Fig VIs
M1-M4
K1-K3
I1-I3
} Sheets

VI SOIL STRUCTURE : EFFECTS OF CLAY TYPE AND ENVIRONMENTAL FACTORS

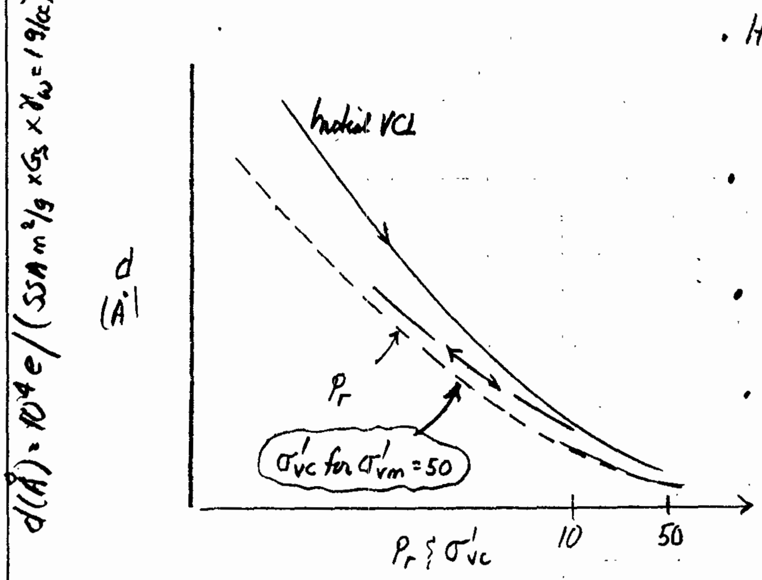
$$\left[\sigma' = (\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a)a_c + (R-A)\right]$$

Note: See Ⓜ4 for index properties of 3 clays tested by Olson & Mesri

1. SMECTITE (Highly flexible plates)

1.1 Na Montmorillonite

1) 1-D Compression : -0.2μm, 10^{-3} NaCl (M1) Used SSA = 800 m^2/g



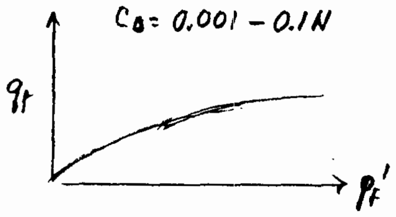
- How calculate $d = \frac{V_v}{SA} = \frac{e V_s}{SSA \cdot W_s} = \frac{e}{SSA \cdot G_s \cdot \gamma_w}$ $W_s = V_s \cdot G_s \cdot \gamma_w$
- Initial loading: $\bar{\bar{\sigma}} \cdot a_c/\sigma' > 0 \rightarrow$ partially flocculated fabric
- U/R from 10 atm → closer to P_r
- U/R from 50 atm → very close to P_r

- Conclusions – During initial loading have significant $\bar{\bar{\sigma}} \cdot a_c/\sigma'$
  – after $\sigma'_{vm} = 50 \rightarrow$ close to ideally dispersed with SSA ≈ 800 so that $\sigma' \approx R-A \approx P_r$

2) 1-D: Effect of min. c_0 (M3) Fig 7b (-2μ) + Fig. V & VI

- VCL much lower
- Swelling " "
- PI = 1100 → 800

3) CIUC data (M4) Fig 9 (-2μ)



- Why $\phi' \approx 6.5 \pm 2°$ & ϕ' (tangent) → ≈ 0°

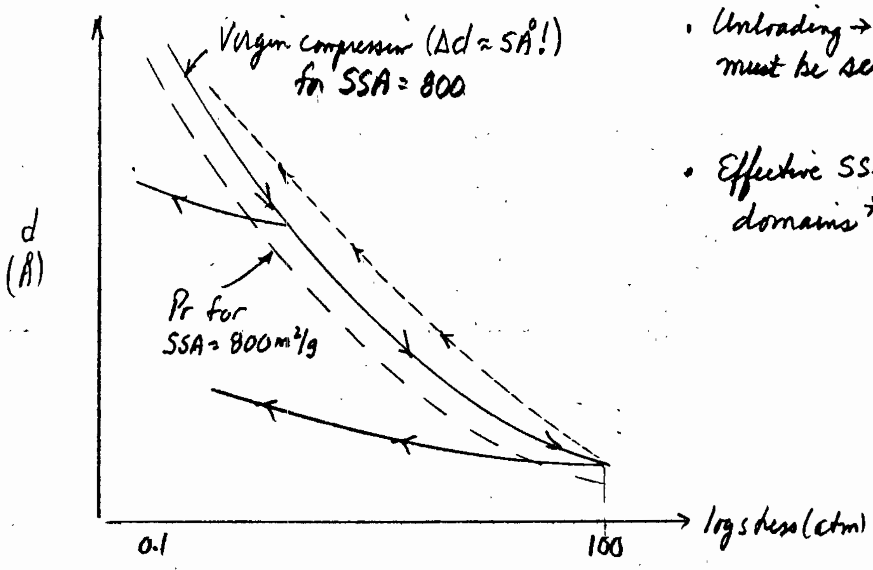
- No effect of min. c_0 not expected by CCL – very odd

4) CD DS ϕ'_r (Kenney, 1967); -2μ Na Mont. Residual strength

NaCl g/l	w_L	I_p	ϕ'_r °
0	1325	1270	4.6
35	620	575	10.2

1.2 Ca Montmorillonite

1) 1-D Compression: ~~0.2 µm~~ 10^{-4} M $CaCl_2$ (M2)



- Unloading → $\sigma'_{vc} < P_r$; hence? must be serious error in SSA
- Effective SSA (ESA): X-ray diffraction → domains* → ≈ 8 layers/particle

- Corrected swelling curve - - - - - - - -
- Conclusions

2) 1-D: Effect of ν & ΔG_0 (M3) Fig. 7a & b + Fig V & VI
- Na → Ca → much lower VCL & SR
- Incr. C_0 for $CaCl_2$ → small effect
- PI only ≈ 170 ± 10

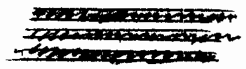
4) CIUC data: ΔC_0 (M4) Fig 8
- $\phi' \approx 15 \pm 2°$ with no effect of ΔC_0

3) 1-D: Effect of ΔD (M3) Fig 6, Fig V & VI
$D = 80\,(H_2O) \rightarrow \underset{EA}{20}$ & $\underset{CCl_4}{2}$ effectively "kills" DL P_r & probably also greatly reduces effective surface area (ESA)
"Mechanical" behavior

5) Conclusions for Na → Ca Mont.
- Ca^{+2} → greatly reduced ESA
- Hence greatly reduced DL effects unless v. high σ'_{vc} → ≈ parallel domains
- More mechanical than PC mechanism

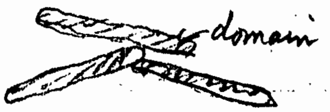
---

* Domain =

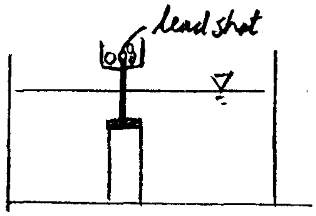


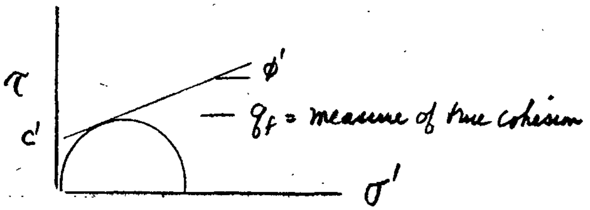
1 particle = several layers "stuck" together (2d ≈ 10Å) since Ca^{+2} acts as a glue

' Fabric



1.3 CIDC(U) data with $\sigma'_3 = 0$ (= drained unconfined compression test)





Data on Vicksburg Buckshot Clay (L & K, 1967) prepared with water
Illite & Smectite, CH w/ $I_p = 35\%$ $\quad\sigma'_{cm} \approx 4$ atm in TX-cell, then removed & submersed for UC tests

