II-1 SOIL COMPOSITION, INDEX PROPERTIES \& SOIL CLASSIFICATION

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   1.1 Phase Relations \& definitions (Fig III-1, p20)
   1.2 Two basic soil types

2. Soil Composition
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   2.2 Silicate
   2.3 Silicate Framework
   2.4 Building blocks of clay minerals
   2.5 Types of bonds
   2.6 Common clay minerals, with two sheets per layer
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   3.2 Granular Soils
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   4.2 Details of USCS
   4.3 Remarks \& Examples

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A Composition of soil
B Data on common clay minerals
C Empirical correlations for density \& strength of granular soil
D1 " " " for cap of consolidation \& ultimate strength of cohesive soil
D2 " " " for drained strength of clay
E Unified Soil Classification System (ASTM D 2487)
1 INTRODUCTION

1.1 Phase Relations & Definitions (L & W Chap.3) See Fig. III-1, p2a

- Know definitions of water content (w), void ratio (e), porosity (n), specific gravity (G = G_s) & unit weight = total (\(\gamma_t\)), dry (\(\gamma_d\)) & buoyant (\(\gamma_b\))
- Remember that \(G = w = S \cdot e\) (for pore fluid = pure water), \(S =\) degree of saturation
- If no prior soil mechanics, see Lambe (1951) Soil Testing for Engineers

1.2 Two Basic Soil Types

1) Particle Size Distribution (MIT Classification)

- Sieve analysis
- Hydrometer analysis (Stokes' law)
  via ASTM D422

2) General Characteristics

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Particles &amp; Features</th>
<th>Hydraulic Conductivity</th>
<th>Practical Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Granular</td>
<td>Large equidimensional</td>
<td>HIGH</td>
<td>Max. U_c very low</td>
</tr>
<tr>
<td></td>
<td>(Cohesiveless)</td>
<td>Large voids</td>
<td></td>
<td>Engr. properties from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Very low SSA</td>
<td></td>
<td>in situ penetration vail</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Only mass forces</td>
<td></td>
<td>Drained loading</td>
</tr>
<tr>
<td>2</td>
<td>Cohesive</td>
<td>Small platy shaped</td>
<td>VERY</td>
<td>Max. U_c very high</td>
</tr>
<tr>
<td></td>
<td>(Clay minerals)</td>
<td>Very small voids</td>
<td></td>
<td>Engr. properties from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High SSA &gt; 10 m²/g</td>
<td></td>
<td>in situ &amp; lab testing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Also surface forces</td>
<td></td>
<td>Undrained loading</td>
</tr>
</tbody>
</table>

SSA = Specific Surface Area (m²/g); \(U_c = U_a - U_w\) = capillary pressure (soil suction)
Weights  | Volumes
---|---
O | $W_W$ | Air | $V_a$ | $V_V$ | Water | $W_W$ | Water
$W_V$ | $W_W$ | $V_a$ | $V_V$ | $V_V$ | Solids | $V_S$ | Solids
$W_S$ | $V_S$

$W_T = W_W + W_S$  \hspace{1cm}  $V_T = V_V + V_S$

Definitions

Specific gravity, $G_S = \frac{V_S}{V_W}$

Void ratio, $e = \frac{V_V}{V_S} = G_S \cdot \frac{w}{s}$

Porosity, $n = \frac{V_V}{V_T}$

Specific volume, $v = \frac{V_T}{V_S} = 1 + e$

Water content, $w = \frac{W_W}{W_S} = \frac{S \cdot e}{G_S}$

Degree of saturation, $S = \frac{V_W}{V_V} = G_S \cdot \frac{w}{e}$

Unit Weights

Water, $\gamma_w = 9.81 \text{ kN/m}^3 = 62.4 \text{ pcf} = 1.00 \text{ T/cm}$

Solids, $\gamma_s = G_S \cdot \gamma_W$

Total, $\gamma_k = \frac{W_T}{V_T} = \left( \frac{G_S + S \cdot e}{1 + e} \right) \gamma_W$

Dry, $\gamma_d = \frac{W_S}{V_T} = \frac{G_S \cdot \gamma_W}{1 + e}$

Buoyant, $\gamma_b = \gamma_k - \gamma_w$; for $S = 100 \%$, $\gamma_b = \left( \frac{G_S - 1}{1 + e} \right) \gamma_w$

\[ G_S \cdot \gamma_w = S \cdot \gamma_w \]

Fig. III-1  Phase Relations (for water as pore liquid)
2. SOIL COMPOSITION

2.1 Overview (See Sheet A)

1) Differences in particle size & shape are mainly due to differences in the types & arrangement of elements in the crystalline structure = MINERAOLOGY (regular structural arrangement of atomic elements → x-ray diffraction pattern)

