Corrected
4/27/96

4/97
4/01

II D INFLUENCE OF TIME ON STRESS-STRAIN-STRENGTH BEHAVIOR OF CLAYS DURING UNDRAINED SHEAR

2. Thixotropy

3. Aging = Secondary Compression

4. Effect of Strain Rate

Sheet A1,2 } Data from Sheahan et al. (1996) from CK_0UC vs $\dot{\varepsilon}$ as f(OCR)
Sheet B } for resedimented BBC

Page No

5. Undrained Creep

6. Summary & Conclusions

Sheet C1, 2 Data on creep rupture and unique log $\dot{\varepsilon}_m$ vs log t_m
" D Data on correspondence
" E1, 2 Data on relaxation

IID: INFLUENCE OF TIME ON STRESS-STRAIN-STRENGTH BEHAVIOR OF CLAYS DURING UNDRAINED SHEAR

1. INTRODUCTION

1.1 Definitions

1) Prior to shear
   a) at constant w (UU): thixotropy
   b) At constant $\bar{\sigma}'$ (CU, CD): "aging" ≡ secondary compression

2) During shear (undrained)
   a) Rate of strain, $\dot{\varepsilon}$, as increase q
   b) Time after applying constant q = creep
   c) " " " " ε = relaxation

1.2 Comment on Drained Behavior

- For drained shear, $\dot{\varepsilon}$ (or t_f) believed to have little effect on $\bar{c}'$, $\bar{\phi}'$ for "ordinary" clays.

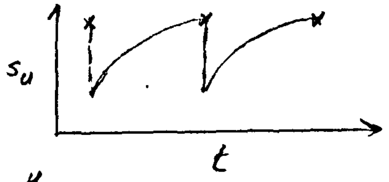
- But NOT for Highly Structured Cemented clays - see Section 4.4

2. THIXOTROPY (Mitchell, 1960 & 1993; O'Neill, 1985)

ASCE, JSMFD 86(3) Both MIT SM thesis

2.1 Definition

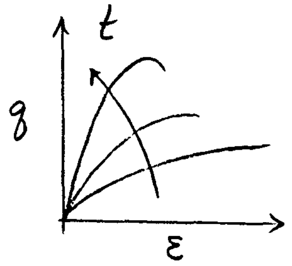
- With some clays, if remold and then store at constant composition → incr. stiffness & strength



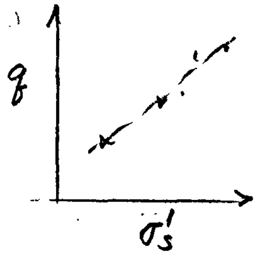
- Thixotropy = isothermal, reversible, time-dependent process occurring under conditions of constant composition & volume whereby a material stiffens while at rest and softens or liquefies upon remolding

2.2 Behavior Measured in UUC Tests

1) Based on limited published data.



plus maybe



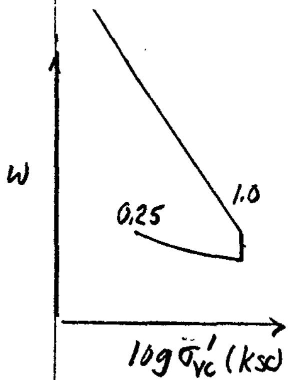
- PhD Berkeley on slurries of clay
- SM MIT UUC ~1960 ±
  (But not DON, 85)

2) Comments

- Storing disturbed tube samples may → incr. s_u w/t
- No correlation TSR = $s_u(t)/s_u(R)$ and soil type, but restricted to clays and generally more important with increasing I_L

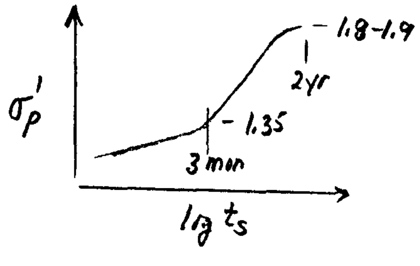
2.3 O'Neill (1985) - Behavior of Block Samples of Resedimented BBC II

Batch σ'_{vm} = 1 ksc + t_c/t_p = 1 cycle & rebounded to σ'_{vc} = 0.25 ksc



1) See p2a for oedometer
σ'_p vs log t_s (t_s = storage time)

- 1 week → σ'_p = 1.1 (expected)
- 3 mon → $\sigma'_p \approx 1.35$
- 2 yr. → σ'_p = 1.9



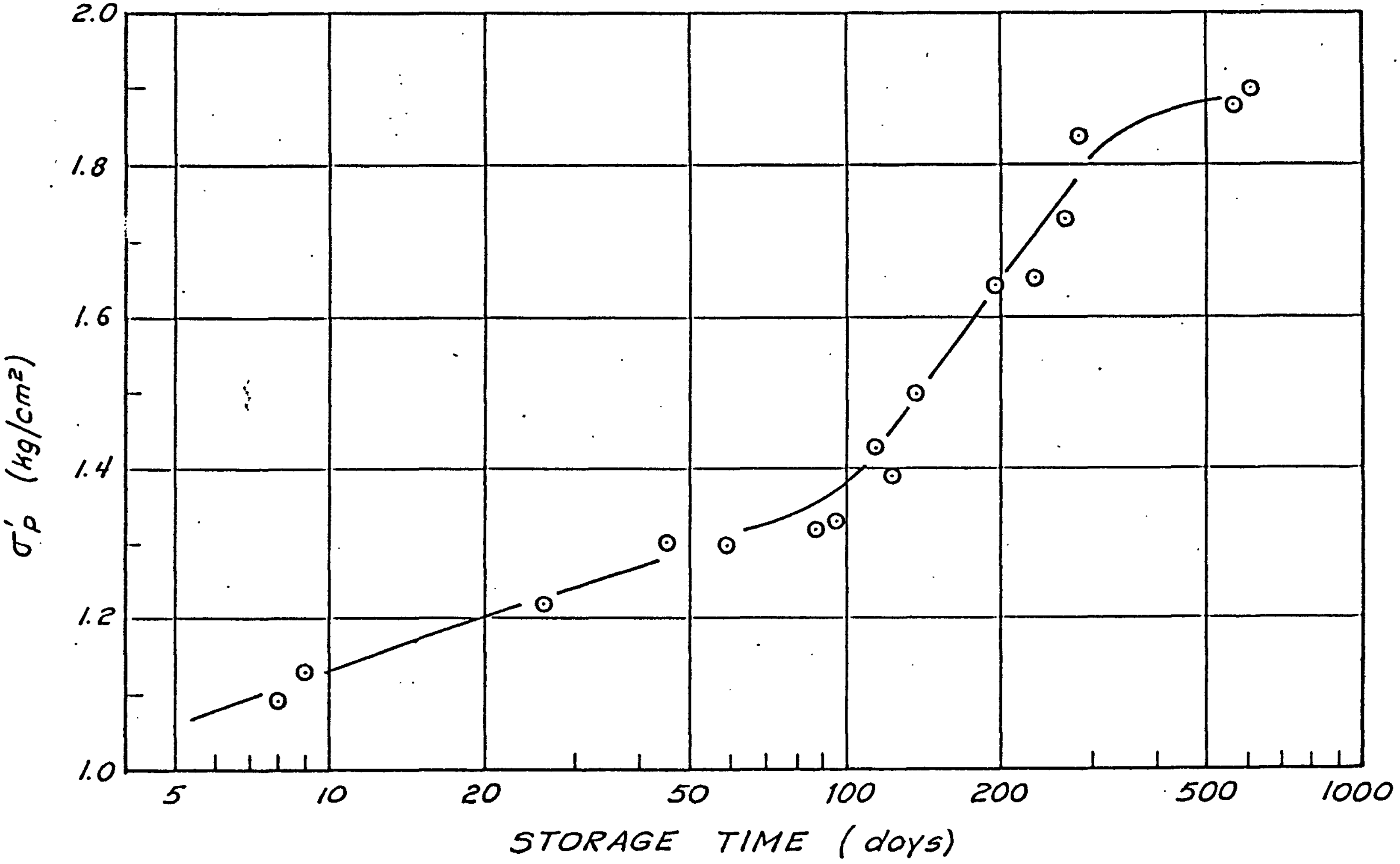
2) During this period

- Δw ≈ 0
- Very little increase σ_s
- Consistent increase in q_f Recompression CK_0UC/E of same magnitude & largely due to Δu_s (see p2a)

CCL
8/85

1.322

II D -



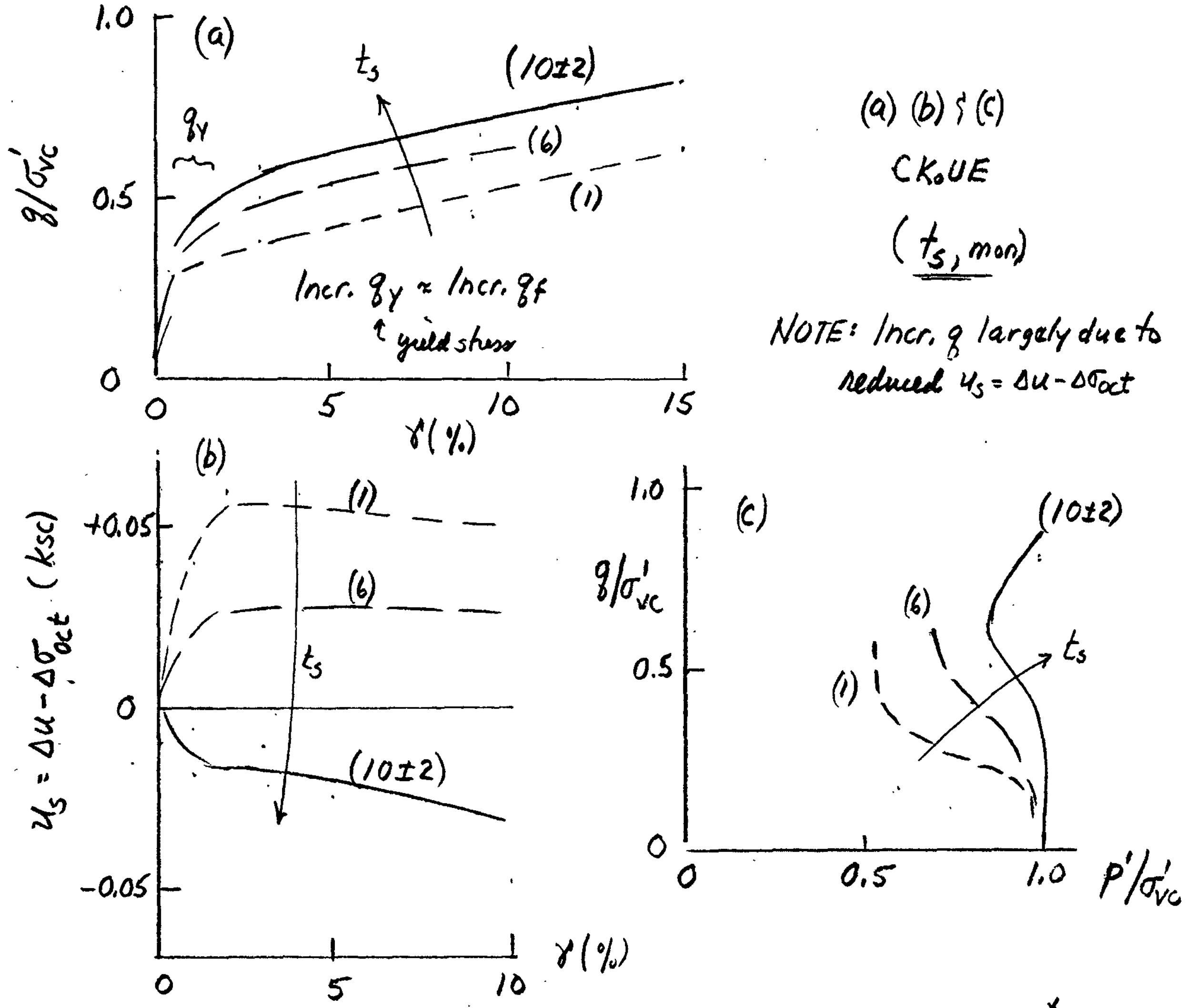
MIT Special Program (1985)
1.605

Figure 6-1 Effect of Thexotropy on Preconsolidation Pressure of Resedimented Boston Blue Clay (after O'Neill, 1985)

p2a

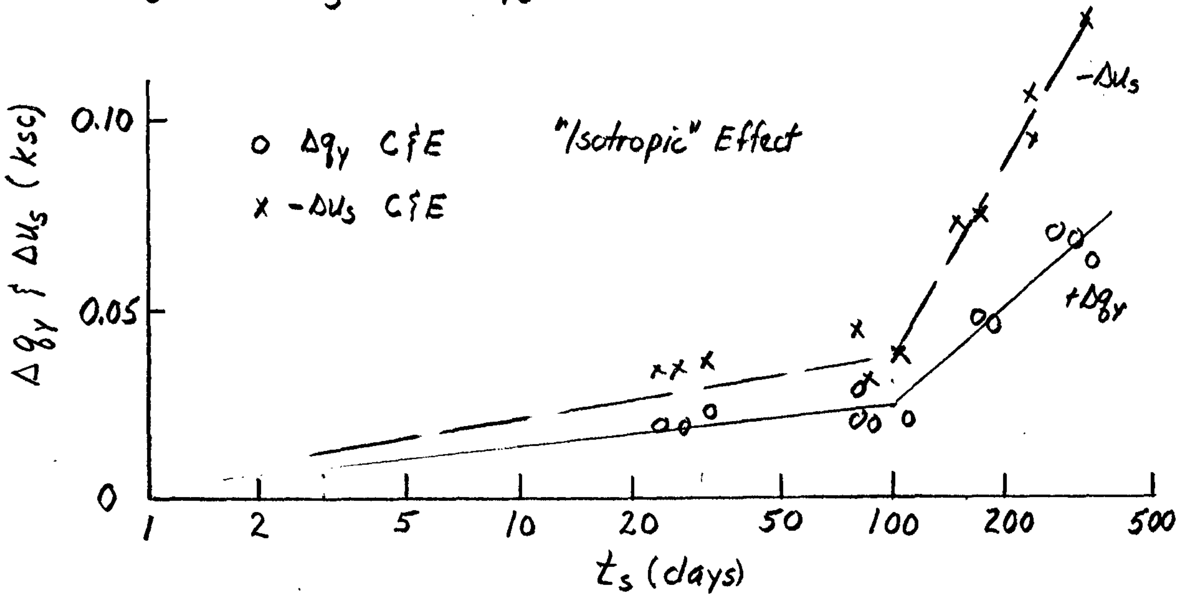
O'Neill (1985) Recompression CK_oU C/E Resed. BBC

(OCR = 4 prior to thixotropy) $\sigma'_{vc} = 0.25$ ksc



(a) (b) & (c)
CK_oUE
(t_s, mon)

NOTE: Incr. q largely due to reduced $u_s = \Delta u - \Delta\sigma_{oct}$



2.4 Possible Mechanisms

1) Reorientation of clay particles (Mitchell, 1976 & 1993 Book)
from "dispersed" → "flocculated". (Δ fabric and interparticle forces)
   - Presumably $\bar{A} > \bar{R}$ and/or $\bar{\bar{\sigma}}_a > \bar{\bar{\sigma}}_r$
   - Berkeley data supposed to show that occurs in compacted clays → large increase in k w/t !

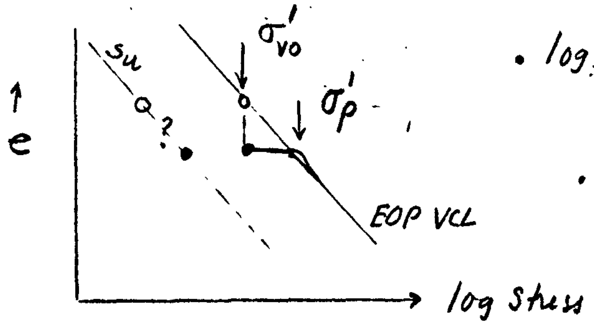
2) Water "structure". Decrease in free energy of adsorbed H_2O → decreasing u → increasing σ_s'
   - CCL liked before BBC data became available

3) "Bugs" (RTM)

4) Conclusions: Mechanism(s) unknown } But some clays (especially at high I_L) certainly get stiffer with time

3. AGING = SECONDARY COMPRESSION

3.1 Review from Treatment of Consolidation



- $\log \frac{\sigma_p'}{\sigma_{vo}'} = \frac{C_{\alpha e}}{C_c} \log(t/t_p)$
- $\frac{C_{\alpha e}}{C_c} = \frac{C_{\alpha \varepsilon}}{CR} = 0.045$ → ≈ 10% increase in OCR per log cycle secondary compression. Does s_u increase by same amount?