Pore Fluid	q_f (g/cm²)
Tap H_2O	60
1M $CaCl_2$	170

1.4 Summary for Smectite (Influence of ν, c_0 & D)

1) 1-D : Location of VCL compared to v. low NaCl c_0
   - a) For 10^{-3} NaCl, incr. $\sigma'_{VC} \rightarrow$ less $\bar{\bar{\sigma}}\cdot a_c/\sigma'$ and can approach $\sigma' \approx R - A = P_r$
   - b) Decr. $P_r \rightarrow$ lowering of VCL
     - Least with NaCl
     - Then for $Na^{+1} \rightarrow Ca^{+2}$ ← (≈ indep. of incr. c_0)
     - more for $D = 80 \rightarrow 20 \rightarrow 2$

   } V. signif. decrease in ESA
   " " increase in $\bar{\sigma}\cdot a_c/\sigma'$

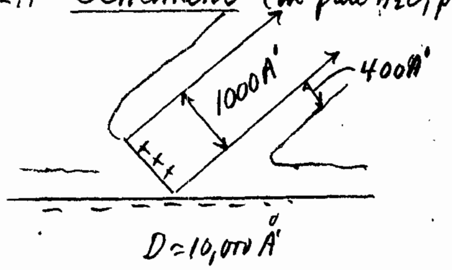
   ↓ Increased importance of "mechanical" response of highly flexible plates

2) 1-D : Amt. of swelling
   - a) Similar to above, but more consistent
   - b) What causes swelling when $R < A$?

3) Effective stress envelope (ϕ') : Incr. $\bar{\bar{\sigma}}\cdot a_c/\sigma' \rightarrow$ increasing ϕ'
   - a) $Na \rightarrow Ca \rightarrow$ large increase ($\approx 6.5 \rightarrow 15°$)
   - b) Δc_0 for NaCl had little effect, which is surprising.
     But Kenney ('67) got $\phi'_r = 4.0 \rightarrow 10.2°$ for zero vs 35 g/l
   - c) Δc_0 for $CaCl^2$ had little effect, since $\bar{\bar{\sigma}}\cdot a_c \gg R - A$ (Mostly mechanical)
   - d) What predicted ϕ' for $D = 20$ & 2?

2. KAOLINITE (Stiff elastic plates)

2.1 Schematic (in pure H_2O, $pH=7$)



- $\sigma' = (\bar{\bar{\sigma}}_r - \bar{\bar{\sigma}}_a)a_c + \cancelto{0}{(R-A)}$
- $\bar{\bar{\sigma}}_a$ electrostatic +/- very important

∴ How Δ pore fluid affects it rather than R-A important for Δ behavior

2.2 1-D Compression

$\left\{\begin{array}{l}\text{For incr. } \sigma'_{vc}\text{, less frictional-adhesional resistance at contacts} \\ \text{facilitates more parallel reorientation of particles}\end{array}\right\}$

1) e vs log P_r & σ'_{vc} Ⓚ① → Why TSPP → lower VCL Also Fig V & VI

2) Data from Olson-Mesri (K2) (

- Why incr. NaCl → lower curve (Fig.1) ≈ $CaCl_2$

- Why incr. pH → lower curve (Fig. 3)

- Why incr. D → lower curve (Fig. 4)
- Why smaller effect of above on SR

2.3 Strength Data

1) CIUC (K3) $\phi' \approx 25\text{-}30°$. Why independent of ν & pH?

2) CIDC(L) $\sigma'_3 = 0$ (L&K'67) $I_p = 30\%$, deposit $pH=7$
$\sigma'_{cm} \approx 4$ atm

Pore Fluid	q_f (g/cm²)
pH ≤ 7	40
pH = 9.5	15
TSPP	0

2.4 Summary of Effects of TSPP, pH, ν, c_0 & D

1) 1-D L/U

- Reduced $\bar{\bar{\sigma}}_a$ (+/- attraction) → less resistance to particle reorientation → less flocculated fabric → lower VCL
- Swelling due to particle "unbending" [illegible]
- Compressibility much less than mica. Why

2) ESE (ϕ')

- Essentially constant since $\sigma' = \bar{\bar{\sigma}} \cdot a_c$ inspite of changes in fabric

3) True cohesion (unconfined drained qf)

- Greatly affected by $\Delta\bar{\bar{\sigma}}_a$ (+/- attraction)

Compressibility is essentially "mechanical" due to [illegible]

(1) Particle reorientation on VCL where amount strongly affected by coef. of friction (μ) at contacts

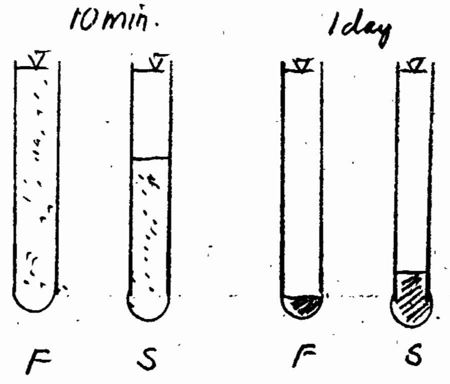
(2) Particle deformation - stored elastic energy

3 ILLITE

For Natural Clay (e.g. BBC)

3.1 Deposition: Fresh vs Sea Water (1.361 II2-3.2.3)

1) Test tubes (S = sea water = 35 g/l → R<A vs F = fresh water → R>A)

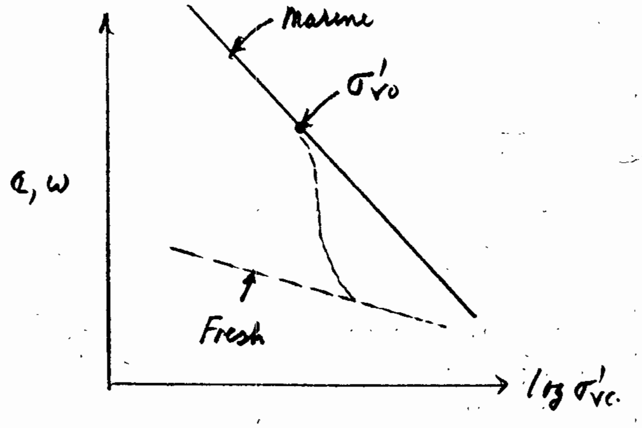


- Why Δ fabric?

S: Large flocs with E-F orientation

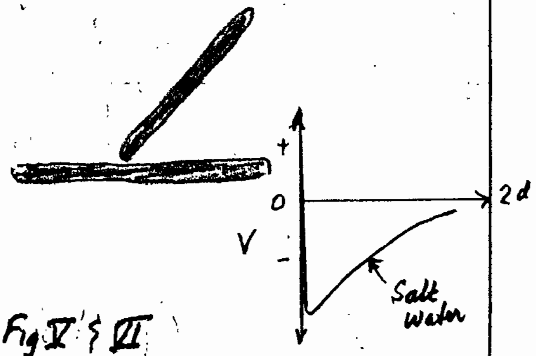
F: Small flocs with more parallel (dispersed orientation

2) Leaching of marine clay



- Compressibility after leaching ----

- Why metastable structure after leaching



3.2 1-D Compression: Fractionated Illite + Fig V & VI

1) Bolt (1956) (~0.2μ) ⒾⅠ Effect of incr. C_o for NaCl

- Lowers VCL, but only after preconsolidation to σ'_{vm} = 5-10 atm
- If had been sedimented, may get reversal in VCLs
- In any case, significant $\bar{\bar{\sigma}} . a_c / \sigma'$