2) Five Main Groups
   • Carbonates: Calcite & dolomite used to make cement
   • Oxides
   • Hydrous Oxides: Gibbsite & brucite name OH’s → sheets in clay minerals
   • Phosphates: Mining for fertilizers
   • SILICATES: > 90% of all Soil

2.2 Silicates

1) Silica tetrahedron

\[ \text{Plan} \]
\[ \text{Expanded Side View} \]

\[ \text{Si}^{+4} \quad \text{O}^{-8} = -4 \text{ net negative charge} \]

\[ \text{Cannot exist alone} \]

Primary valence bonding (covalent & ionic)

2) How these silica tetrahedra are arranged via the number of shared oxygens → different silicate minerals

<table>
<thead>
<tr>
<th>Glassstone (1946)</th>
<th>Element</th>
<th>O</th>
<th>Si</th>
<th>Al</th>
<th>Fe</th>
<th>Mg</th>
<th>Ca</th>
<th>Na</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valence</td>
<td>-2</td>
<td>+4</td>
<td>+3</td>
<td>+2</td>
<td>+2</td>
<td>+2</td>
<td>+1</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>Ionic Dia. (Å)</td>
<td>2.8</td>
<td>0.9</td>
<td>1.0</td>
<td>1.5</td>
<td>1.3</td>
<td>2.0</td>
<td>1.9</td>
<td>2.65</td>
<td></td>
</tr>
</tbody>
</table>

\[ 1 Å = 10^{-8} \text{cm} = 10^{-9} \text{m} \]
2.3 Silicate Frameworks & Composition of Granular Soils

Tetrahedra form 3-D array so that all oxygen are shared — one Si per two oxygen. Very resistant to weathering — large particle.

1. Quartz \( \text{Si}_2\text{O}_5 \times 4 = \text{Si}_4\text{O}_8 \)
2. K Feldspar \( \text{KAl}\text{Si}_3\text{O}_8 \)
3. Plagioclase

Relative abundance in sand & silt size particles. See Sheet A for other "granular" minerals, e.g. Calcite = 4, Dolomite = 5, Muscovite = 6.

2.4 Building Blocks of Clay Minerals

1) All basal oxygen of silica tetrahedra are shared

\[
\begin{align*}
\text{Silica Sheet} & = \quad \text{Silica Sheet} \\
4\text{Si}_2\text{O}_3 & - 20 \\
\text{Silica Sheet} & = -4
\end{align*}
\]

Still not useful; therefore continue with octahedral sheets.

2) Hydrous oxide octahedral sheets

- **G = Gibbsite** \[ 6\text{OH}^{-1} \]
  \[ 4\text{Al}^{3+} \]
  \[ 6\text{OH}^{-} \] \( \text{Al}_4(\text{OH})_2 \) minus some OH's

- **B = Brucite** \[ 6\text{OH}^{-} \]
  \[ 6\text{Mg}^{2+} \]
  \[ 6\text{OH}^{-} \] \( \text{Mg}_6(\text{OH})_2 \) " " "

3) Which silica & hydrous oxide sheets are combined (via primary valence bonding) to form a LAYER and how these layers are "glued" together to form particles — different clay minerals
2.5 Types of Bonds

1) Primary Valence (Covalent, Ionic, Metallic) = very strong (15-100 kcal/mol)

2) Hydrogen bonding = intermediate (= 4-5 kcal/mol for water)

3) Van der Waals = universal attractive force (= 1×10^5 of H-bonds)

\[ \text{Water} = H_2O ; \text{Dipole} \quad \text{H}_4\text{O}_7^{105°} \rightarrow \text{(+)} \]

2.6 Common Clay Minerals with Two Sheets per Layer (Sheet A+B)

1) Kaolinite \((\text{Al}_2) [\text{Si}_4] \text{O}_8 (\text{OH})_8\)

\[ \text{Gibbsite} - 4\text{OH} \rightarrow \text{Al}_4(\text{OH})_8 \]

\[ \text{Strong glue between layers (H-bonding + van der Waals)} \]

\[ \text{produces large hexagonal platy shaped particles} \]

**Edge View**

\[ l = 1000Å \quad (140 \text{ layers}) \quad \{ \text{SSA} = 10 \text{ m}^2/\text{g} \} \]

\[ l = 10,000Å = 1 \mu\text{m} \rightarrow \frac{t}{l} = 1/10 \]

- Weathering conditions: High rainfall, good drainage, low pH, SiO₂ rich, genetic and
- Used for pottery in Kasapetis; tamped for lab experiments

2) Halloysite

\[ = 10Å \]

\[ \text{Some basic compaction as kaolinite, but } 4\text{H}_2\text{O} \]

\[ \text{molecules trapped between layers during} \]

\[ \text{formation (hydrated form). Air drying removes} \]

\[ \text{this water} \rightarrow \text{dehydrated form} \]