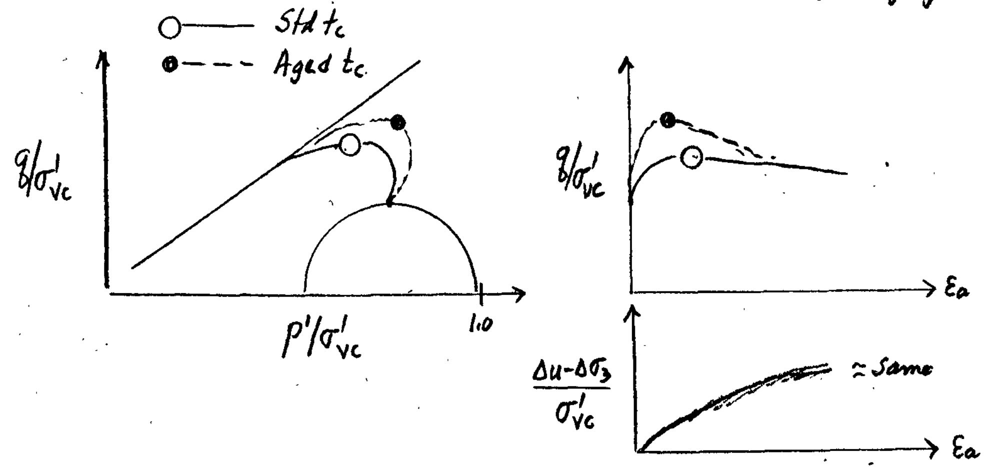
Given "fact" (à la Mesri) that $C_{\alpha e}/C = 0.045 \pm 0.015$ ($C = -\Delta e / \Delta \log \sigma_{vc}'$)
for most cohesive soils (Both OC & NC)
   - Only important at low OCR (i.e. "high" C → high C_α)

{ Should not vary in consistent fashion with changes in I_p }
∴ Tokyo Fig. 39 very suspect

3.2 Influence on CAUC Tests (OCR=1)

(Bjerrum & Lo 1963; Ladd 1965; Vaid & Campanella 1970)

Note: Aging at constant K_c



1) Aging leads to:
   - a) Modest increase in s_u/σ'_{vc}, say ≈ 5-7%/$\Delta\log t_c$
   - b) Large increase in E_u/σ'_{vc} (Ladd 1965 reports 60±10%/$\Delta\log t_c$ from CIUC tests)
   - c) Perhaps decrease in ε_f

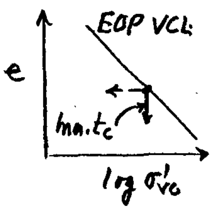
2) If same Δu vs ε_a, then:
   - a) Lower shear induced $u_s = \Delta u - \Delta\sigma_{oct}$ (consistent with incr. OCR)
   - b) Increased resistance at particle contacts since same Δu vs ε_a implies same displacement at contacts

3) Behavior of aged vs. mechanical precompression at same OCR?
   Aging probably → stiffer initial response (i.e., higher E_u)

3.3 MIT Standard Practice for SHANSEP Testing

Perform CK_oU tests after t_c ≈ 1 day ($\log t_c/t_p \approx 1$ → ≈ 1 log cycle)

1) Minimize $+\Delta u$ due to "stopping" secondary compression →



2) Standard t_c → more consistent data

3) To instill some "structure" in the clay (i.e., make stiffer) that was destroyed by consolidation beyond in situ σ'_p

NOTE: Empirical aspect of SHANSEP. Also actual OCR is slightly higher that reported (since aging increases σ'_{vm})

3.4 Influence of Consolidation Time on CK_0UDSS Data

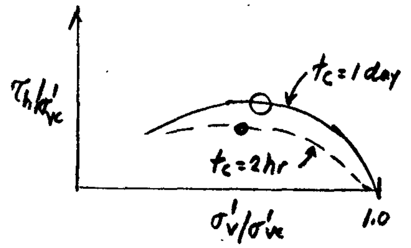
1) As per 3.3, SHANSEP CK_0U tests typically use $t_c \simeq 1$ day at test σ'_{vc} (≠ test σ'_{vm}) when attempting to predict initial in situ undrained shear behavior of naturally OC clays.

2) However, during staged construction, foundation clay is still undergoing consolidation, i.e., presumably lies on t_p (EOP) compression curve. Therefore there will not be any "aging" (secondary compression).

3) Following compares $t_c = 1$ day vs $t_c = 2$ hr ("EOP") for two plastic soils at Peak strength (each average of 2 tests) at $\dot{\gamma} = 5\%/hr$

Soil	t_c	γ_f(%)	τ_h/σ'_{vc}	
Fresh Kills, NY Organic Silt ($I_p = 60\%$)	1 day	14.5 ±0.5	0.296 ±0.018	
	2 hr	14.1 ±4.9	0.257 ±0.020	→ −13%
Sargipe, Brazil Offshore CH ($w_N = 65\%$)	1 day	9.4 ±0.2	0.238^{5} $\pm 0.003^{5}$	
	2 hr	$\simeq 7.6^{5}$ ±0.9	0.2163 ±0.0067	→ −9.3%

} Ave. = −10.5%



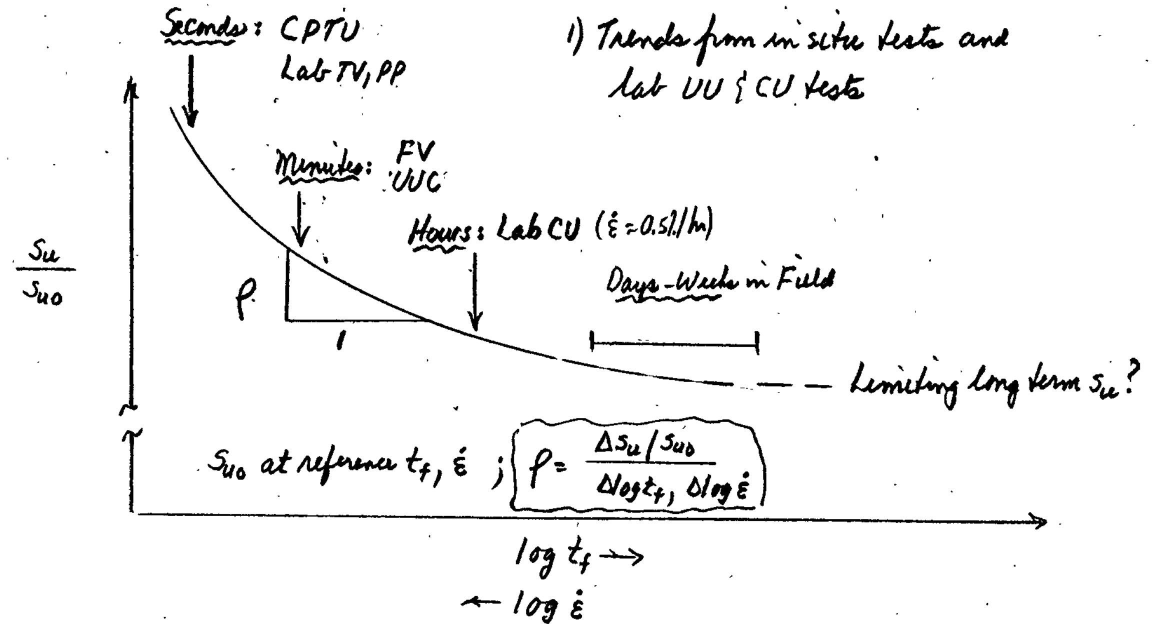
NOTE: For $\dot{\gamma} = 0.5\%/hr$, reduction → −11.8%

4) Effect is significant: Therefore should use $t_c \simeq t_p$ (EOP) to obtain s_u/σ'_{vc} for OCR = 1 "underconsolidated" soil.

4. EFFECT OF STRAIN RATE

4.1 Overview :

1) Trends from in situ tests and lab UU & CU tests



2) Reported values of ρ and comments [also see Sheahan et al. 1996, JGE, 122(2)]

a) Most of the early (<1970) data came from UUC tests → unknown OCR

b) Most CU data with known OCR from CIUC tests

NC Typical $\rho \approx 10 \pm 5\%$; t_f = 1 min → 1 week

High OCR " " ≈ 15% ; t_f = 5 min → 1 week

[Note: Undisturbed CL-ML Haga Clay, CK_0UC at OCR = 10-40 → $\rho \approx$ 30-35%!
(Andersen & Stenhamar, 7/82, JGE)]

3) Implications when comparing s_u data having different t_f / $\dot{\varepsilon}$

a) Compare UUC at $\dot{\varepsilon}$ = 1%/min vs CK_0UC at $\dot{\varepsilon}$ = 0.5%/hr → 2 log cycles

b) $\Delta q_f \approx 20 \pm 10\%$ for $\rho = 10 \pm 5\%$ at low OCR

" ≈ 30-60% for ρ = 15-30% at high OCR

4) Extreme case: Offshore Alaska at Smith Bay ; CL-CH Pleistocene clay

s_u(UUC, FV & CPTU (N_k=15)) ≈ 3 × s_u(DSS)
from SHANSEP with well defined
σ'_{vo} & σ'_p profiles

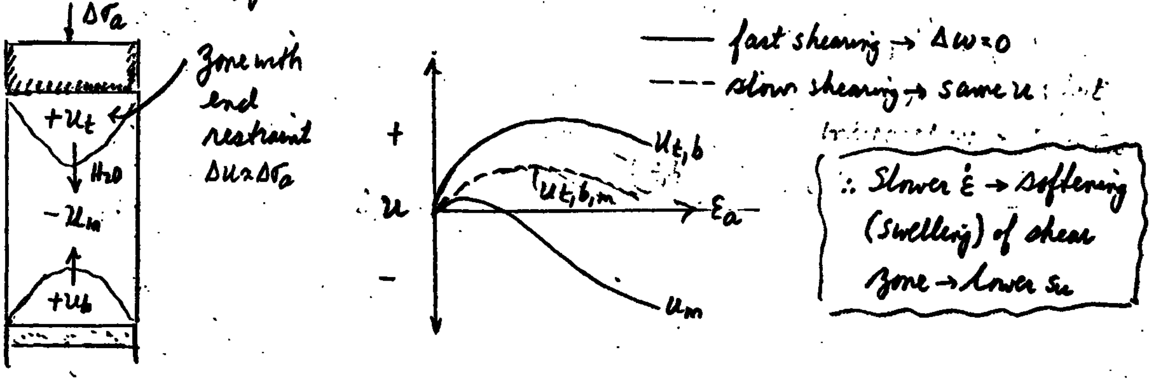
I_p ≈ 25%, T ≈ -1°C
z = 1-5.5 m
OCR = 40-8

Young (1986) MIT SM thesis

4.2 Results from CIUC Tests at High OCR: Fixed End Caps

NOTE: Also applies to UUC testing at varying $\dot{\varepsilon}$

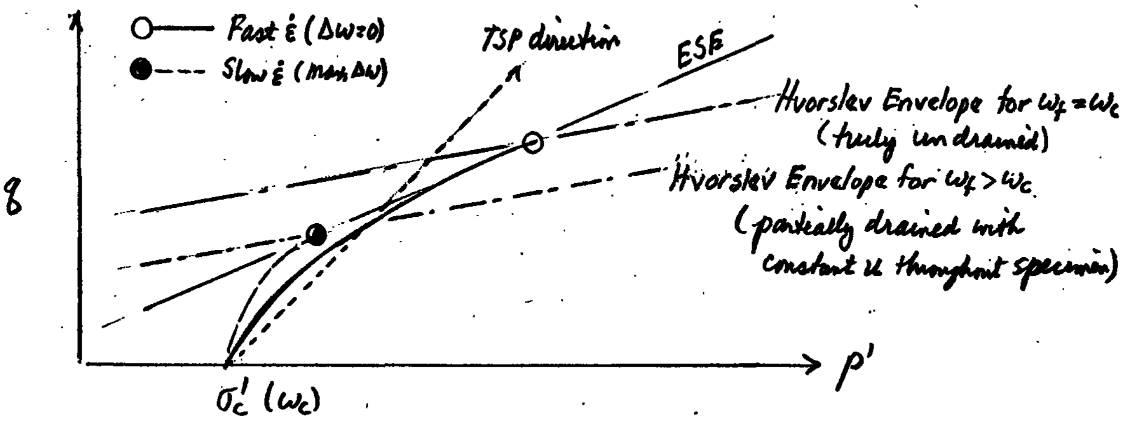
1) Overview of problem (also see Notes on measurement of c' & ϕ', IB)



∴ Slower $\dot{\varepsilon}$ → softening (swelling) of shear zone → lower s_u

2) Results on OCR = 16 CH clay [Richardson & Whitman 1963, Geot 13(4)] → CCL reinterpretation

CIUC with u_m (at middle → correct ESP)



3) Conclusions.

a) Regular UUC/CU tests at varying $\dot{\varepsilon}$ on high OCR clay are partially drained; hence decr. in s_u at slower rates due in part to softening of shear zone

b) Need lubricated end caps to measure correct Δs_u vs $\Delta\dot{\varepsilon}$

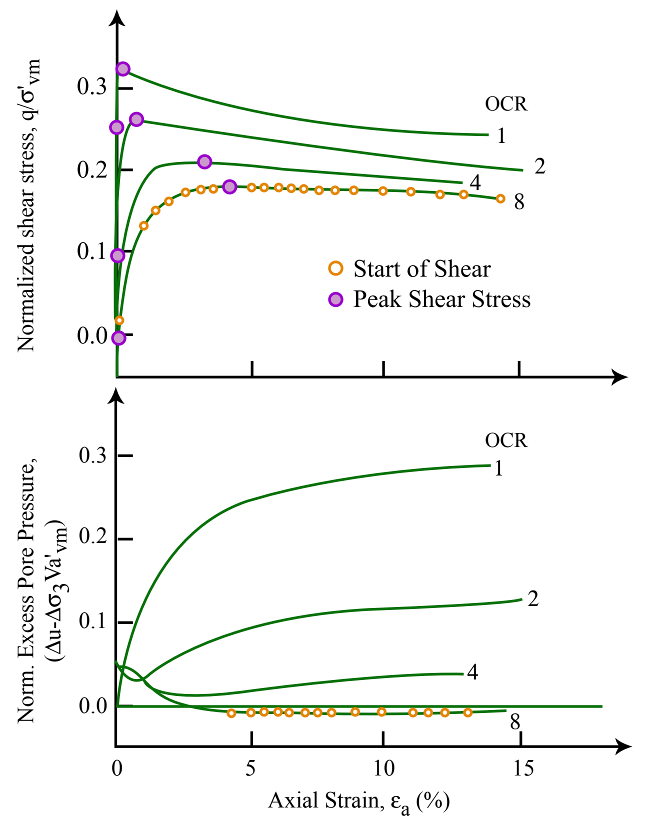
c) Will in situ shearing of high OCR clay also → softening of potential shear zone, and hence lower s_u?
CCL doesn't know, but probably possible (need to study literature)

4.3 Results from CK₀UC Test on RBBC at OCR=1, 2, 4 & 8: Lubricated End Caps and Mid-Specimen u Data

[Sheahan 1991 MIT ScD thesis; Sheahan et al. 1996, JGE, 122(2)]

1) Test Program

- 1st MIT automated TX cells, $\dot{\varepsilon} = \overset{\text{Slow}}{0.05}, \overset{\text{Std}}{0.5}, \overset{\text{Fast}}{5}$ & $\overset{\text{V.Fast}}{50}$%/hr
- $\rho_{0.5} = (\Delta S_u / S_{uo}) / \Delta \log \dot{\varepsilon}$, where S_{uo} at $\dot{\varepsilon} = 0.5$%/hr.
- Cell fluid = oil to prevent membrane leakage
- Measured u both at base & ℄ probe

