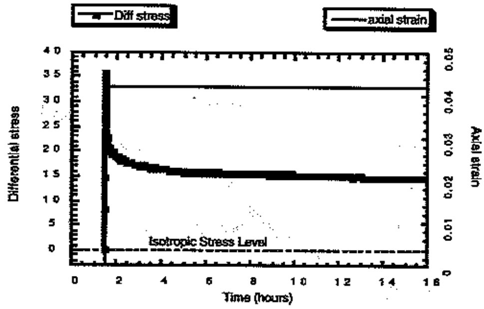


Fig 7.— Ottawa sand + 10% Montmorillonite clay stress relaxation under triaxial loading conditions and constant axial strain

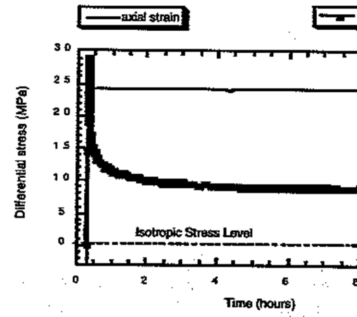
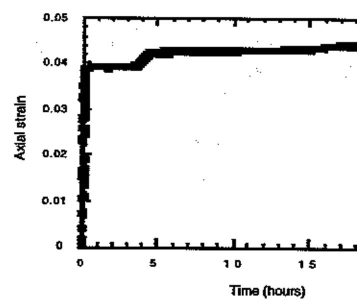
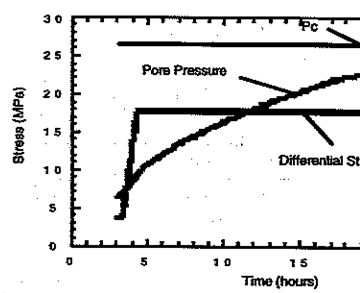


Fig 8.— Wilmington sand sample stress relaxat loading conditions and constant axial strain.

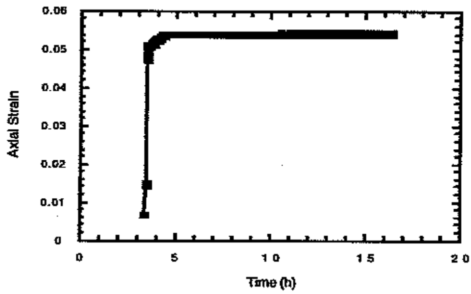


(a)

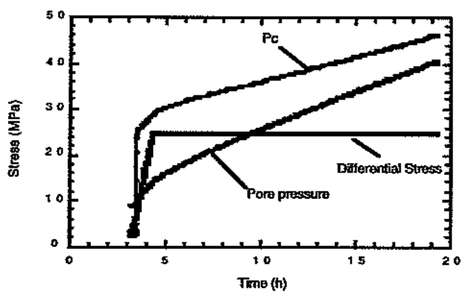


(b)

Fig— 9. (a) The strain history of the Lentic sa compression. (b) The stress history of the same transient increase of pore pressure under consta



(a)



(b)

Fig 10.— (a) The strain history of the uniaxial strain test on the Lentic sand subject to a step strain. (b) Following the step strain, both the pore pressure and confining pressure increase.

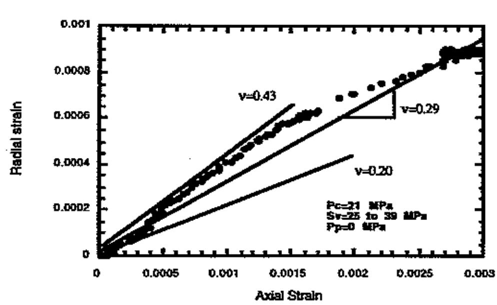


Fig 11.— The relationship between principle strains under triaxial compression of the Lentic sand.

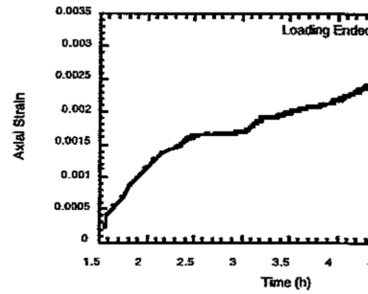


Fig 12.— Strain history of the uniaxial strain e: the stress ratio of the Lentic sand.

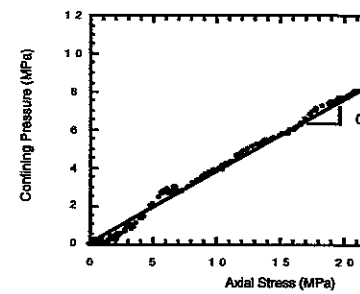


Fig 13.— The principle stresses of the Lentic s compression with a constant confining pressu

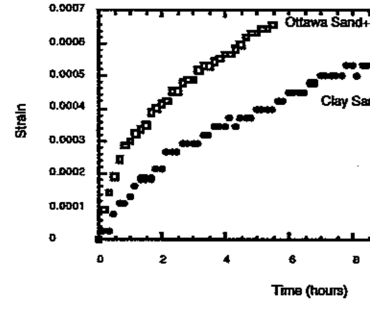


Fig 14.— The compression of pure clay di same clays used in the Ottawa sand synth markers) compared to creep in a sample of Montmorillonite clay. Both samples con volumes of the same clay.