2) Olson & Mesri (1970) (I2) Fig. 4 Effect of ν & D for v. low C_0
(-2μ)

a) VCL at low σ'_{vc}: Na > Ca > EA >> CCl_4 = Air, but almost reversed at high σ'_{vc}.
— all "mechanical"

b) Swelling, Max C_s: Na > Ca > EA >> CCl_4 = Air ← expect from DL theory

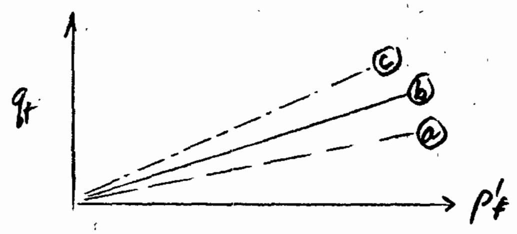
c) Hence complex interaction of effects of changing importance of R-A, effective surface area (probably), coef. of friction during reorientation on both initial fabric & changes during virgin compression. With decreasing P_r, (R-A), "mechanical" behavior becomes more important

(I3) Fig. 5: Effects of ΔC_0 for Na & Ca - See notes on (I3) →
again complex interaction.

d) For both sets of data, hard to understand without quantitative measurements of ESA and fabric

3.3 Strength Data

1) CIUC (I2) Fig. 7
(-2μ)



ⓐ Na, low C_0 $\phi' \simeq 16°$
ⓑ Na, high C_0 $\simeq 21°$
ⓒ Ca, all C_0 $\simeq 26°$
} Decreasing P_r
} Maybe decr. ESA

3) CIDC(L) $\sigma'_3 = 0$ (L&K '67) BBC $I_p = 16\%$ Deposited 16 g/l NaCl
$\sigma'_{cm} = 4$ atm

Pore Fluid	q_f (g/cm²)	
Tap H_2O	5-10	} Large decr. in P_r (R-A)
16 g/l NaCl	40±5	} Less difference in P_r (R-A)
1M $CaCl_2$	60±5	

2) Kenney (1967) Residual friction angle (ϕ'_r) on -2μ

H_2O	$\phi' = 16°$	$w_L = 50$	$I_p = 20$
35 g/l NaCl	= 23°	= 100	= 60

4. "SUMMARY"

1) $\sigma' = (\overline{\overline{\sigma}}_r - \overline{\overline{\sigma}}_a)\, a_c + (R - A)$

Ads. H2O Born | vdw electrostatic primary | DL vdw

2) Need to understand / appreciate how Δ environment affects both contact & long range forces

a) Effect on initial fabric

- effective surface area (ESA)
- floc size
- particle orientation

b) Amount of $\sigma' \rightarrow \overline{\overline{\sigma}} \cdot a_c$ vs $(R - A)$

↑ strength generation ($\overline{\overline{\tau}} \approx$ 100's atm)

friction & cohesion

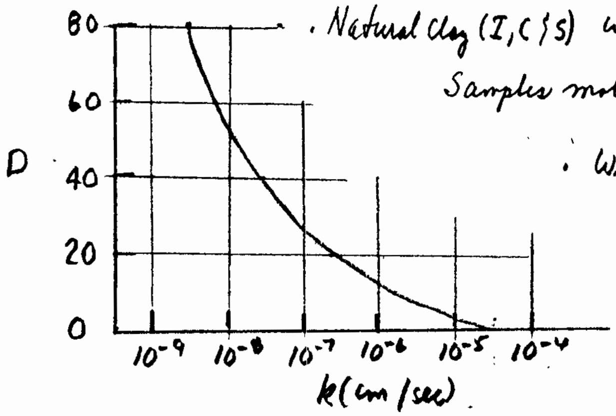
↖ ability to remake contacts

c) Mechanical vs PC compressibility

3) Very different behavior for changes in ν, c_0, D & pH

- Smectite
- Kaolinite
- Illite
- Mica

4) Effect of dielectric constant on k (Fernandez / Quigley 1985) 1.361 II2 3.3



- Natural Clay (I, C & S) $w_L = 38$, $I_p = 20.5$ SSA = 120 m²/g

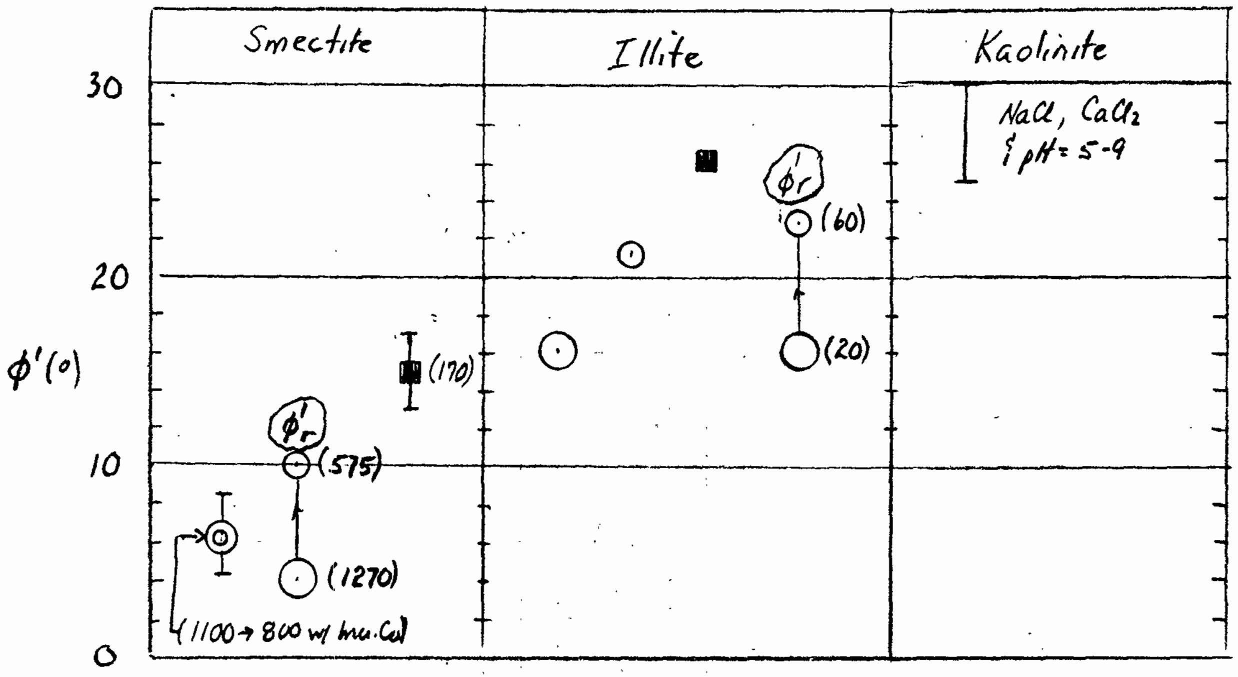
Samples molded at $e = 0.8$ ($w \approx 30\%$)

- Why 10^4 increase in k?

5) Summary of ϕ' data : Data from Olson (74) except ϕ_r' from Kenney (67)

○ NaCl, Low c_0 ○ NaCl, High c_0 ■ $CaCl_2$

(PI, %)



6) Is there a consistent change in compressibility and strength with change in Atterberg Limits?

7) Bottom Line:
Except for Mica & Kaolinite, very difficult to fully understand - explain how Δ pore fluid affects strength and compressibility (especially VCL) of Smectite & Illite without having quantitative measurements of fabric (especially "particle" orientation & effective surface area).

(e at σ'_{vc} = 64 ksf) → e ≈ 1.0 ±0.3 for all data!