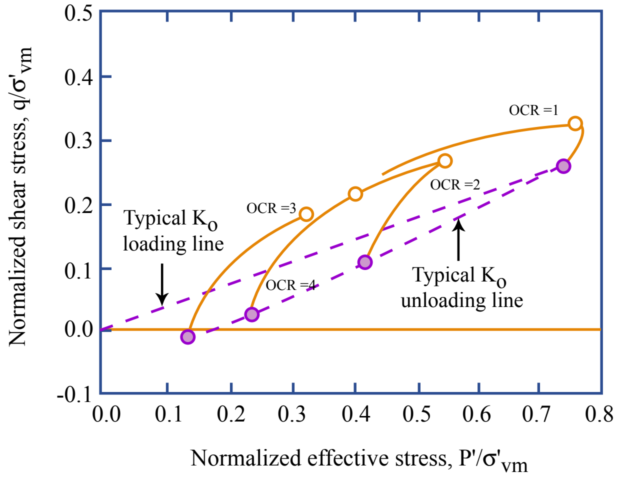


Typical normalized shear stress and excess pore pressure versus strain for CK₀UC tests on resedlmented BBC at reference strain rate (ε_a = 0.5%/h)

2) Behavior at reference $\dot{\varepsilon} = 0.5$%/hr

- See Fig. 1 & 2
- Note that data normalized to σ'_{vm}

OCR	q_f/σ'_{vm}	p'_f/σ'_{vm}	ε_f(%)
1	0.322	0.761	0.15
2	0.261⁵	0.552	0.7
4	0.213⁵	0.418	3.0
8	0.180	0.328⁵	4.2



Typical normalized effective stress paths for CK₀UC tests on resedlmented BBC at reference strain rate (ε_a = 0.5%/h)

○ ***Peak shear stress***
● ***Start of Shear***

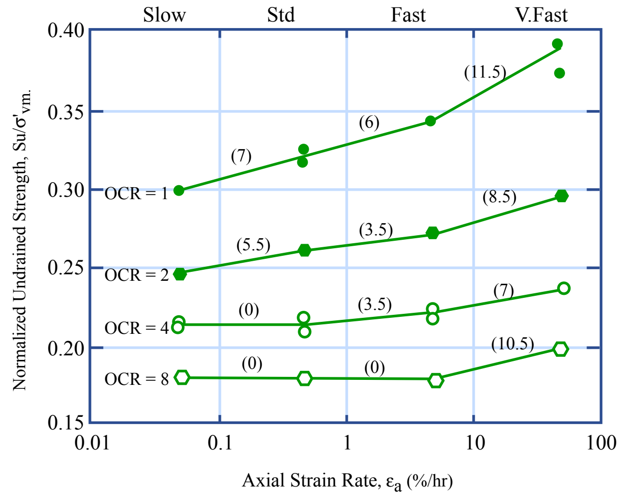
Figures by MIT OCW.

4.3 Cont

3) Overview of effects on s_u

a) s_u/σ'_{vm} vs log $\dot{\varepsilon}$ as f(OCR): Fig 11

$\dot{\varepsilon}$ = 0.05 5 50%/hr
|— Zone A —|— Zone B —|



Normalized sheer strength versus strain rate CK$_O$UC tests, resedimented BBC

Figure by MIT OCW.

Zone B (Fast → Very fast)

- get effect at all OCR that is ≈ constant
- $\rho_{0.5}$ = 9.4 ± 2.0%

Zone A (Slow → Fast)

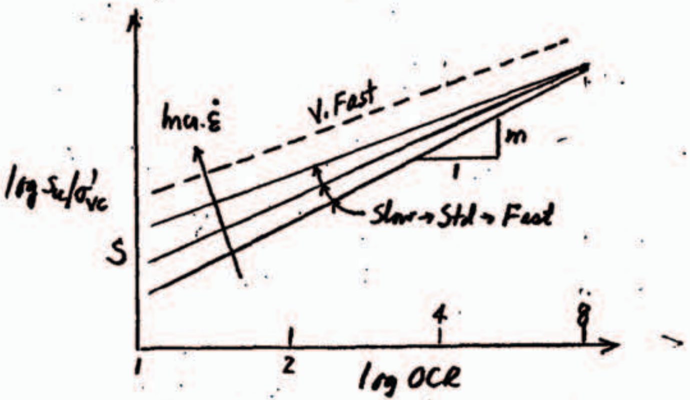
- $\rho_{0.5}$ decreases with increasing OCR (1st data to show this!)
- $\rho_{0.5}$ goes to zero with increasing OCR more rapidly at lowest $\Delta \log \dot{\varepsilon}$ range.

b) Log s_u/σ'_{vc} vs log OCR as f($\dot{\varepsilon}$): Table 4

TABLE 4. SHANSEP Parameters for BBC at Different Strain Rates

Strain rate $\dot{\varepsilon}_a$ (%/h) (1)	S^a (2)	m^b (3)	r^2 (4)	Number of observations n (5)
0.05	0.298	0.757	0.9997	6
0.5	0.320	0.714	0.9993	6
5	0.340	0.689	0.9997	5
50	0.373	0.686	0.9984	8

[a] S = value of s_u/σ'_{vc} at OCR = 1, based on regression analysis.
[b] m = strength increase exponent [refer to Eq. (3)].



Complex trends

- Slow → Fast $\dot{\varepsilon}$ → increasing S & decreasing m
- Fast → Very Fast $\dot{\varepsilon}$ → increasing S at constant m

4.3 Cont.

4) Overview of effects on stress-strain & ESP behavior

a) Shear stress vs ε_a

- See Sheet A1 & A2 for q/σ'_{vc} vs ε_a → very consistent trends
- Fig. 12 of Sheet B shows that normalized $\Delta q/\Delta q_{max}$ vs ε_a is unique at OCR = 2, 4 & 8 (very important for soil modeling).

  Post peak behavior at OCR = 1 is scattered

b) Pore pressure vs ε_a

- Look at shear induced: $\Delta u_s = \Delta u - \Delta\sigma_{oct} = \Delta u - \frac{1}{3}\Delta\sigma_a$ vs ε_a
- on Sheets A1 & A2
- Increases in s_u are always accompanied by lower Δu_s

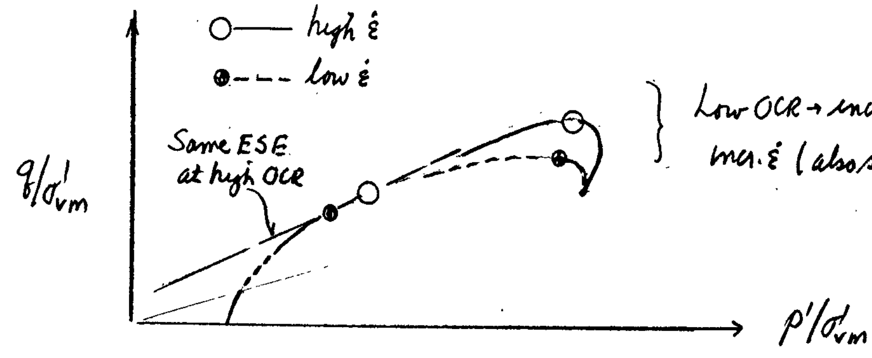
  (also see Fig 13a, Sheet B), e.g.

  OCR = 1, increasing $\dot{\varepsilon}$ → incr. s_u & decr. Δu_s

  OCR = 8, $\dot{\varepsilon} = 0.05$ to 5, $\Delta s_u = 0$ → no change in Δu_s

c) Effective stress paths and failure envelopes

- See Sheets A1 & A2 for ESP → consistent trends



Low OCR → incr. ϕ'_p with incr. $\dot{\varepsilon}$ (also see Fig 13b, Sheet B)

OCR = 1 & 2 • Low OCR: Increased s_u due to both lower Δu_s & higher ESE (ϕ'_p)
OCR = 4 & 8 • High OCR: Increased s_u due only to lower Δu_s (same ESE)

4.3 Cont

5) Summary of CK_0UC testing program on RBBC (& practical implications for non-structured clays)

a) Very fast shearing → increased s_u that is ≈ constant at all OCR ($\rho_{0.5} \approx 10\%$). Applies to in situ testing & Lab UUC, TV etc.

b) At slower strain rates, strain rate sensitivity ($\rho_{0.5} > 0$) decreases with increasing OCR.

Hence for field loading, would not expect design s_u of moderate to high OCR clays to be < measured lab CK_0U testing

c) Strain rate sensitivity (incr. in s_u with incr. $\dot{\varepsilon}$) is caused by two mechanisms:

1) Increasing $\dot{\varepsilon}$ → decreasing Δu_s : Occurs at all OCR

2) Increasing $\dot{\varepsilon}$ → increase in ESE at peak strength : Occurs only at low OCR

- at OCR ≤ 2, $+\rho_{0.5}$ due to both decreased Δu_s & incr. ϕ/p

- at OCR ≥ 4, $+\rho_{0.5}$ due only to decreased Δu_s

d) At OCR > 1, obtain unique $\Delta q/\Delta q_{max}$ vs ε_a independent of $\dot{\varepsilon}$ (simplifies modeling)

4.4 Behavior of Highly Structured (Cemented-Sensitive) vs "Ordinary" Clays

1) Observations from 1-D Consolidation Data

Hypothesis A
- Unique ε vs log σ'_{vc} during primary, i.e. independent of $\dot{\varepsilon}$
- Appears reasonable for saturated clays of low-moderate S_t
- Same mechanisms cause creep as occur during primary, e.g. slippage at particle contacts

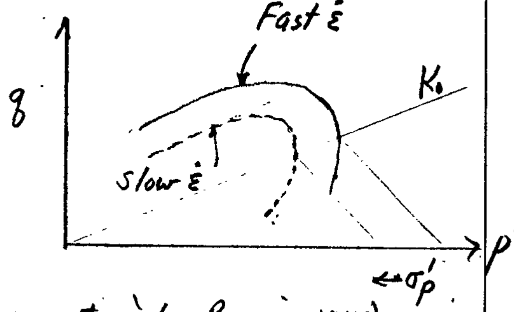
Hypothesis B
- Unique $\varepsilon - \dot{\varepsilon} - \sigma'_{vc} \rightarrow$ same ε vs log $\sigma'_{vc}/\sigma'_p(\dot{\varepsilon})$
- Better model for high $I_L - S_t$ Canadian clays
- "Structural Viscosity" due to time dependent strength of cementation bonds (true cohesion) } CCL

2) CU Test Programs at Varying $\dot{\varepsilon}$ by Lefebvre & LeBoeuf (1987)

- 5 block samples from 3 sites, $I_p = 10 \pm 3$ & 40%, $I_L = 2.3 \pm 0.6$
  $\sigma'_p = 140 \pm 45$ kPa

a) CU Tests on INTACT Clay, $\sigma'_{vc} \approx \sigma'_{v0}$ (see p12a)

- Approx same Δu vs ε up to peak s_u at $\varepsilon_f < 1\%$, and hence $\approx$ same prefailure ESP



$\therefore$ Lower s_u with decr. $\dot{\varepsilon}$ due to lower yield stress = failure envelope

- attributed to rate dependent cementation bonds ("structural viscosity" of cohesion component à la Bjerrum, 1973)

b) CU Tests on DESTRUCTURED Clay, $\sigma'_{vc} > \sigma'_p$ (see p12b)

- Decreasing $\dot{\varepsilon} \rightarrow$ higher Δu $\therefore$ Lower s_u due to lower p'_f (and also lower ϕ'_p for CAUC tests à la RBBC)

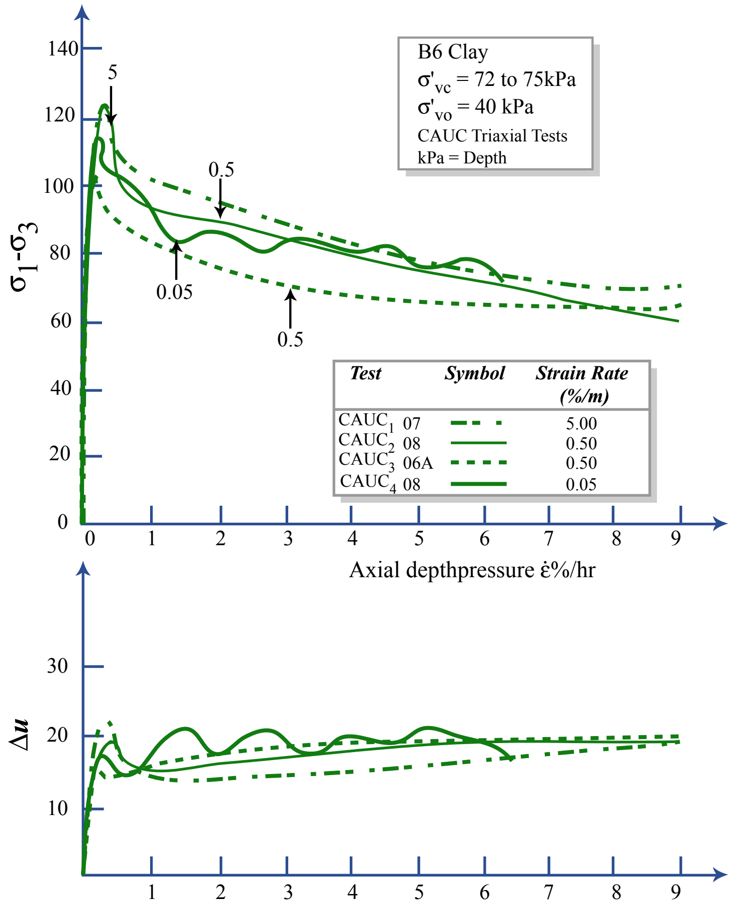
NOTE: Both test series $\rightarrow$ same ρ (Fig 16, p12b), but due to different mechanisms

CCL 4/29/89 4/25/96 1.322 II D

Lefebvre & LeBoeuf (1987) JGE, ASCE 113(5)

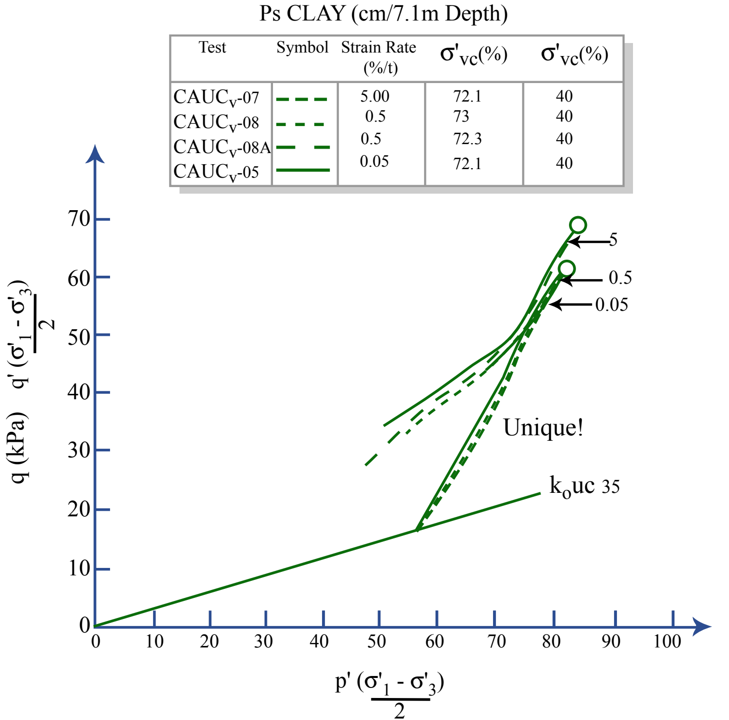
CU Test Data on "Intact" Highly Structured Clay ($\sigma'_{vc} \approx \sigma'_{vo}$)

Note: Vaid et al [1979, CGJ, 16(1)] observed similar behavior for Canadian Cemented clay: $\sigma'_p = 950$ kPa; $I_L = 1.4$, $S_t = 100$; CIUC testing.



Stress strain and pore pressure strain curves for B6 Clay

Figures by MIT OCW.

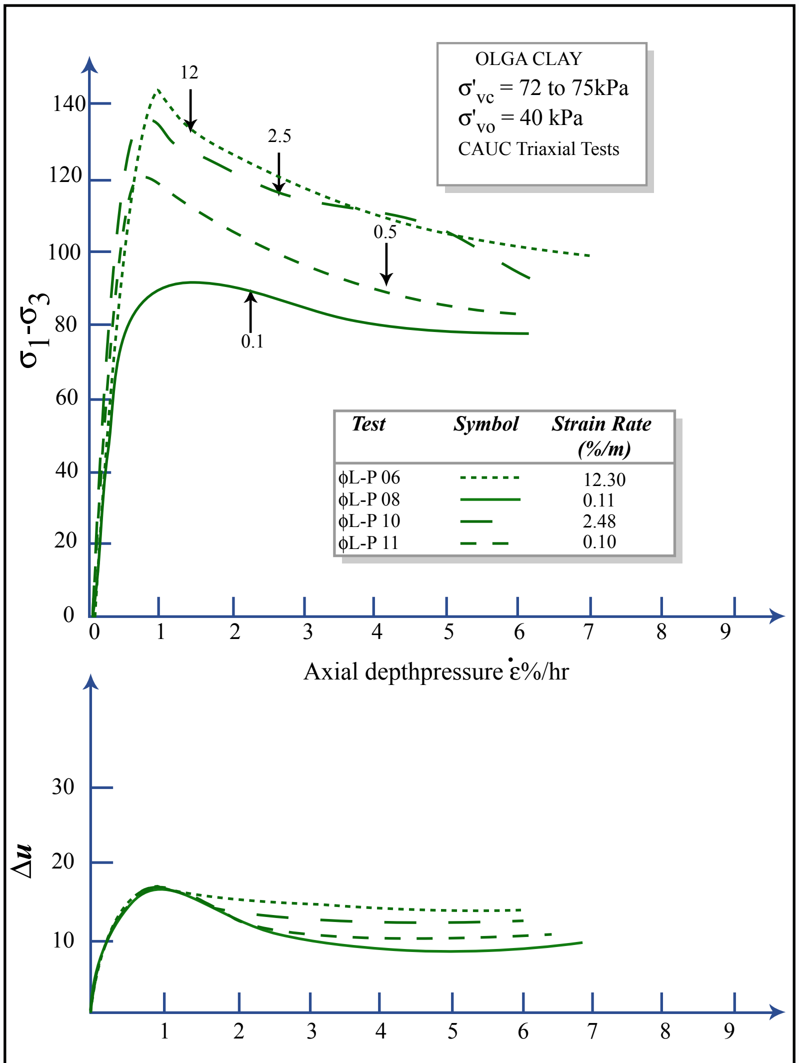


Stress Paths for Structured B6 Clay

CAUC $I_p = 10\%$ $I_L = 2.5$

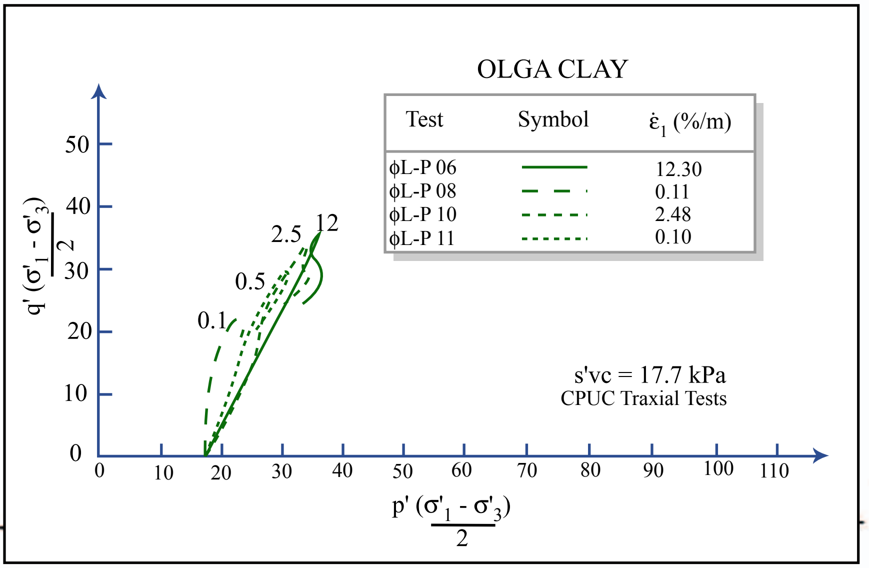
B = Broadback $\sigma'_p = 175$ kPa $\dot{\varepsilon}$ %/hr

(SEBJ NBR Project)



Stress strain and pore pressure strain curves for OLGAClay

Figures by MIT OCW.



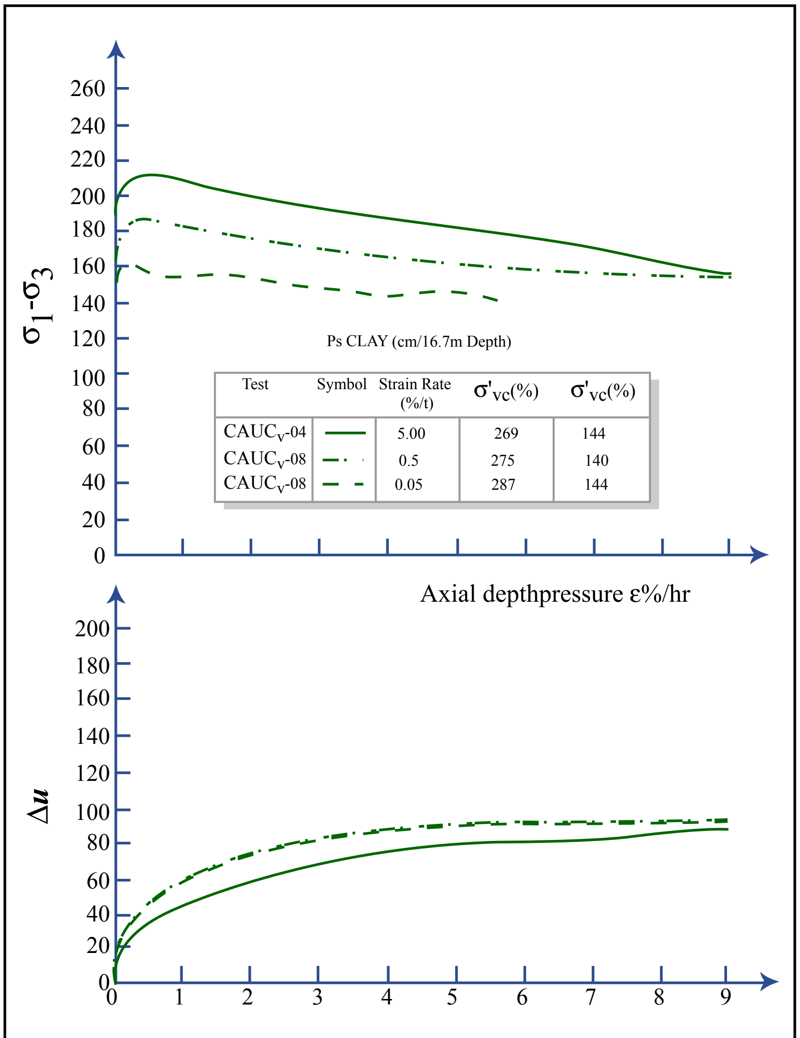
CIUC $I_p = 40\%$ $I_L = 1.55$

$\sigma'_p = 78$ kPa

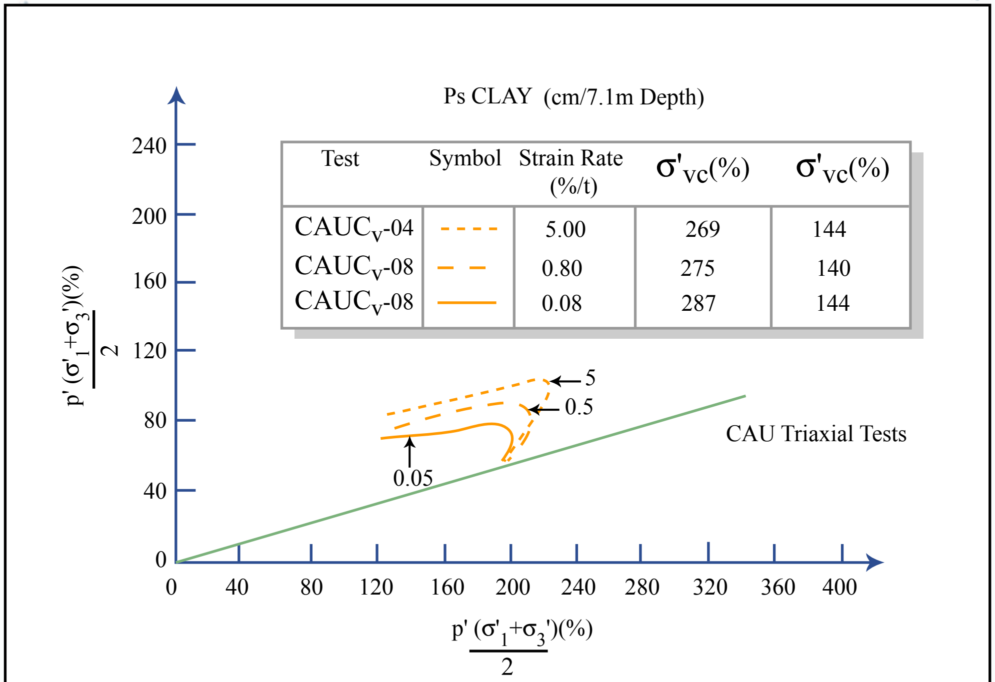
$\dot{\varepsilon}$ %/hr

- Approximately same Δu vs ε up to ε_f at peak undrained q_f (especially B6 → unique ESP independent of $\dot{\varepsilon}$)
- Therefore decrease in s_u due to lowering of failure envelope, i.e., brittle cementation bonds exhibit "structural viscosity"

CU Test Data on "Destructured" Clay ($\sigma'_{vc} > \sigma'_p$)



Stress-strain and pore pressure strain for normally consolidated B6 Clay

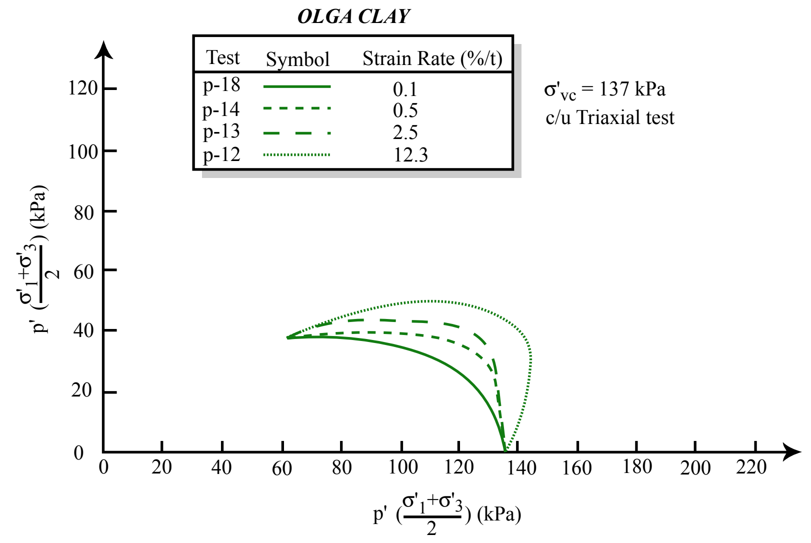


Stress paths for normally consolidated B6 clay

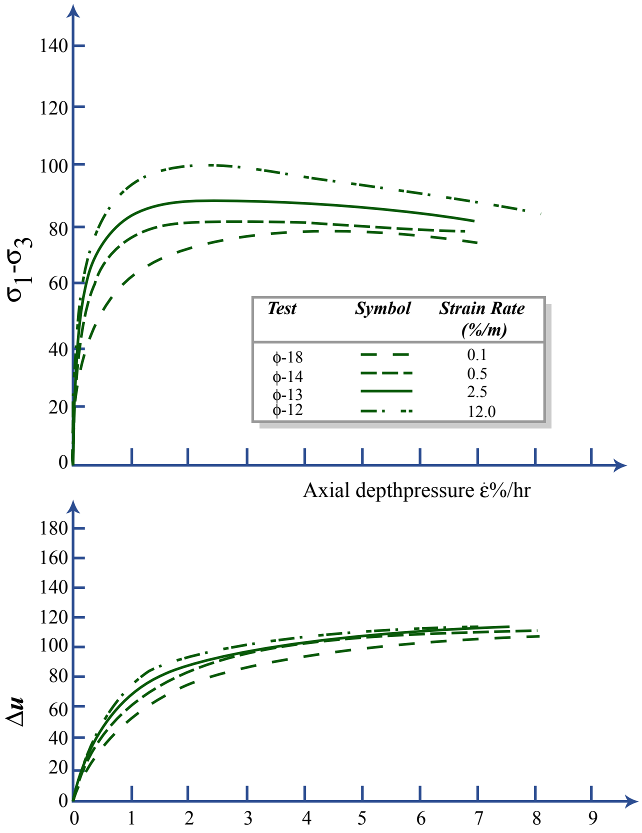
Figures by MIT OCW.

CK₀UC $I_p = 14\%$ $I_L = 1.8$

$\sigma'_p = 145$ $\sigma'_{vc} = 270$



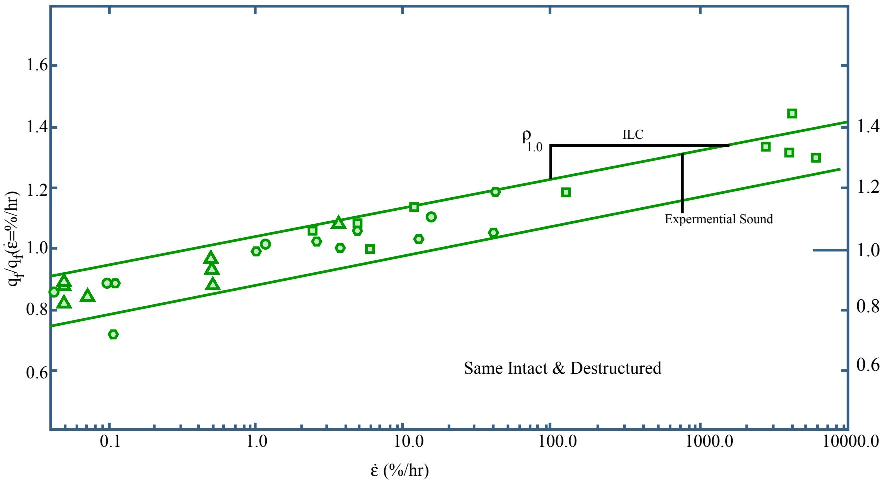
Stress paths for Normally consolidated Olga Clay



Stress-strain and pore pressure-strain curves for normally consolidated Olga clay

CIUC $\sigma'_{vc} = 1.7\sigma'_p$

Figures by MIT OCW.



CHANGE OF UNDRAINED STRENGTH RATIO, NORMALIZED TO UNDRAINED STRENGTH RATIO AT $\dot{\varepsilon}_1$ = 1.0%/h, WITH STRAIN RATE FOR ALL INVESTIGATED CLAYS.