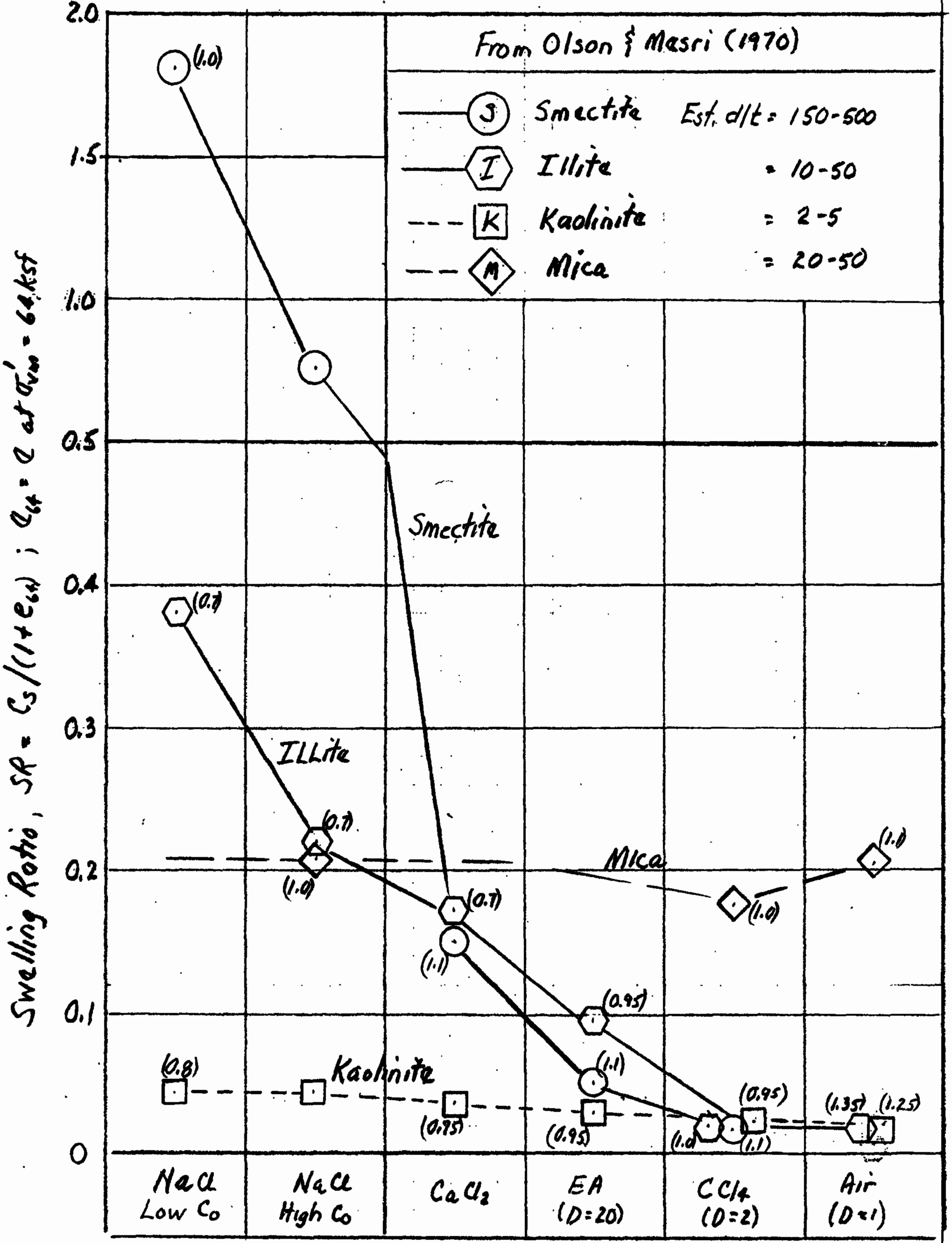


Fig. VI Effect of Clay Mineral & Pore Fluid on Swelling Ratio

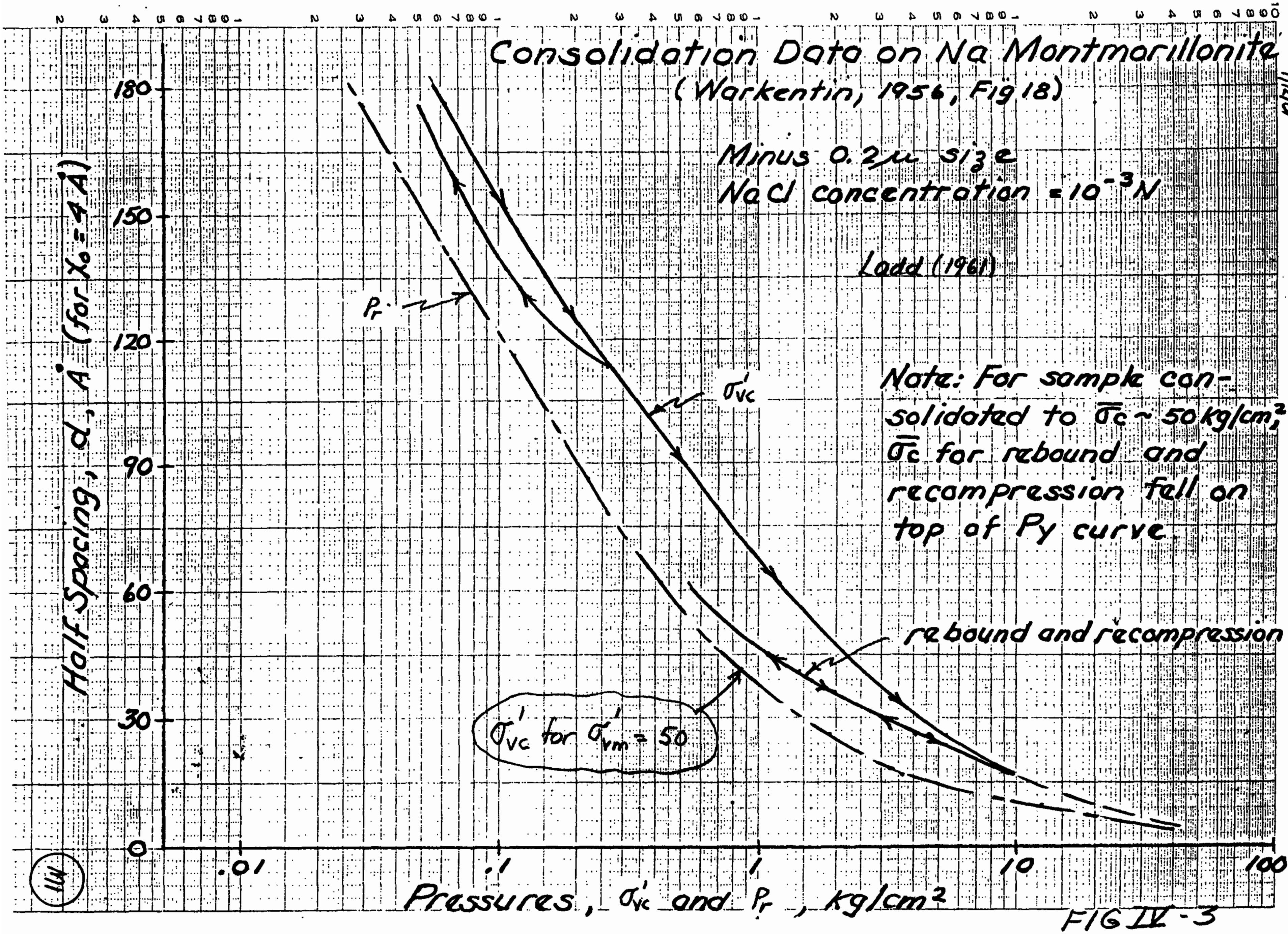

Consolidation Data on Na Montmorillonite
(Warkentin, 1956, Fig 18)
Minus 0.2μ size
NaCl concentration = 10^{-3}N
Ladd (1961)
Note: For sample consolidated to $\bar{\sigma}_c \sim 50$ kg/cm²; $\bar{\sigma}_c$ for rebound and recompression fall on top of P_r curve.
rebound and recompression
σ'_{vc}
P_r
σ'_{vc} for $\sigma'_{vm} = 50$
Half Spacing, d, Å (for $X_0 = 4$ Å)
180
150
120
90
60
30
0
.01
.1
1
10
100
Pressures, σ'_{vc} and P_r, kg/cm²
111