4.5 Concluding Remarks

1) Be aware of most published data on $\dot{\varepsilon}$ effects due to experimental problems
   - a) membrane leakage → incr. Δu → decr. s_u
   - b) End restraint at high OCR → softening in shear zone → decreasing s_u
   - c) if very low t_c, arrested $+\Delta u$ due to secondary compression may → confusing Δs_u vs $\Delta\dot{\varepsilon}$ (e.g. Holzer et al. 1973 CGJ, CIUC tests on SFBM)

2) It is likely that all cohesive soils will exhibit strain rate sensitivity at very fast strain rates (say $\dot{\varepsilon} > 5$-$10\%/hr$) that will affect interpretation of in situ tests and lab UUC, TV, etc. tests. Can get very high $\rho \approx 10-30\%$

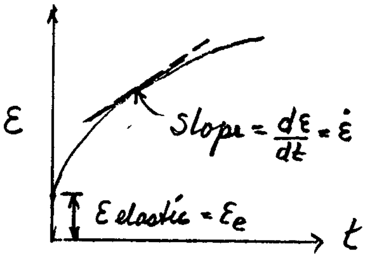
3) For non-structured clays similar to Resedimented BBC, Sheahan et al. (1996) present the only good CK_0UC vs. $\dot{\varepsilon}$ data as f(OCR). Principal conclusions are: (for $\dot{\varepsilon} \leq 5\%$)
   - a) at low OCR ≈ 1:
     - $\rho_{0.5}$ due to both lower Δu_s and increased ϕ'_p
     - Should expect strain rate effects in field
   - b) at moderate to high OCR:
     - $\rho_{0.5}$ due mainly or only to lower Δu_s
     - Strain rate effects in field may be very small since $\rho \to 0$ w/ incr. OCR at low $\dot{\varepsilon}$

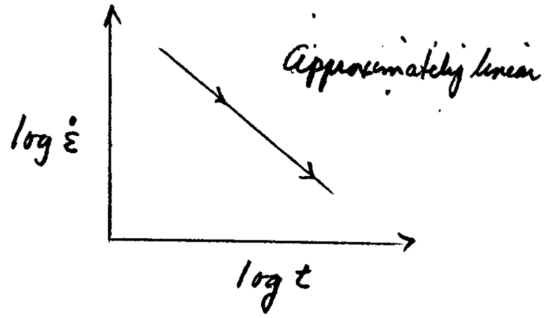
4) For Canadian cemented clays, expect significant strain rate effects in both lab and field over entire $\dot{\varepsilon}$ range (for both consolidation and drained/undrained shear)

5. UNDRAINED CREEP

5.1 Introduction (Constant q testing)

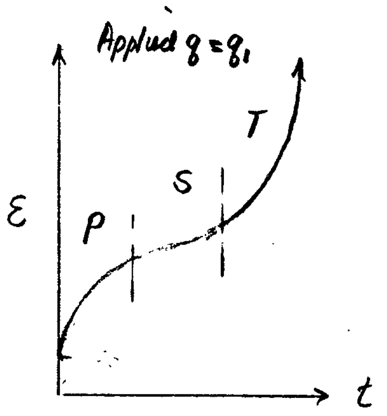
1) "Low" Stress Level (Only "primary")

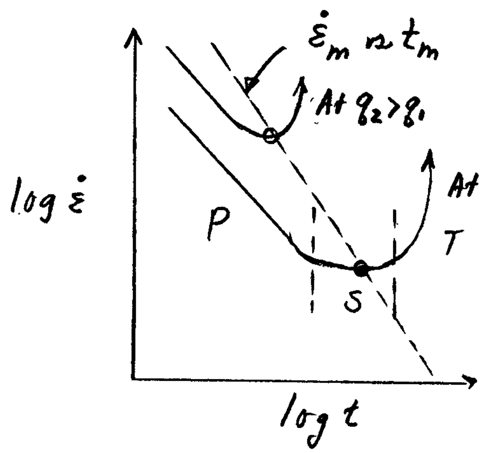




- Will model w/ Singh-Mitchell 3 parameter eqn.

2) "High" Stress Level → Creep Rupture





Transient ≡ Primary = $\dot{\varepsilon}$ decreasing
Viscous ≡ Steady State ≡ Secondary = $\dot{\varepsilon}$ "constant" → $\dot{\varepsilon}_m$ (inflection point if creep rupture)
Tertiary = $\dot{\varepsilon}$ increasing → creep rupture

3) Questions,

- Physical explanation of behavior (if possible)
- Mathematical models of behavior, at least for primary
- How to estimate q that will not → creep rupture (limiting long term q_f)
- "Correspondence" between creep & constant $\dot{\varepsilon}$ test data

5.2 Singh-Mitchell 3 Parameter Eqn. (1968, 1976, 1993 book) & JSMFD 94(1)

1) Eqn.

$$\dot{\varepsilon} = A\, e^{\bar{\alpha}\bar{D}} (t_1/t)^m$$

- "Derived" from Rate Process Theory
- Restricted to Primary creep

t_1 = reference t

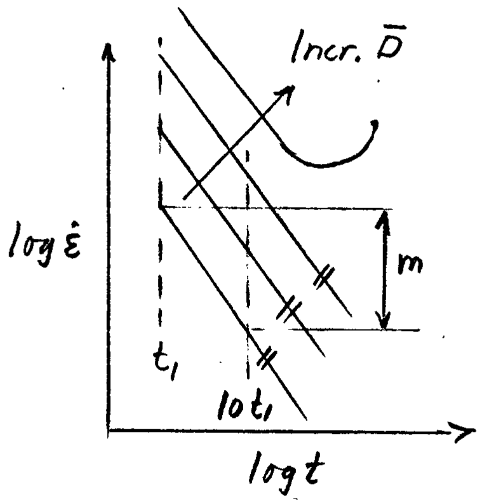
$\bar{D} = \Delta q/\Delta q_f$ (Δq_f at reference $\dot{\varepsilon}$)

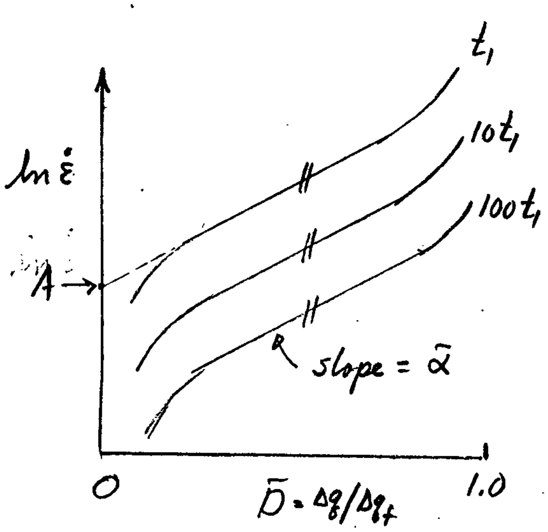
$m = -d\log\dot{\varepsilon}/d\log t$

$\bar{\alpha} = d\ln\dot{\varepsilon}/d\bar{D} = 2.3\, d\log\dot{\varepsilon}/d\bar{D}$

$A = \dot{\varepsilon}$ at $t = t_1$, $\bar{D} = 0$

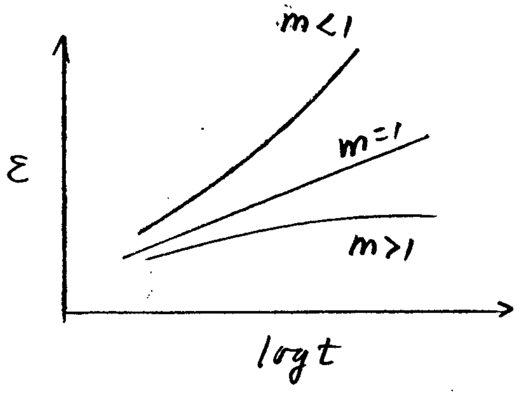
2) Basic plots





$\bar{\alpha}$ presumed constant for $\bar{D} \approx 0.3 - 0.9$

3) Significance of m (Presumed basic soil property by S-M; lower m → more creep susceptible)



$m=1 \rightarrow \dot{\varepsilon}t$ = constant (like constant C_α)

$m<1$ more "creep susceptible" à la S-M w/ $\dot{\varepsilon}t$ increasing with t

Slope $= d\varepsilon/dt = \dot{\varepsilon} = \dfrac{0.434\,(d\varepsilon/d\log t)}{t}$

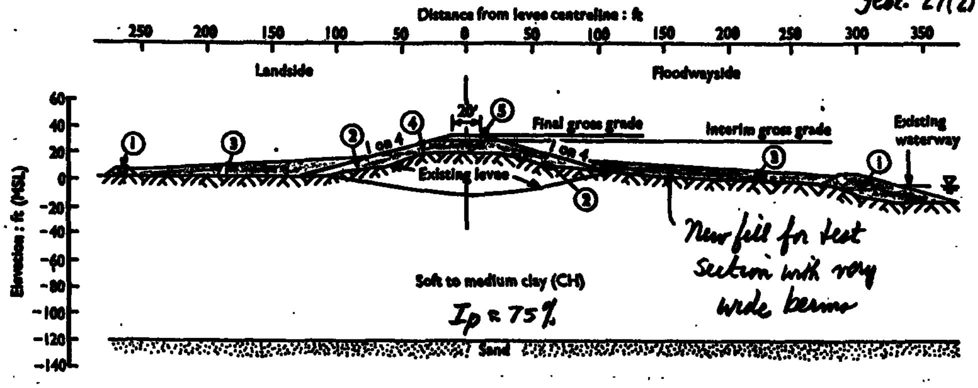
$$\varepsilon = \varepsilon_1 - \frac{A e^{\bar{\alpha}\bar{D}} t_1}{(1-m)} + \underbrace{\frac{\dot{\varepsilon}t}{(1-m)}}_{*} \quad \Big\}\ m \neq 1$$

* Is negative for $m>1$ → substraction of less neg. no. w/ incr. t → incr. ε w/ time

4) Results from MIT research on flood control levees along Atchafalaya River in Louisiana next to Gulf of Mexico (Edgers et al. 1973 MIT report)

a) Problem (EABPL)

R. FOOTT AND C. C. LADD (77) Geot. 27(2)



- "Existing" levees : construction 1930 to 1970 to maintain net grade of 15 ft
  Caused accumulated ℄ ρ of up to 35 ft!
- Very expensive test sections (above) did not perform much better, i.e. excessive lateral deformations (undrained creep) → excessive ℄ settlement

b) Results from creep testing on EABPL clay

	Test	$\bar{D}$	m	$\bar{\alpha}$
Sl.OC	UUC	0.75-0.9	0.95	4.7
NC	CK_0UC	0.5-0.9	0.55±0.1	4±0.2
	CK_0UDSS	0.5-0.85	0.85-0.9	4±0.4

} m = 0.55 to 0.95 for this highly creep susceptible clay

5) Campanella & Vaid (1974 CGJ) tests on low I_p NC Haney Clay

- CIUC → m = 0.6 • CK_0UC → m = 0.35 • CK_0UPSC → m = 0.5

∴ m = 0.35 - 0.6 for clay that is not very creep susceptible

6) Conclusions

d) However, eqn. still useful for modeling given set of primary creep data

a) m & $\bar{\alpha}$ are not material properties since they vary with mode of shearing

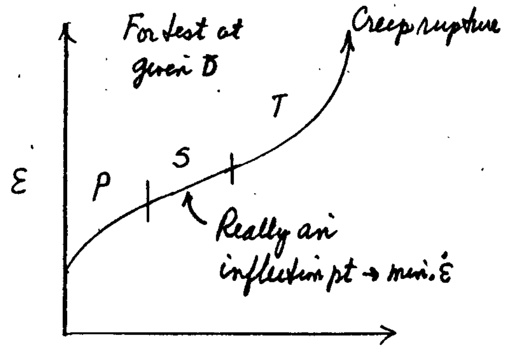
b) $\boxed{\text{Value of m is not valid criterion for creep susceptibility, i.e. lower m does not mean more highly creep susceptible}}$

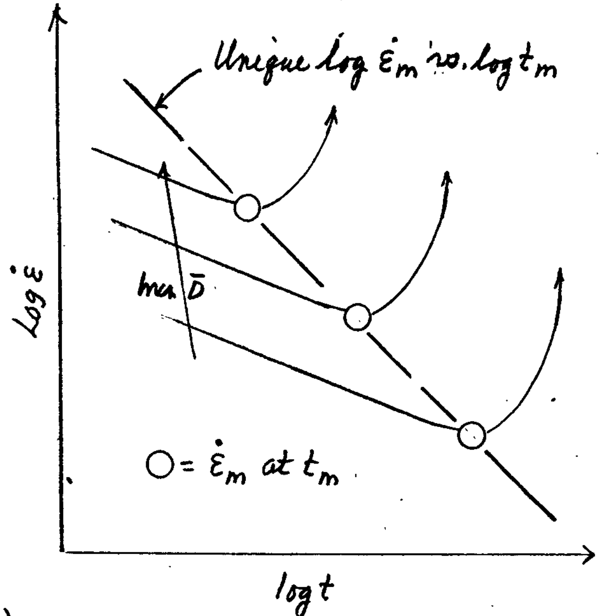
(see Section 5.6 for new criteria)

c) Techniques do NOT exist to predict undrained creep in the field [even though S-M eqn. has been added to "MCC" to do this, e.g. Borja et al. 1990, JGE, 116(9)]

5.3 Creep Rupture

1) General Behavior: Results from creep tests run at varying $\bar{D} = \Delta q/\Delta q_f$





∴ Creep tests (of given type) run at varying $\bar{D}$ yield unique relationship between minimum strain rate ($\dot{\varepsilon}_m$) and the time (t_m) to reach $\dot{\varepsilon}_m$

2) Strain at Minimum Strain Rate (ε_m)

- Experimental data show approximately constant strain (ε_m) along the log $\dot{\varepsilon}_m$ vs log t_m relationship
- $\dot{\varepsilon}$ is decreasing before reaching ε_m, and then accelerates after reaching ε_m. This suggests that "damage" starts to occur near ε_m, leading to a weakened material that eventually fails in creep rupture

3) Creep Rupture Data on Haney Clay (Sheet C1)

- Fig 2 shows log $\dot{\varepsilon}$ vs log t data from CIUC, CK₀UC and CK₀UPSC tests on NC clay → 3 different log $\dot{\varepsilon}_m$ vs log t_m relationships
- Fig. 3 shows constant ε_m for each test series. However, ε_m decreases from $\varepsilon_m = 2.8\%$ for CIUC tests to $\varepsilon_m = 0.3\%$ for CK₀UC tests

4/99 4/01 5.3 Continued

4) Log $\dot{\varepsilon}_m$ vs $\log t_m$ and ε_m Data for Other Materials (Sheet C2)

- Figs. 1 and 3 show $\log \dot{\varepsilon}$ vs $\log t$ data from unconfined compression tests on frozen Manchester Fine Sand (ice saturation $S_i = 40\%$) and polycrystalline ice, respectively, and their unique $\log \dot{\varepsilon}_m$ vs $\log t_m$ relationships

- Fig. 4 summarizes the unique $\log \dot{\varepsilon}_m$ vs $\log t_m$ relationships for frozen MFS ($S_i = 20\%, 40\%$ & 100%), ice and CIUC/CK_0UC tests on Haney clay.

- Note the shift to the right in $\log \dot{\varepsilon}_m$ vs. $\log t_m$ with increasing ε_m (i.e., increasing ε_m → longer time to reach critical strain at which "damage" → increasing $\dot{\varepsilon}$)

- Log $\dot{\varepsilon}_m$ vs $\log t_m$ can be modeled by $\dot{\varepsilon}_m = \beta t_m^{\gamma'}$; data in Fig. 4 show $\gamma' = -1.0 \pm 0.2$

5) Summary of Main Points

a) Should plot $\log \dot{\varepsilon}$ vs $\log t$ from creep tests in order to identify the minimum strain rate ($\dot{\varepsilon}_m$) at $t = t_m$

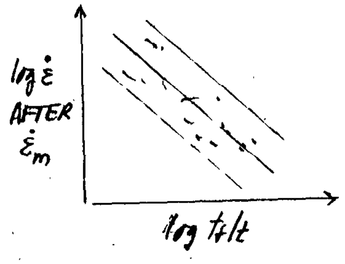
b) Creep data from different types of tests (e.g., UC → CIUC → CK_0UC) and different materials (clay → ice) each show unique $\log \dot{\varepsilon}_m$ vs $\log t_m$ (with slope $\gamma' = -1.0 \pm 0.2$) relationships having a constant ε_m

c) This ε_m represents onset of "damage" that → increasing $\dot{\varepsilon}$ and eventual creep rupture

6) Predictions of Creep Rupture

- The literature contains equations & plots to predict when creep rupture will occur.

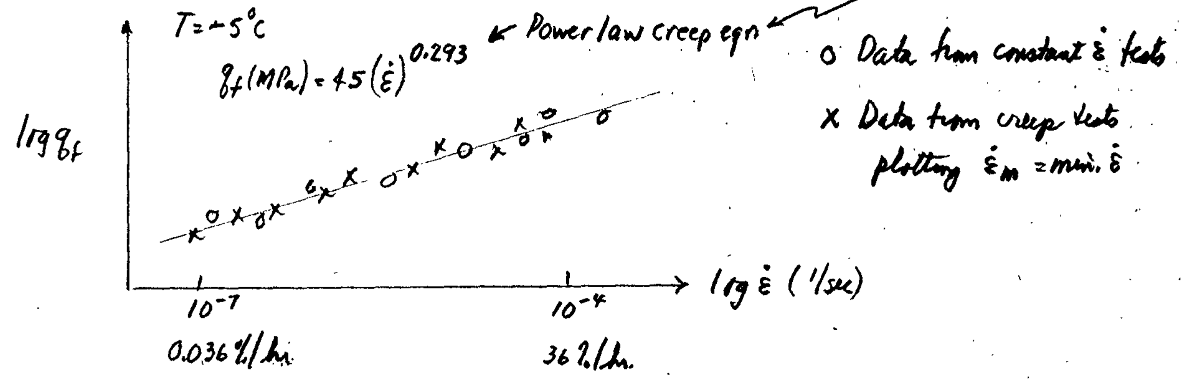
- However, the scatter in data for different soils and different types of tests is so large that eqn/plots have little practical significance.



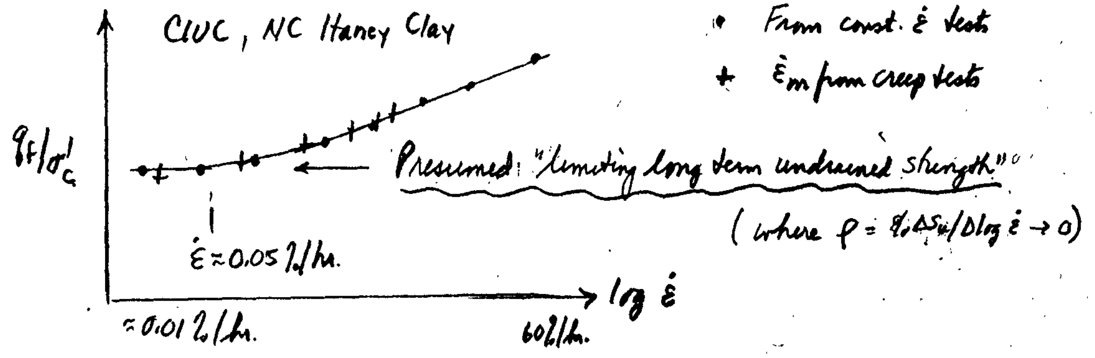
5.4 "Correspondence"

1) This topic addresses the issue between results from constant $\dot{\varepsilon}$ tests and from creep tests that eventually rupture.

2) Extensive data on polycrystalline ice* (within so-called ductile region with minimal cracking) show a unique relationship between strength and strain rate using $\dot{\varepsilon}_m$ for the creep tests, $q = C(\dot{\varepsilon})^{1/N=3.41}$



3) There are little data on clays comparing constant $\dot{\varepsilon}$ and creep testing. However, results for NC Haney clay (see sheet D) also show correspondence when use $\dot{\varepsilon}_m$ for creep tests



4) Conclusion:

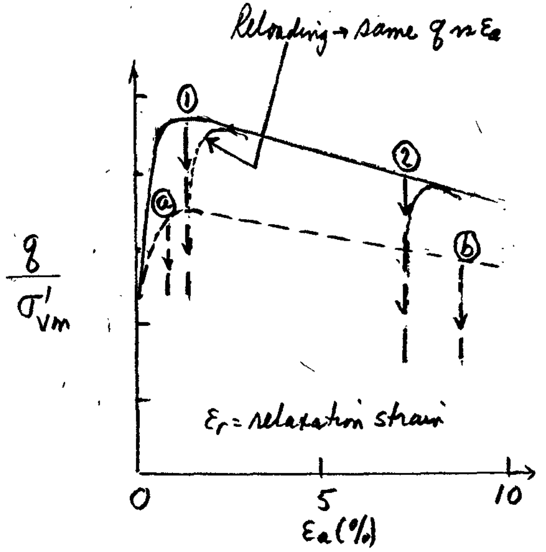
$\boxed{\text{Use } \dot{\varepsilon}_m \text{ from creep tests for comparison with } s_u \text{ vs. } \log\dot{\varepsilon} \text{ from constant } \dot{\varepsilon} \text{ tests}}$

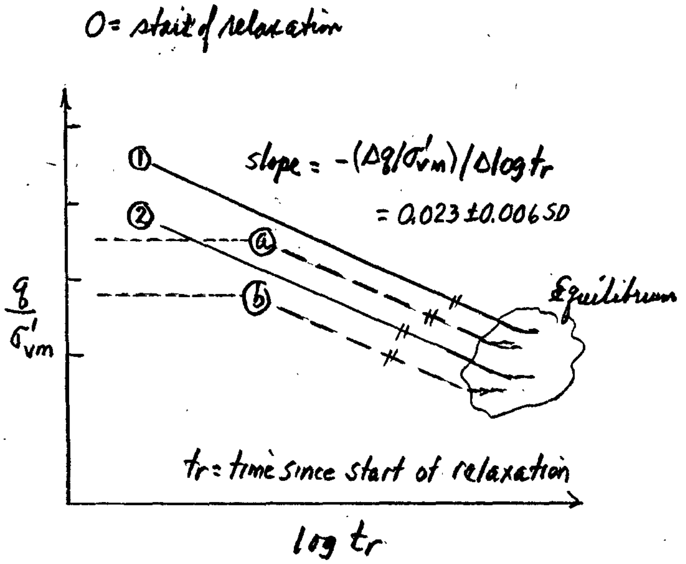
* Mellor & Cole (1983) Cold Regions Science & Technology, p207-230

5.5 Relaxation

1) Refers to decrease in q (relaxation) at constant strain after shearing at constant $\dot{\varepsilon}$ up to the relaxation strain level (ε_r)

2) Overview of CK_oUC data from Sheahan et al. [1994, ASTM, GTJ 17(4)] on resedimented BBC (part of test program discussed in Section 4.3)





- For fast shearing to ε_r: relaxation starts quickly
- For slow " " " : start of relaxation is delayed

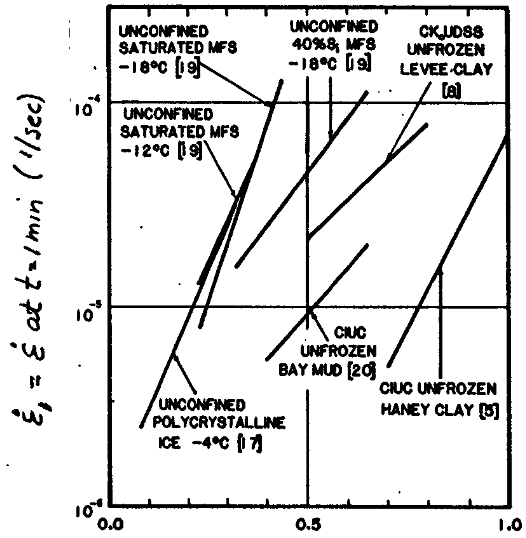
} Approx same slope independent of $\dot{\varepsilon}$, ε_r and OCR

- For relaxation from relatively small strain levels ($\varepsilon_a \le 1.5\%$), equilibrium stresses ended up close to NC K_o line. Relaxation from larger strain level ($\varepsilon_a \ge 2.5\%$ → Δ structure of clay) → equilibrium at higher K.

3) See Sheets E1 & E2 for actual test data (mostly for OCR = 1)
   - Fig. 1 = q/σ'_{vc} vs ε_a
   - Fig 2 = ESP data
   - Fig 3 : q/σ'_{vc} vs $\log t_r$
   - Fig 5 : Equilibrium stresses

5.6 Criteria For High Creep Susceptibility

Fig. 3 Ting et al. (1983) JGE 109(10)



$\bar{D} = \Delta q / \Delta q_f$ (q_f at reference $\dot{\varepsilon}$)

1) m per se is not reliable criterion

2) Fig. 3 plots $\dot{\varepsilon}$ at t = 1 min vs. $\bar{D}$ from creep tests on variety of materials.

- Haney clay w/ low creep susceptibility plots to lower, right (low $\dot{\varepsilon}_1$ at high $\bar{D}$)
- Ice & frozen sand w/ high creep susceptibility plot to upper left (high $\dot{\varepsilon}_1$ at low $\bar{D}$)

3) Therefore, materials with high creep susceptibility have a high initial strain rates at low shear stress levels.

4) However, value of m is still relevant since:

- high m → rapid decay in $\dot{\varepsilon}$ with time
- low m → slow " " " " "

6. SUMMARY AND CONCLUSIONS

6.1 Measurements of s_u

1) Strain rate sensitivity of saturated cohesive soils ($\rho = (\Delta s_u/s_{u0})/\Delta \log \dot{\varepsilon}$)
   - All soils have significant ρ at very fast strain rates (say $\dot{\varepsilon} > 5\text{-}10\%/hr$). ρ may range from $\approx 10\%$ to $> 35\%$/log cycle
   - Cemented, sensitive Canadian clays probably have significant ρ at all strain rates
   - For "unstructured" clays (like RBBC), value of ρ at slow to moderate $\dot{\varepsilon}$ probably decreases with increasing OCR (Section 4.3)

2) Must consider $\Delta\dot{\varepsilon}$ (or Δt_f) when comparing s_u data from different types of shear tests:
   - For in situ tests, CPTU $t_f \approx$ seconds & FVT $t_f \approx$ minutes
   - Lab UUC, Std $\dot{\varepsilon} = 1\%/min \rightarrow t_f \approx$ minutes
   - Lab CK_0UTX, $\dot{\varepsilon} \approx 0.5\%/hr \rightarrow t_f \approx$ hours

3) For SHANSEP/Recompression CK_0U testing programs, many major labs use

$$\underbrace{\cdot\ TX\ \ \dot{\varepsilon} \approx 0.5\%/hr}_{\text{Should be ok for most clays at OCR}>1} \qquad \underbrace{\cdot\ DSS\ \ \dot{\gamma} = 5\%/hr}_{\text{May be somewhat unsafe for low OCR clays}}$$

6.2 Predictions of Undrained Creep

1) The Singh-Mitchell 3 parameter eqn. (Section 5.2) is widely used to model primary creep data from lab tests. However, its use to predict in situ creep is suspect (due to variations in parameters with different modes of shearing, plus problems with its incorporation in an effective stress soil model)

2) One probably can assume correspondence between constant $\dot{\varepsilon}$ tests and creep rupture tests (using $\dot{\varepsilon}_{min}$) when developing s_u vs $\log \dot{\varepsilon}$ correlations

6.2 Cont.

3) It is still difficult to predict when undrained creep is likely to cause "excessive" deformations in the field.

- Refer to Foott & Ladd (1981) → loading at low FofS of low E_u soil with long consolidation time
- Might also run some CU creep tests for comparison with data in Fig 3, p21

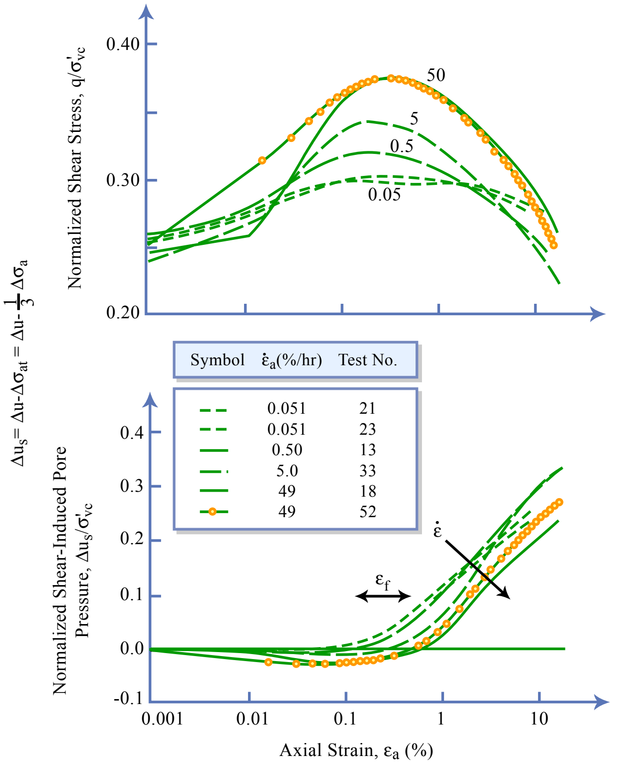
4) Will a loaded clay undergo undrained creep rupture in the field at a significant time after the end of loading?
CCL thinks highly unlikely, but many others will disagree

6.3 Miscellaneous

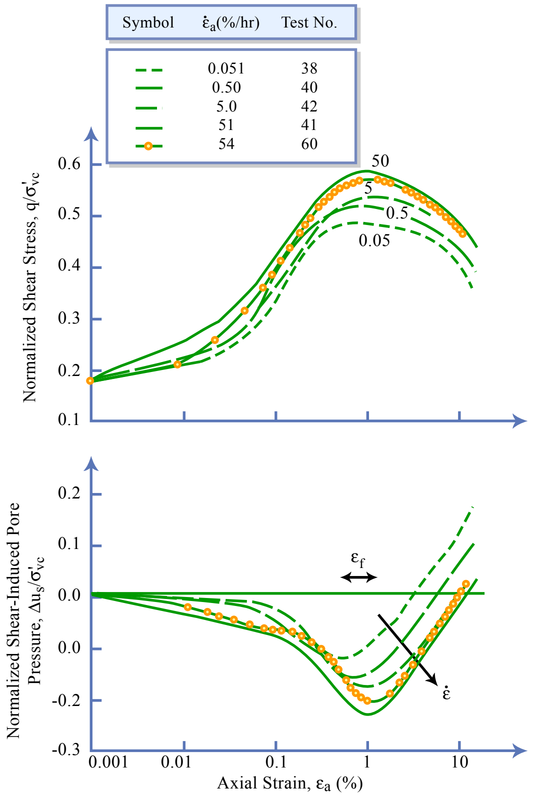
1) The importance of thixotropy in situ remains unclear

2) For NC clays that are still consolidating, use $t_c = t_p$ (vs. std. $t_c \approx 1$ day) for CK_0U testing

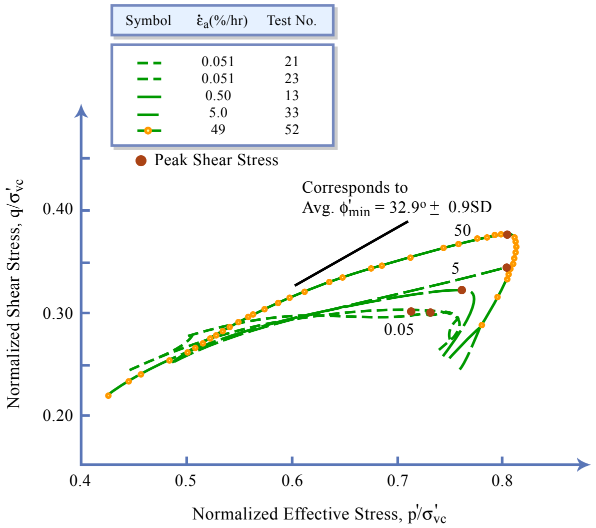
CCL 4/96 1.322 II B



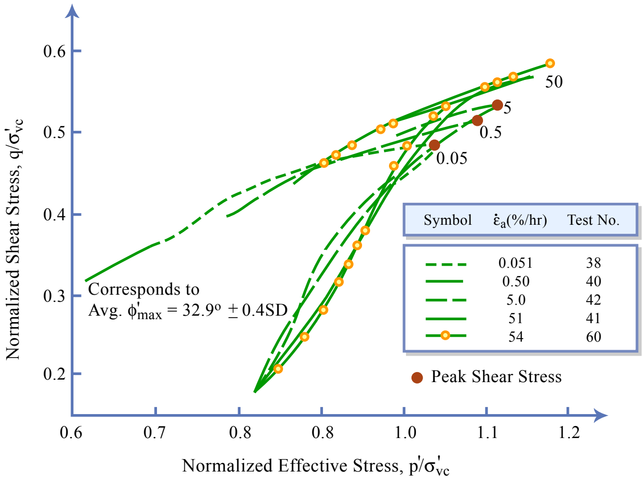
Normalized Shear Stress and Shear-induced Pore Pressure vs. Strain, OCR = 1 CK$_0$UC Tests, Resedimented BBC



Normalized Shear Stress and Shear-induced Pore Pressure vs. Strain, OCR = 2 CK$_0$UC Tests, Resedimented BBC



Normalized Effective Stress Paths, OCR = 1 CK$_0$UC Tests, Resedimented BBC



Normalized Effective Stress Paths, OCR = 2 CK$_0$UC Tests, Resedimented BBC

Figures by MIT OCW.