FIG IV-3

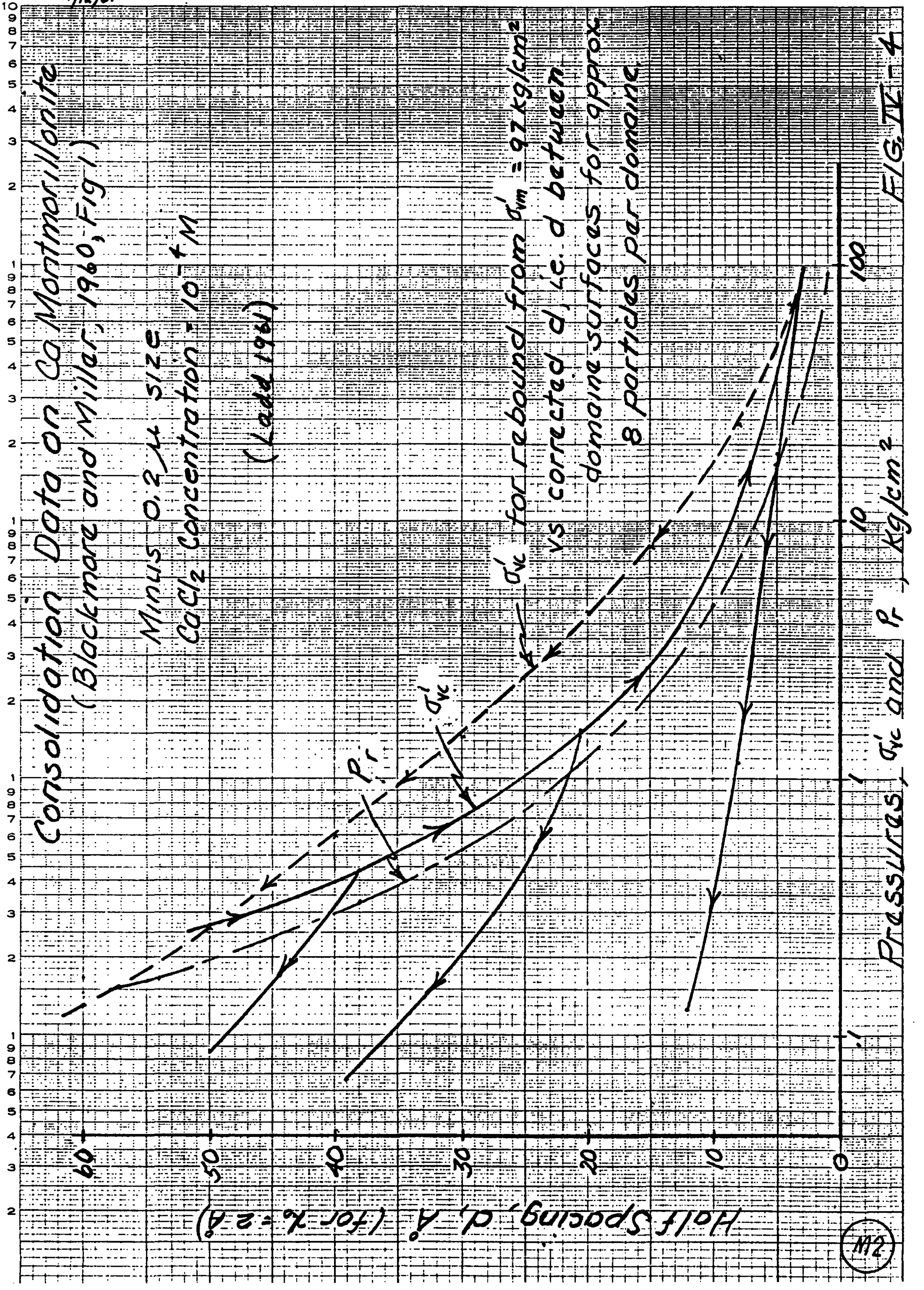


FIG. IV-4

Consolidation Data on Ca Montmorillonite
(Blackmore and Millar, 1960, Fig 1)

Minus 0.2 μ size
$CaCl_2$ Concentration = 10^{-4} M

(Ladd 1961)

σ'_{vc} for rebound from σ'_{vm} = 97 kg/cm² vs corrected d, i.e. d between domaine surfaces for approx 8 particles per domaine

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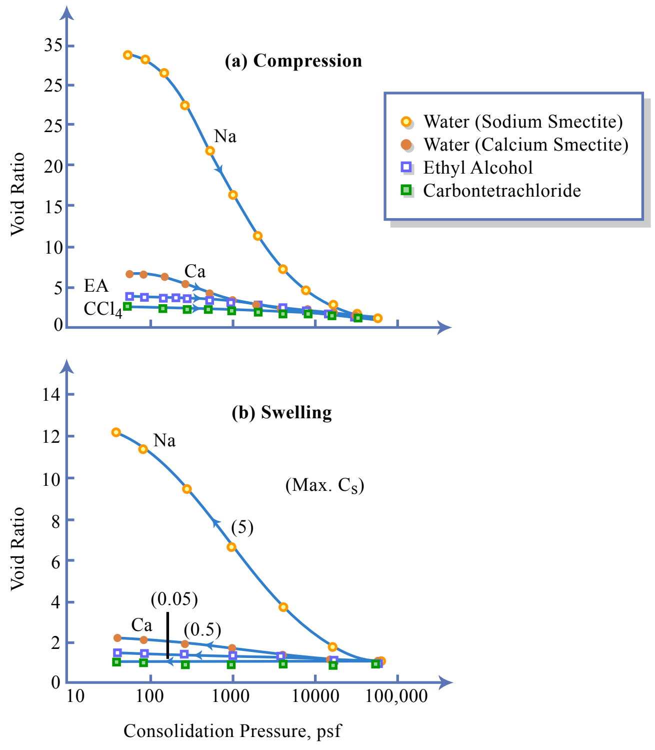
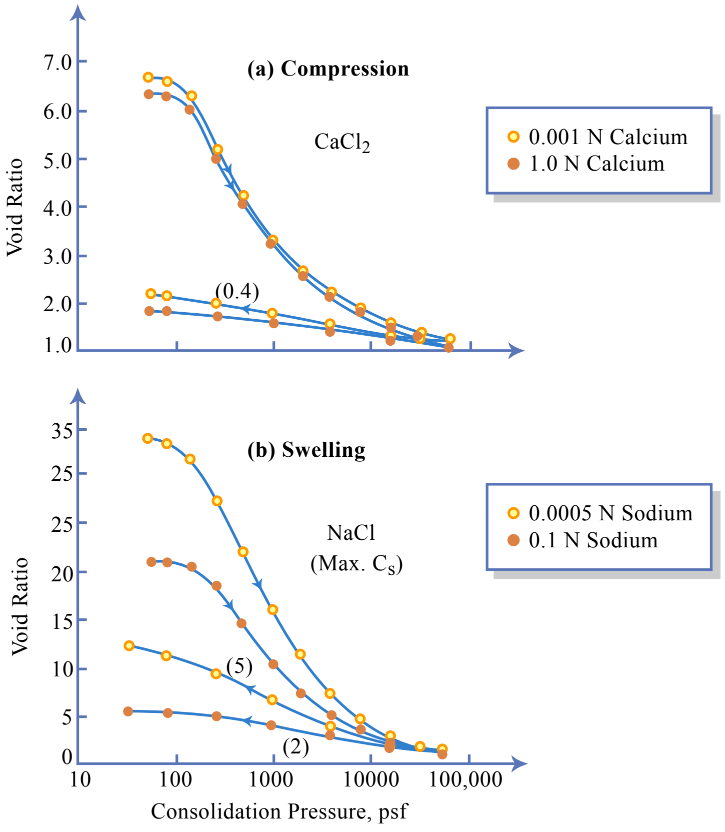
1.322 A-VI



One-dimensional Consolidation Curves of Smectite in Various Pore Fluids

Effect of pore fluid



One-dimensional Consolidation Curves of Smectite in Water

Effect of salt conc.

Figures by MIT OCW.

M3

Adapted from:
Olson & Mesri (1970)

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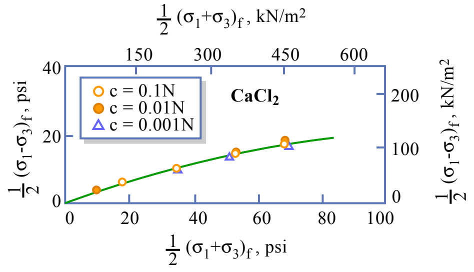
Adapted from Olson & Masri (1970) and Olson (1974) *

Figure by MIT OCW.