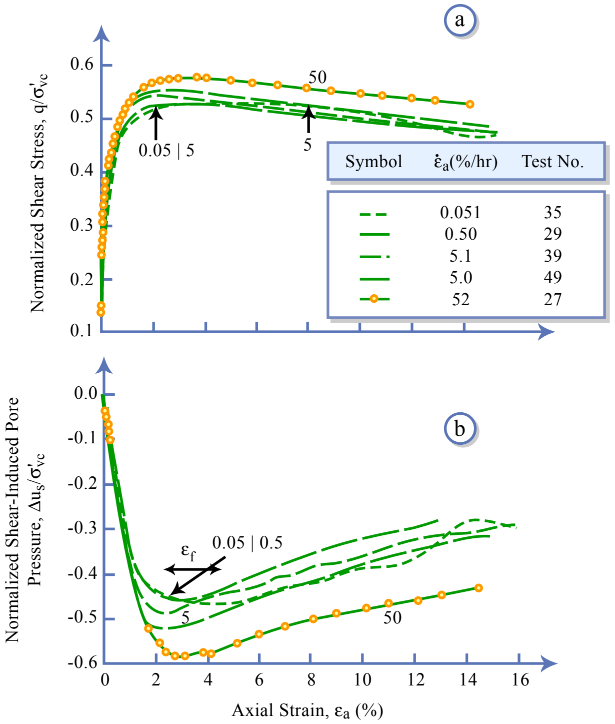
CK$_0$UC Tests on Resedimented BBC as f($\dot{\varepsilon}$) : OCR = 1 & 2

Adapted from: Sheahan et al. (1996)

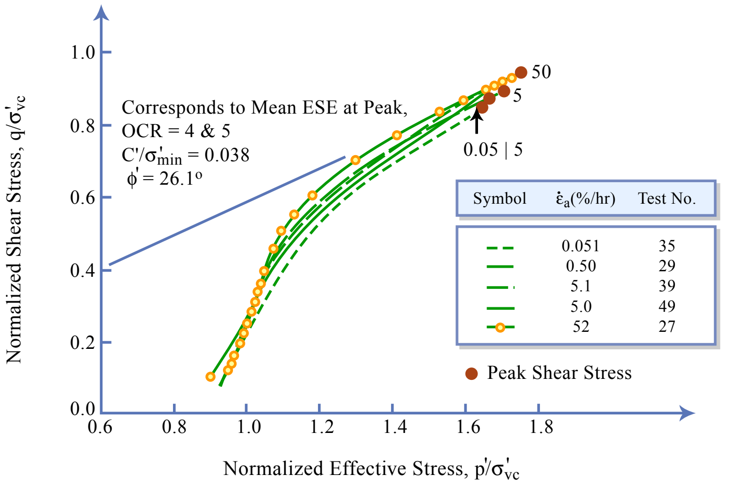
A1

CCL 4/96 1.322

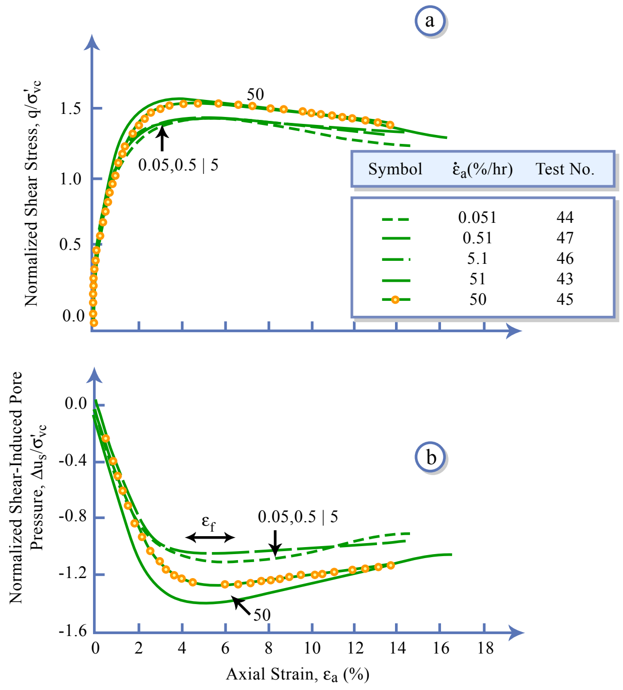
IIB



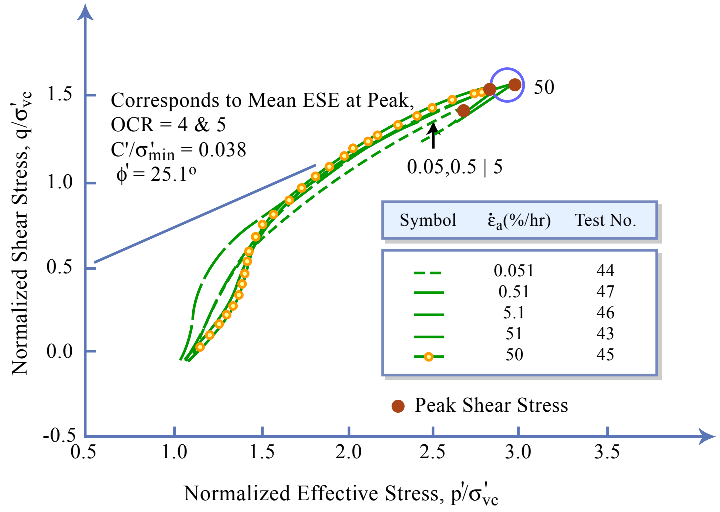
Normalized Shear Stress and Shear-induced Pore Pressure vs. Strain, OCR = 4 CK_0UC Tests, Resedimented BBC



Normalized Effective Stress Paths, OCR = 4 CK_0UC Tests, Resedimented BBC



Normalized Shear Stress and Shear-induced Pore Pressure vs. Strain, OCR = 8 CK_0UC Tests, Resedimented BBC



Normalized Effective Stress Paths, OCR = 8 CK_0UC Tests, Resedimented BBC

Figures by MIT OCW.

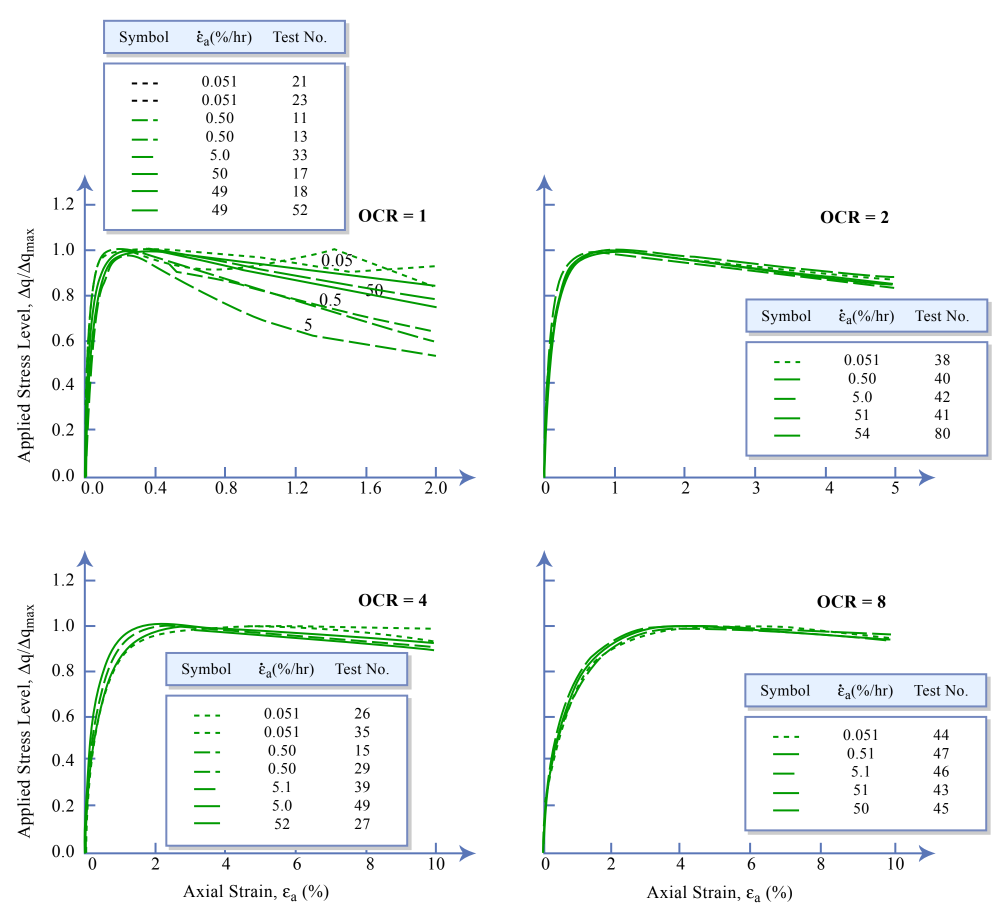
CK_0UC Tests on Resedimented BBC as $f(\dot{\varepsilon})$: OCR = 4 & 8

A2

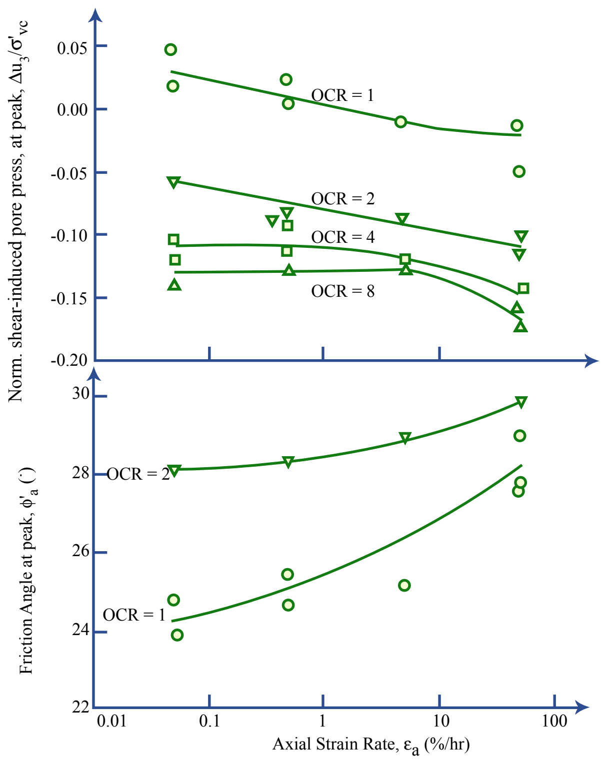
Adapted from: Sheahan et al. (1996)

CCL 4/96 1.322

II B



Axial Shear Stress Level vs. Strain, CK_0UC Tests, Resedimented BBC



Summary plots of Mechanisms: (a) Normalized Shear-induced pore pressure and (b) Friction angle at peak versus strain rate, CKoUC tests, resedimented BBC

Unique NORMALIZED Shear Stress ($\Delta q/\Delta q_{max}$) vs ε_a (especially OCR = 2, 4 & 8)

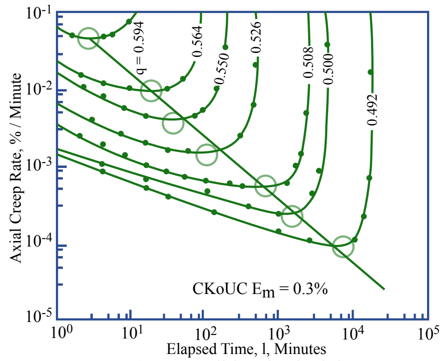
Increasing s_u always accompanied by decreasing Δu_s

Increasing s_u at low OCR also accompanied by increasing ϕ'_p

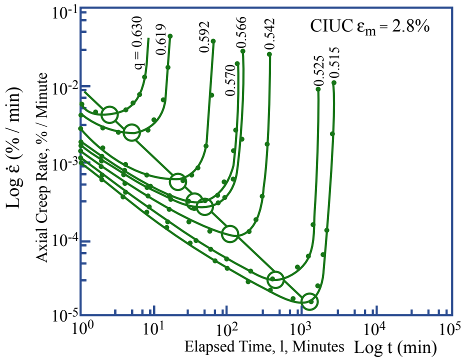
Figures by MIT OCW.

Adapted from: Sheahan et al. (1996)

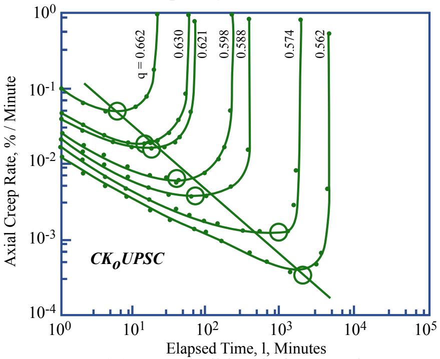
B



(a) Consolidated Triaxial



(B) Isotropically consolidated Triaxial



(C) K_o consolidated Plane Strain

Creep rate behavior of normally consolidated undisturbed Haney clay.

Figure by MIT OCW.

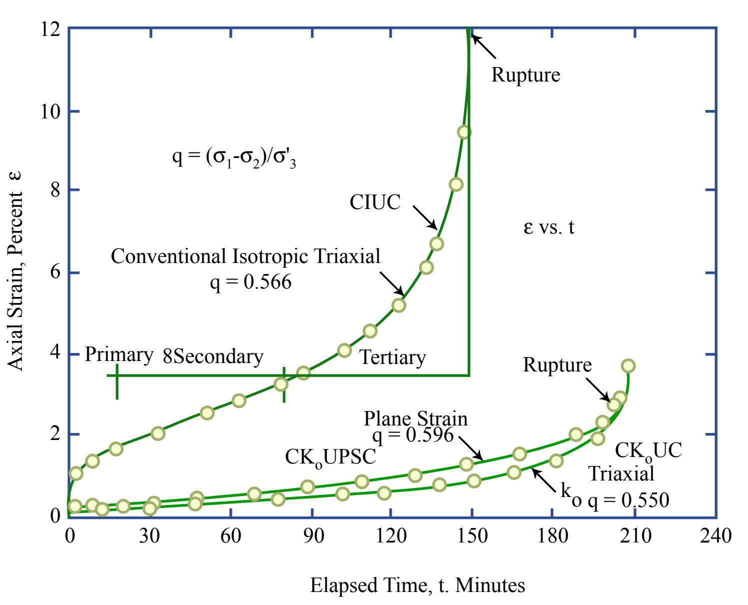


Figure by MIT OCW.

Campanella & Vaid (1974) CGJ, 11(1).

N.C. Haney Clay $w_L = 44$, $I_p = 18$

Lab $\sigma'_{vc}/\sigma'_p = 1.5$

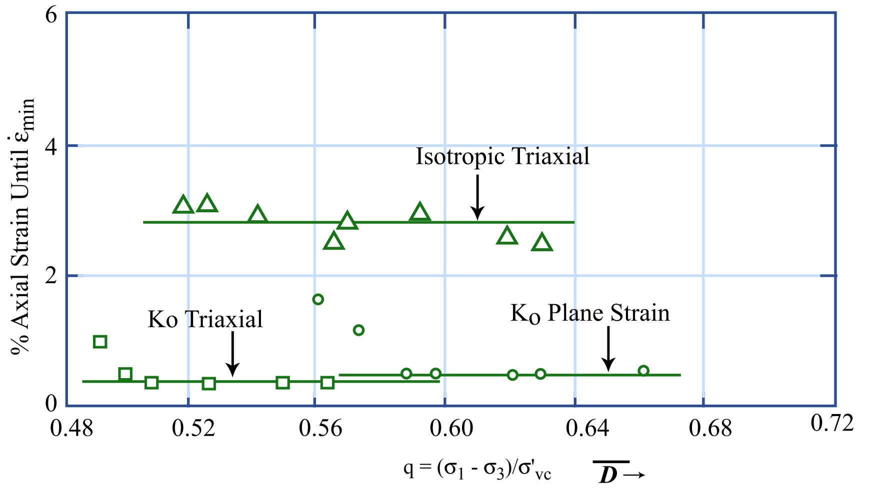
- Fig. 2 : log $\dot{\varepsilon}$ vs log t at varying $\bar{D}$

○ = location of min $\dot{\varepsilon} = \dot{\varepsilon}_m$ at $t = t_m$

(lines through $\dot{\varepsilon}_m - t_m$ by CCL)

- Fig. 3 Axial strain at $\dot{\varepsilon}_m = \varepsilon_m$

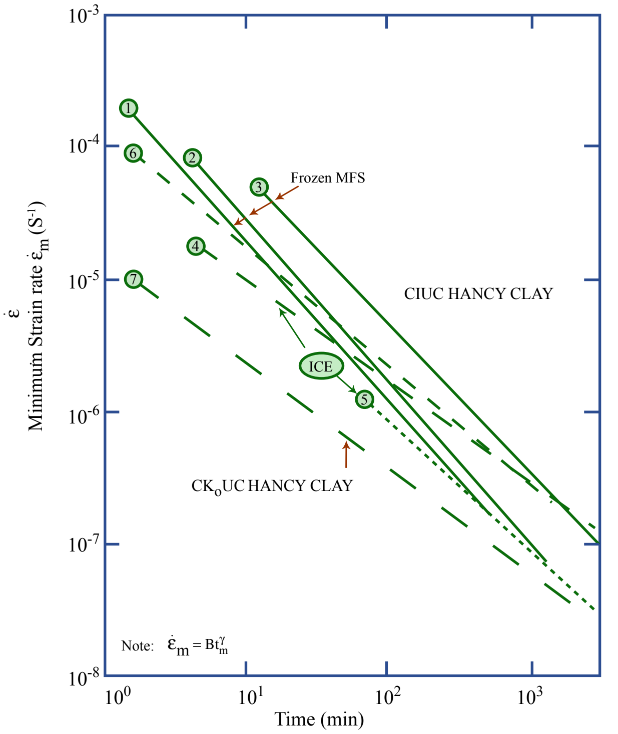
Test	ε_m (%)
CIUC	2.8
CK_oUPSC	0.5
CK_oUC	0.3



Axial strain until minimum strain rate as a function of creep stress.