PROPERTIES OF CLAYS

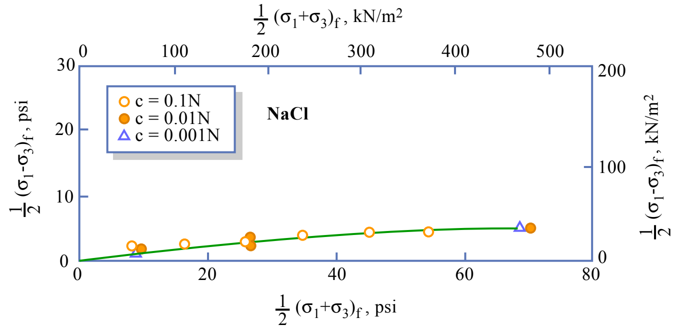
Mineral	Supplier, source, trade name	Liquid limit (%)	Plastic limit (%)	Specific gravity	Surface area, in square meters/gram	Cation exchange capacity, in milliequivalents /100g	Fraction finer than 0.002 mm	Estimated ratio of diameter to height	CEC SSA
Kaolinite	Minerals and Chemicals Philipp Corp, Kioadyke olay, Mcintyre, Georgia	40 to 50	27 to 31	2.55	14	3 ± 1.5	47	2-5	0.2 ± 0.1 But low?
IIltte Fractionated	J.L. Eades, Dept. of Geology, Univ. of Illinois, Marblehead, Wisconsin	83 to 104	31 to 32	2.60	95 ± 5	25	100	10-50	= 0.25 OK
Smaotite	American Colloid Company, Wyoming Vololay	190 to 1,150	31 to 47	2.65 to 2.80	500 to 700	100	97	150-500	= 0.17 OK ± 0.03

$$\left\{\begin{array}{ll} \text{Na} & \text{PI} = 1100 \longrightarrow 800 \text{ with } C_o = 10^{-4} \longrightarrow \text{IN} \\ \text{Ca} & \text{PI} \approx 170 \pm 10 \text{ for} \longrightarrow C_o = 10^{-3} \longrightarrow \text{IN} \end{array}\right\}$$



φ' ≈ 15 ± 2°

Failure envelope for specimens of calcium montmorillonite at pore-water electrolyte concentrations of 0.1 N, 0.01 N, and 0.001 N



φ' ≈ 6.5 ± 2°

Tangent φ' → ≈ 0

Failure envelope for sodium montmorillonite at pH = 7 and range in pore-water electrolyte concentration from 0.001 N to 0.1 N

MA

* Olson & Mesri (1970) ASCE, JSMFD, 96(6), 1863-1878
Olson, R.E. (1974) ASCE, JGD, 100(11), 1215-1225

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1/12/01

1.322 Part A-VI

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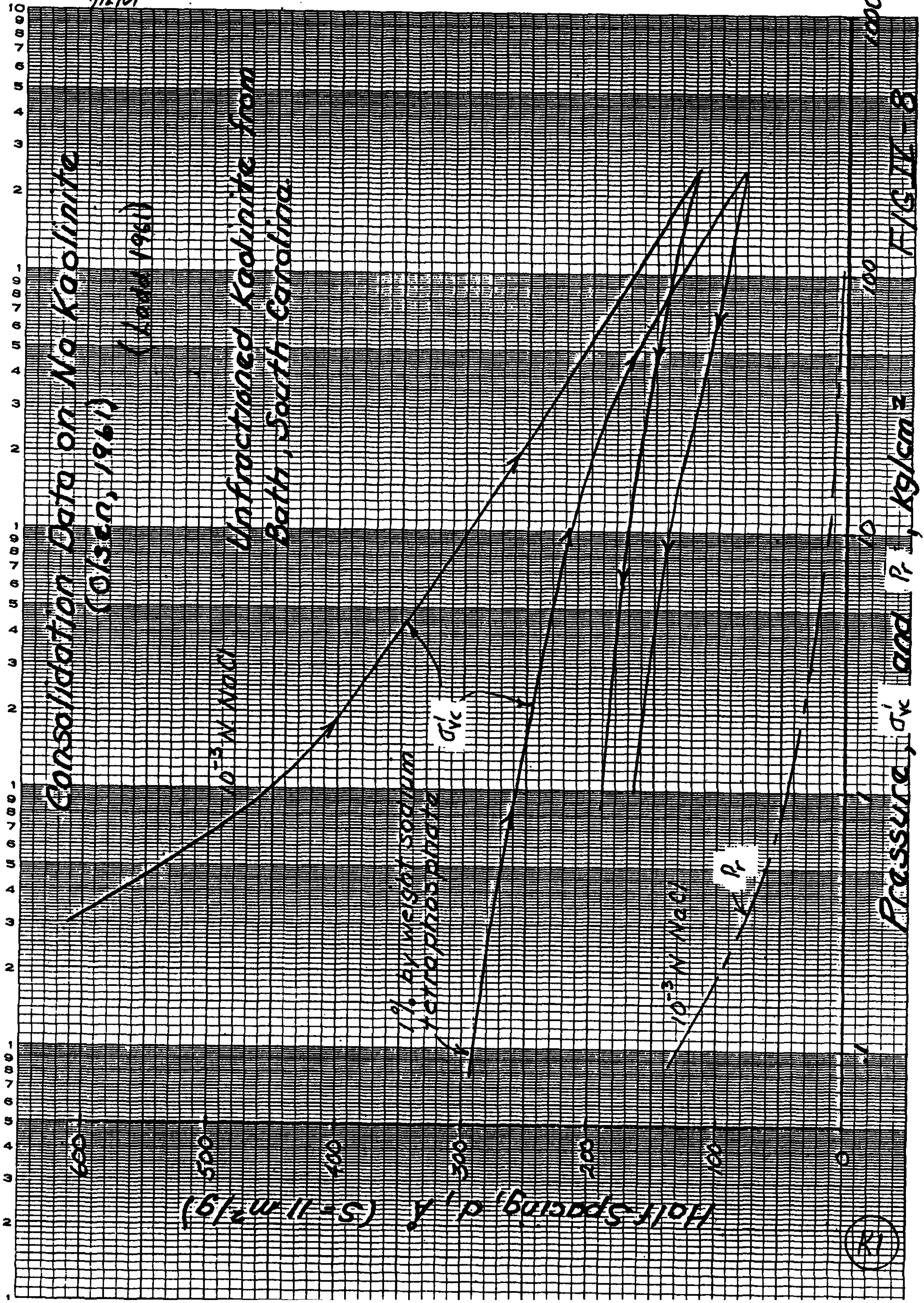


FIG. VI-8

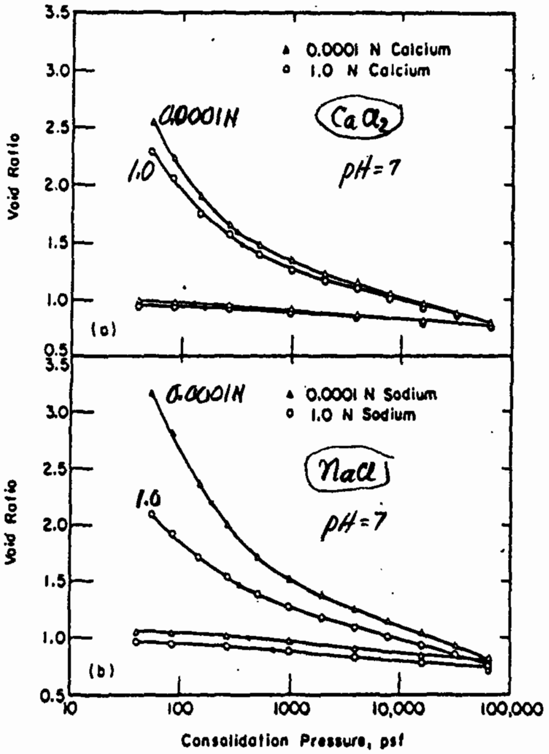
Consolidation Data on Na Kaolinite (Olsen, 1961) (Ladd 1961)

Unfractioned Kaolinite from Bath, South Carolina

EUGENE DIETZGEN CO.
MADE IN U.S.A.

SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

Olson & Mesri (1970) 1-D Consolidation of Kaolinite (47% -2μ)



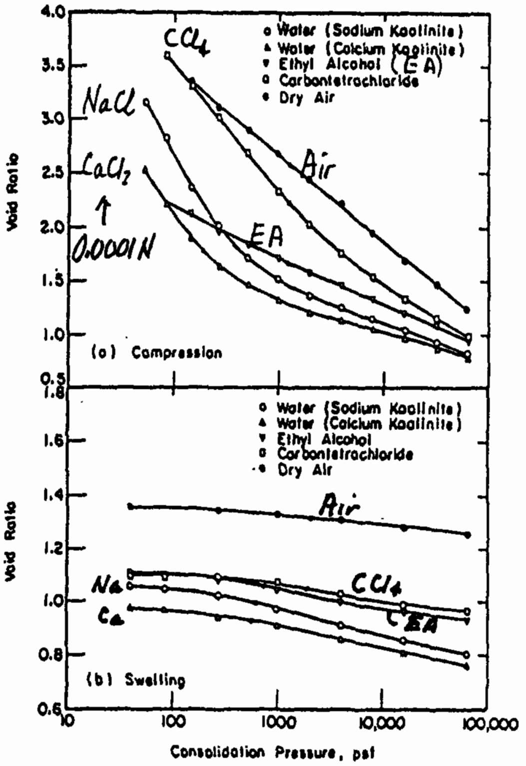


FIG.1 Incr. C_0 → less $\bar{\bar{\sigma}}_a$ → less flocculated structure

FIG.2 Decreasing D → incr. $\bar{\bar{\sigma}}_a$ (+/-) & reduced $\bar{\bar{\sigma}}_r$ → higher contact resistance → more flocculated

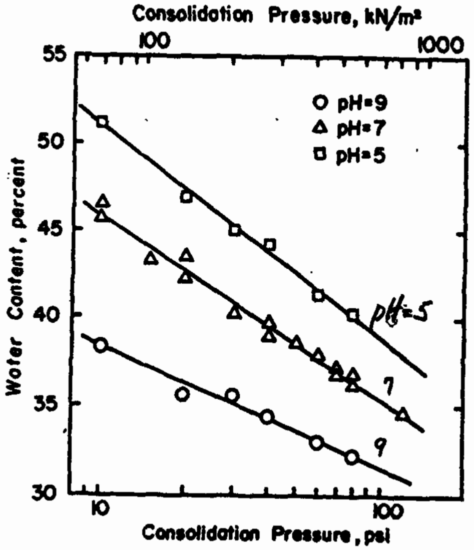
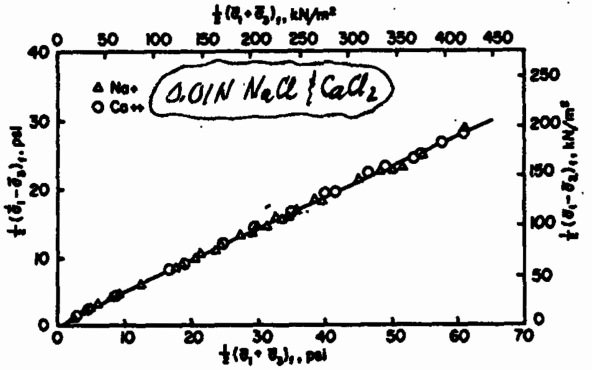


FIG. 3.—Virgin Consolidation Curves for Sedimented Specimens of Sodium Kaolinite at Values of pH = 5, 7, and 9

Olson (1974)

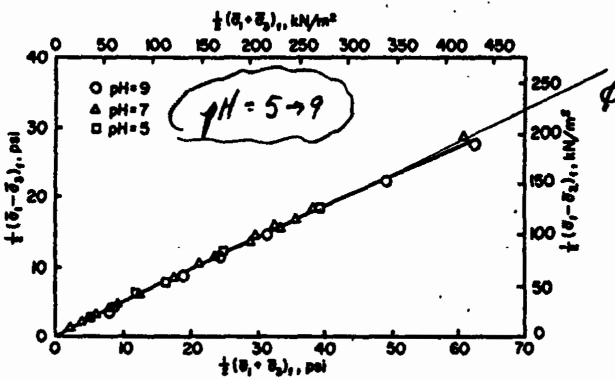
Incr. pH → less + edge charge → less $\bar{\bar{\sigma}}_a$ attraction

CIUC Olson (1974)



$\phi' \approx 25\text{-}30°$

FIG. 1.—Failure Envelope for Sedimented Specimens of Homoionic Kaolinite—All Tests Are of $\bar{R}$ Type with Failure Defined at Point of Stress-Path Tangency (Both Normally Consolidated and Overconsolidated Specimens Are Included; pH = 7 and C = 0.01 N)



$\phi' = 28°$

FIG. 4—Failure Envelope for Normally Consolidated, Sedimented Specimens of Sodium Kaolinite at Values of pH = 5, 7, and 9 (All Tests Are $\bar{R}$ Compression Tests with Failure Defined at Point of Stress-Path Tangency)

Although increasing pH affects compression curve (Fig 3 of K2), still get same ϕ' since $\bar{\bar{\sigma}}\cdot a_c / \sigma' = 1.0$

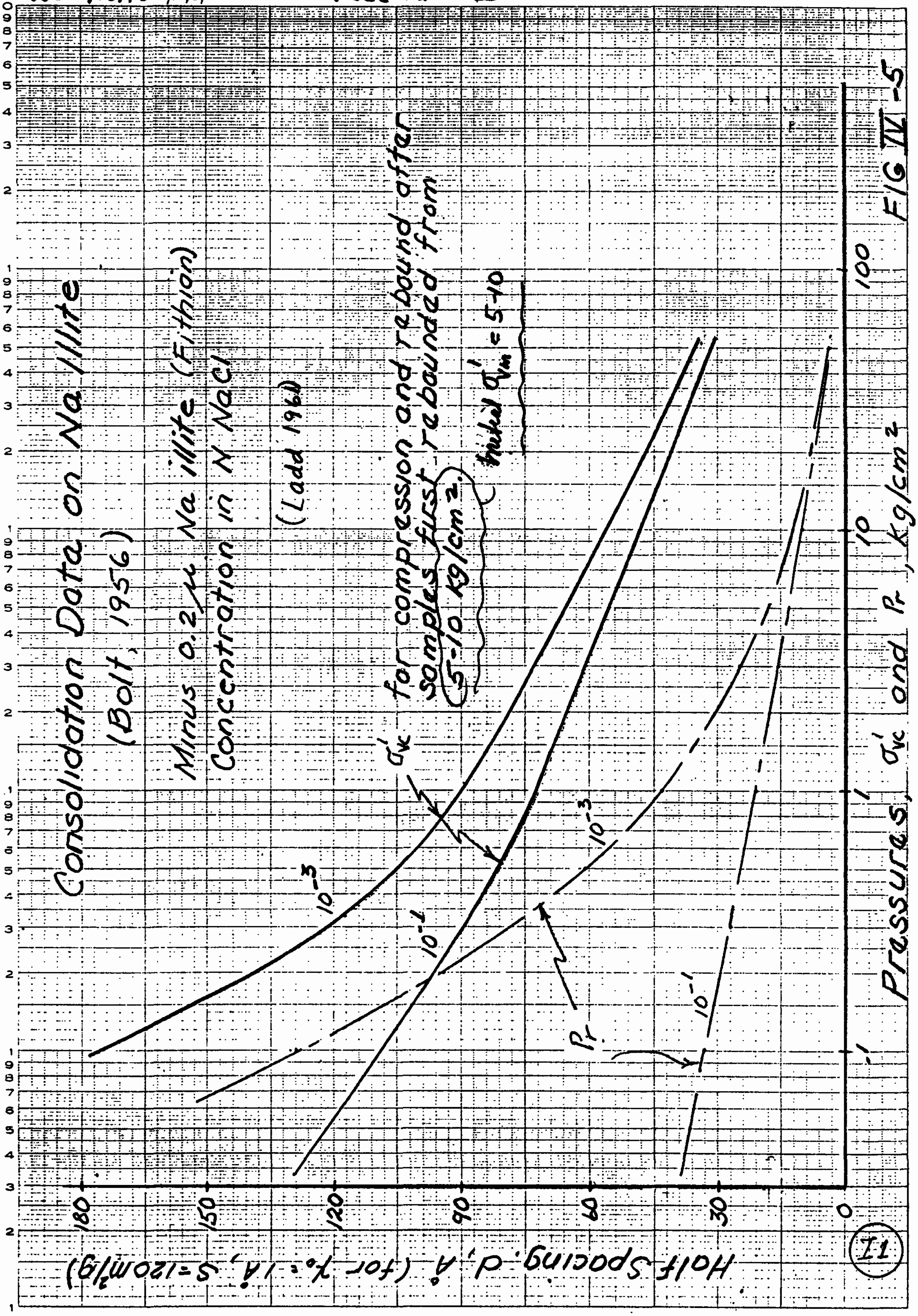

Consolidation Data on Na Illite
(Bolt, 1956)
Minus 0.2 μ Na illite (Fithian)
Concentration in N NaCl
(Ladd 1961)
σ'_{vc} for compression and rebound after samples first rebounded from (5-10 kg/cm².)
(Initial σ'_{vm} = 5-10
10^{-3}
10^{-1}
10^{-3}
10^{-1}
P_r
P_r
Pressures, σ'_{vc} and P_r, kg/cm²
.1
1
10
100
Half Spacing, d, Å (for x_0 = 1Å, S=120m²/g)
180
150
120
90
60
30
0
I1

FIG IV-5

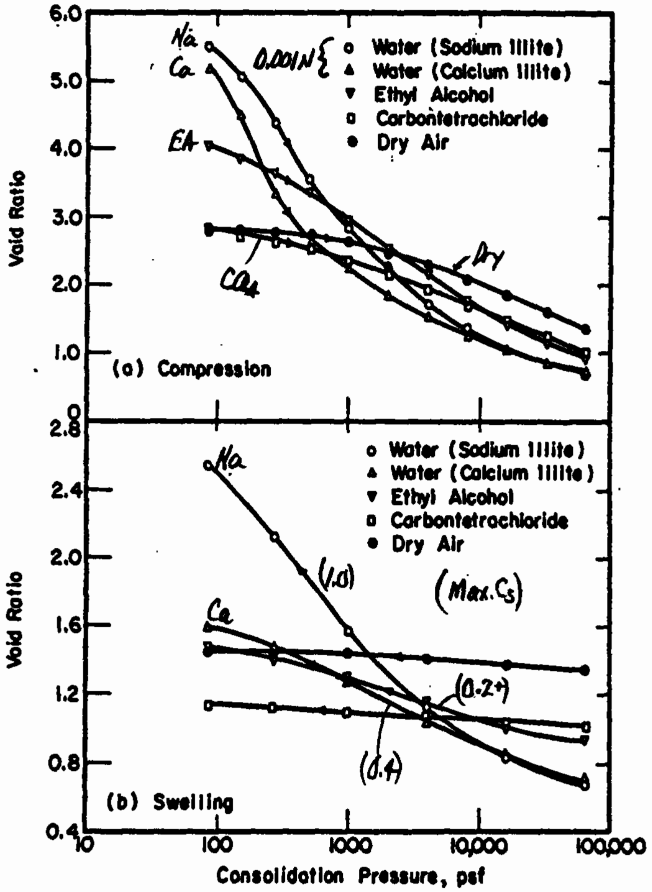
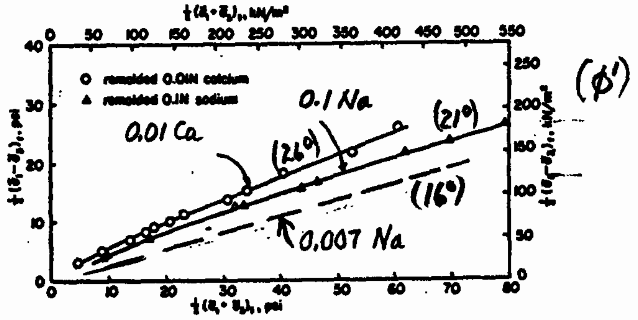


FIG. 4.—ONE-DIMENSIONAL CONSOLIDATION CURVES OF ILLITE IN VARIOUS PORE FLUIDS

Olson & Mesri (1970)

Note: See Fig. 5 (I3) for effect of CCl4 on Na & Ca Illite

FIG. 6.—Failure Envelope for Remolded and Sedimented Specimens of 0.01 *N* Calcium Illite (Failure Was Defined as Point of Stress-Path Tangency)



Olson (1974)

CIUC

Note: No effect of Ca for Ca Illite

Fig. 7.—Failure Envelopes for Remolded Specimens of Calcium and Sodium Illite (Failure Was Defined at Point of Stress-Path Tangency)

Olsen & Mesri (1970)

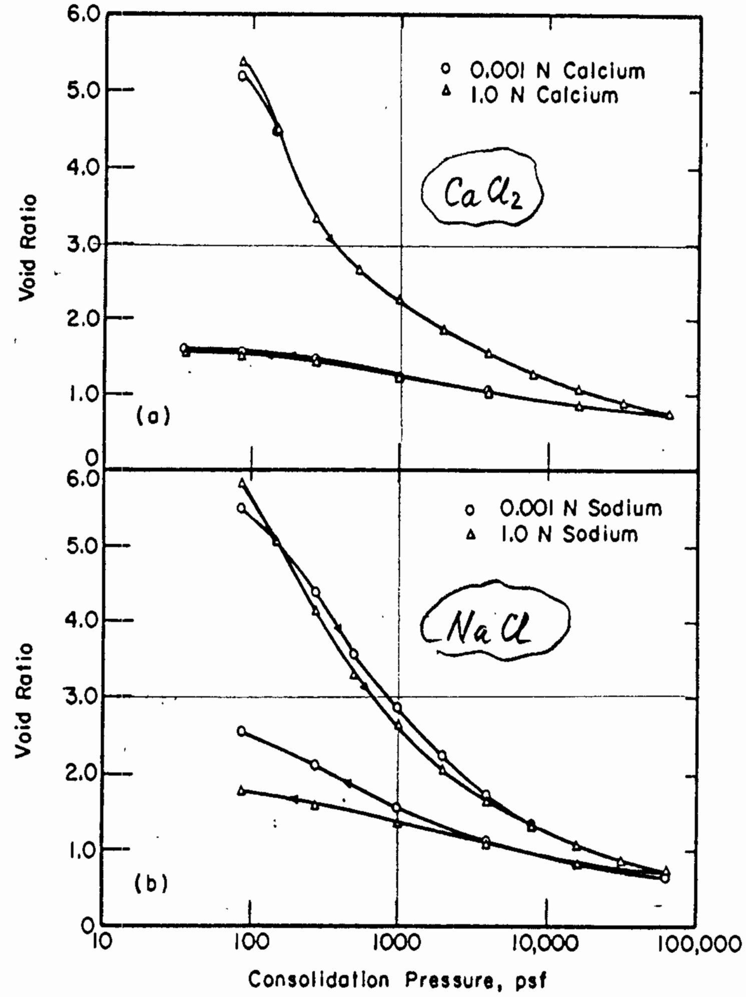


FIG. 5.—ONE-DIMENSIONAL CONSOLIDATION CURVES OF ILLITE IN WATER

- Low Na c_0 → increased swelling, as expect from DL theory
- Δ val. Na → Ca → slightly lower VCL } Started from slurry, not real sedimentation
- Δc_0 → little change in VCL
- many case, significant $\bar{\bar{\sigma}} \cdot a_c / \sigma'$