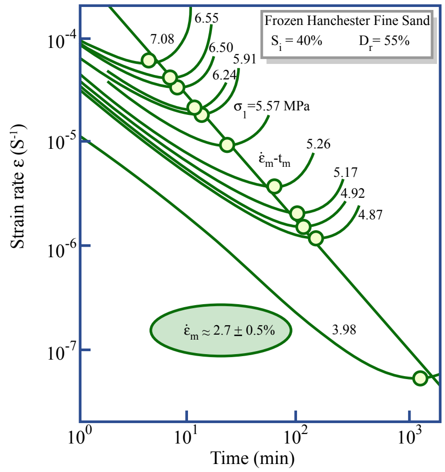
Figure by MIT OCW.

CCL 4/27/96 1.322 II D



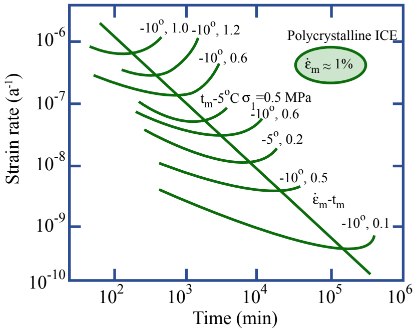
No.	Material	Testing	Reference	B^o	γ^o	r^2	No. Tests	ε_m (%)
1	20% S_i MFS	Uniaxial	Martin Ting & Load (1981)	2.8×10^{-4}	-1.2	0.987	7	2.1
2	40% S_i MFS	Uniaxial		4.2×10^{-4}	-1.2	0.993	40	2.7
3	100% S_i MFS	Uniaxial		8.1×10^{-4}	-1.2	0.991	28	4.6
4	Ice	Uniaxial	k_{uo} (1972)	7.9×10^{-5}	-0.8	0.987	7	≈ 1
5	Ice	Uniaxial	Jacka, in Lue (1979)	6.5×10^{-5}	-1.0	0.996	8	
6	Unfrozen Haney Clay	CIUC	Campanella & Void (1974)	1.3×10^{-4}	-0.9	0.997	8	2.8
7		CK_oUC		1.5×10^{-5}	-0.8	0.987	7	0.3

Summary of minimum creep rate: Correlations of time to minimum for various materials



Results of unconfined (uniaxial) compressive creep testing of 40% saturated, 55% relative density Manchester fine sand at - 18.8°C (data from Martin et al. 1981)

Figures by MIT OCW.



Results of unconfined (uniaxial) compressive creep testing of polycrystalline ice. (data by Jacka, see Lile 1979).

Ting (1983) CGJ. 20(1)

C2

CCL 4/30/99 1.322 II D

4/96

Figures by MIT OCW.

Adapted from:

Vaid & Campanella (1977) JGED 103(7)

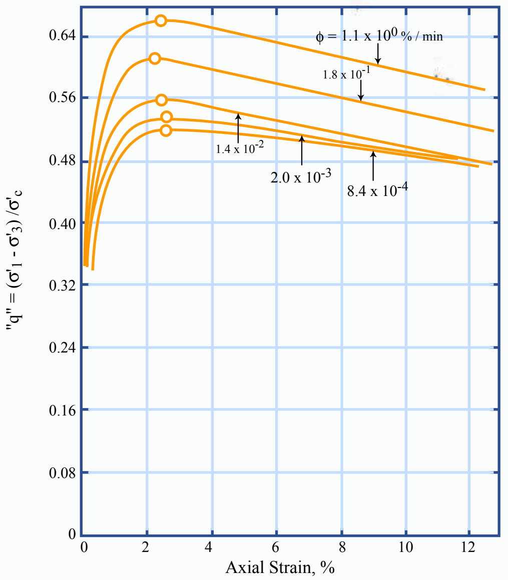
CIUC OCR=1 Haney Clay

Fig. 2 Constant $\dot{\varepsilon}$: take peak •

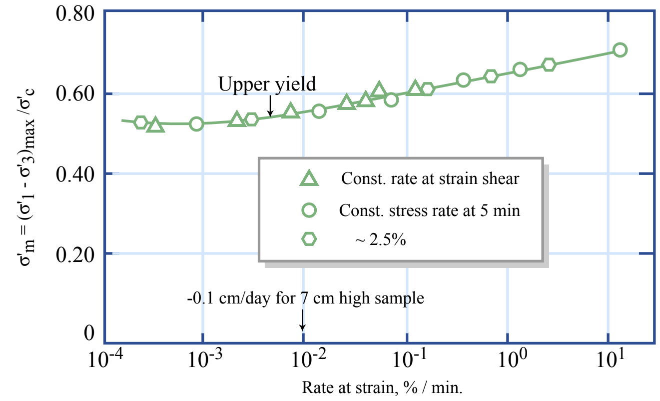
" 5 Constant stress,
use $\dot{\varepsilon}_m$ +

↓

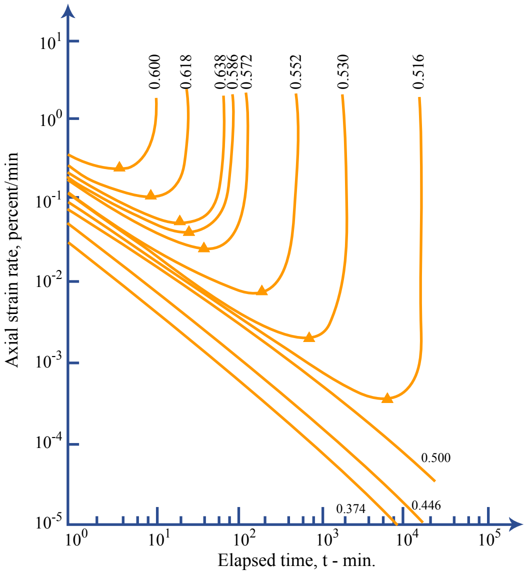
Fig 3 "Correspondence"



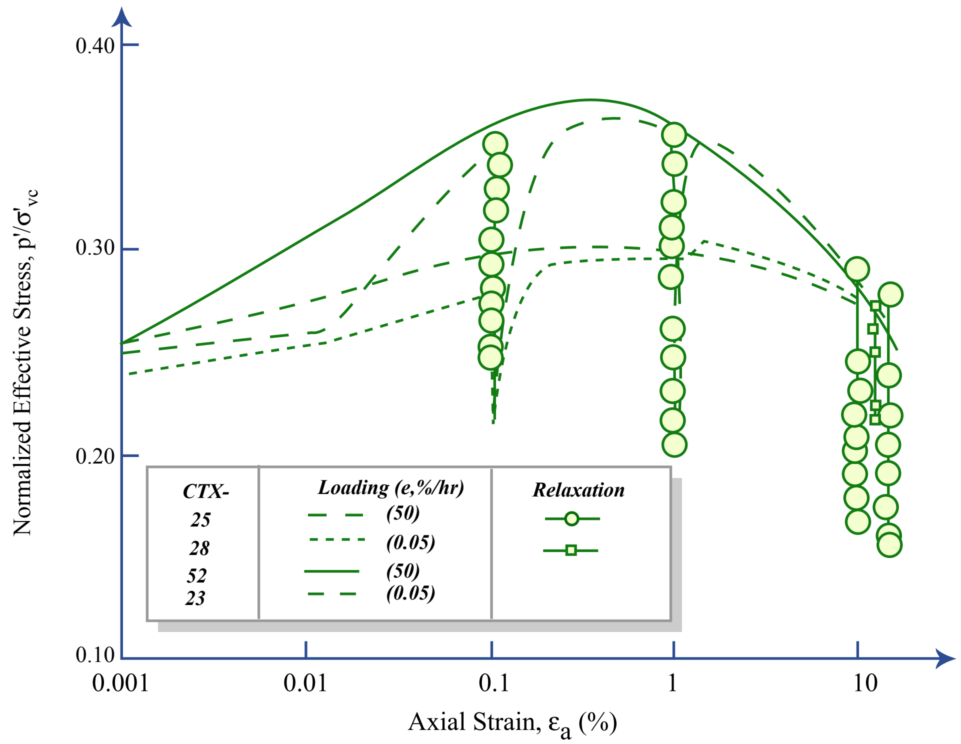
Influence of rate strain on undrained stress-strain behavior in constant rate of strain shear.



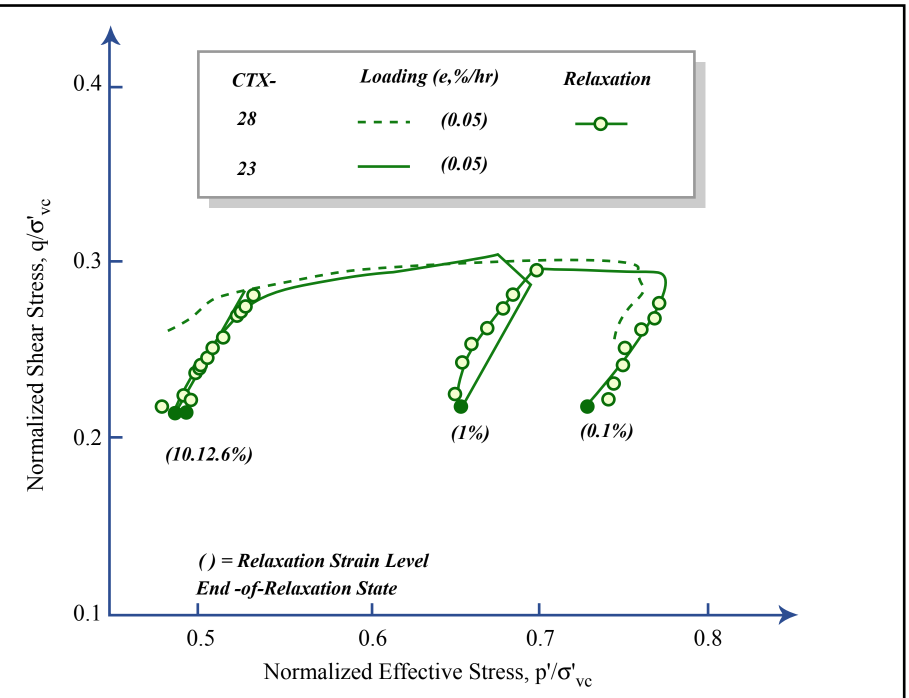
Strain rate dependence of undrained strength in constant rate of strain Shear and constant stress creep



Variation of creep rate with time in constant stress creep



Stress-strain curves, relaxation versus constant strain rate CKoUC tests, resedimented BBC: OCR =1

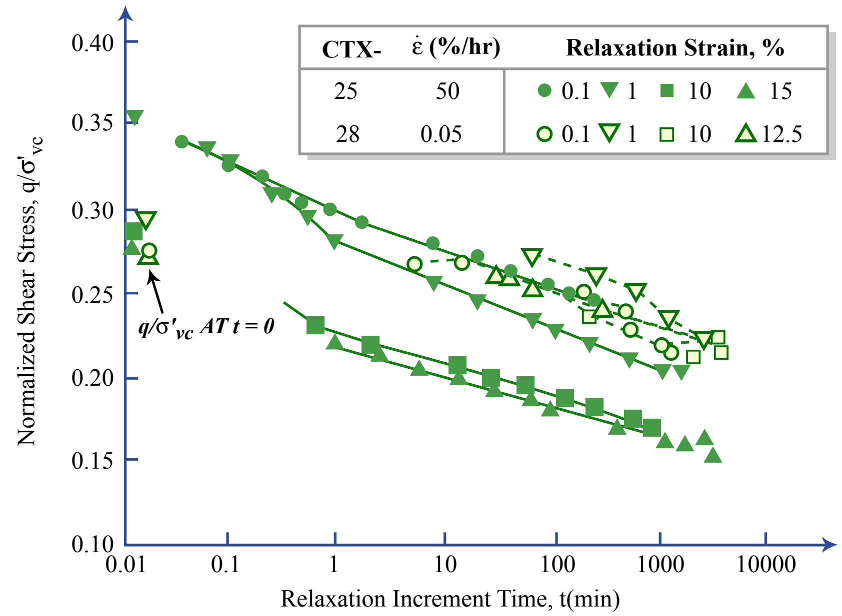


Effective stress paths, relaxation versus constant strain rate CKoUC tests, resedimented BBC.OCR = 1,0.05%/h

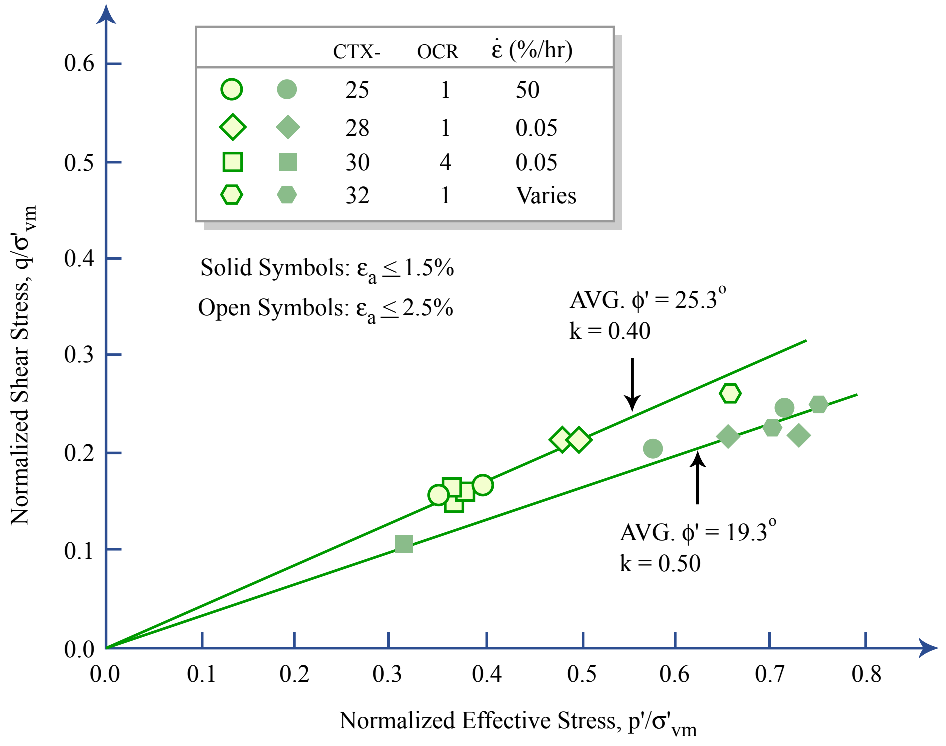
Figures by MIT OCW.

Relaxation data from CKoUC tests on RBBC

Adapted from: Sheahan et al (1994)



Shear stress decay with time, CKoUC relaxation tests on resedimented BBC: OCR =1



Stabilized stress states at the end of relaxation phases, CK$_0$UC relaxatin tests on resedimented BBC.

Figures by MIT OCW.

Relaxation data from CK$_0$UC tests on RBBC

Adapted from: Sheahan et al. (1994)