- Due to slight misalignment in crystal structure of \(\text{G}+\text{Si} \)

\[ \text{sheets, get pronounced warping} \rightarrow \text{hollow tube particles} \]

- Tubular particles + trapped \(\text{H}_2\text{O} \rightarrow \text{high } \rho \text{ and} \]

\[ \text{low } \rho_d \text{ (even after compaction). But good fill material,} \]

\[ \text{e.g., wpf } = 50\% ; \rho_{\text{max}} = 70 \text{pcf} \]
2.7 Common Clay Minerals with Three Sheets per Layer (Sheet A & B)

1) Muscovite (Mica) \( K_2(Al_4)\left[Al_{2}Si_{4}\right]O_{20}(OH)_4 \)

\[ \text{Geblete - } 3OH^- \rightarrow Al(OH)_2 \]
- During mineral formation, 1 of \( Si^{4+} \) replaced by \( Al^{3+} \) in silica sheet.
- Called Isostructural Substitution (IS)
- Resultant negative charge in layer balanced by potassium cations (\( K^+ \))
- Three \( K \) cations act as a very strong glue between layers \( \rightarrow \) very large plate-like particles (can see mica flakes in some granular soils)
- Consider muscovite as reference mineral for "red" 3:1 clay/layer clay minerals, e.g., illite, montmorillonite, chlorite, etc.

2) Illite (Hydrous Mica) \( K(Al, Mg, Fe)_{4-x}\left[Al_{2}Si_{8}\right]O_{20}(OH)_4 \)

- Basic structure of mica altered due to
  - either \( G \) or \( B \) for octahedral sheet
  - less isomorphous substitution of \( Al \) for \( Si \)
  - less \( K \) glue \( \rightarrow \) much smaller particles

\[ t \approx 100 \AA \]
- Flaky (plate) shaped particles
- \( l \approx 3000 \AA = 0.3 \mu \) (10 layers)
- SSA \( \approx 80 \, \text{m}^2/\text{g} \)
- \( \frac{t}{l} \approx 1/30 \)

- Most common clay mineral. Especially dominant in old chernozem, marine clays, such as Champlain clays in E Canada and Boston Blue Clay
3) Montmorillonite (Part of Smectite group) \( (A_{3.3}Mgo_{7}) [Si_8]CO_{20} (OH)_4 \)

- Relatively small amount of IS of Mg\(^{2+}\) for Al\(^{3+}\) in gibbsite sheet + larger separation of mineral/plate charges
- Relatively low negative charge in layer is balanced by exchangeable cations, i.e., Na\(^{+}\) can be replaced by Ca\(^{2+}\) or Mg\(^{2+}\), etc.
- Common mineral in arid regions from weathering of volcanic ash, alkaline igneous rocks, etc.
  (Gulf of Mexico, etc.)

(a) Sodium Montmorillonite (Bentonite)

- \( \text{Na}^{+} \) cations do not glue layers together. Hence can get one layer = flaky shaped particle
- \( SSA \approx 800 \text{ m}^2/g \) (69 = area of football field)
- Was used as axle grease; now used for drilling mud, slurry walls, etc.
- Major problem soil since highly expansive & may lose residual \( \Phi'_0 \) (\( \Phi'_1 \))

(b) Montmorillonite with other exchangeable cations

- Ca\(^{2+}\), Mg\(^{2+}\), Fe\(^{3+}\) act as moderate glue that can restrict interlayer spacing to \( \approx 5-10 \text{ Å} \) and hence greatly reduce effective SSA. However, may still be expansive and have rather low \( \Phi'_0 \)

4) Chlorite (Sheet B)

- Variation of I or M where positively charged Brucite sheet (\( \text{Ca}^{2+}, \text{magnesium} \)) provides very strong glue between layers = very small SSA. Fairly common in marine illite clays

5) Vermiculite (Sheet B)

- Variation of mica where K replaced by Ca or Mg cations, which greatly reduces bonding between layers so that can have one layer = particle
- Hence very high SSA. However, not very common clay mineral
2.8 Relationship Between Soil Composition and Engineering Properties

1) Mineralogy does strongly affect the size and shape of particles in soil. For cohesive soils, knowledge of the composition is helpful in predicting and/or explaining unusual or adverse behavior, e.g.
   - Halloysite → very low φ
   - Montmorillonite → highly expansive
   - Illite → quick clays (Part II-2)

2) However, composition per se cannot predict the engineering properties of most cohesive soils because of the following complicating factors:
   (a) Variation in particle size of same mineral
      - Quartz: from stone size to all silt size (Rock Hour)
   (b) Cementing agents (e.g., CaCO₃, Al/Fe oxides, organic matter) cause aggregation of particles → much lower effective SSA
   (c) Usually have several minerals in most soils
      - Take 50-50 mixture
        - Clay → very low k
        - Sand and clay
      - Sand → very high φ
   (d) Effect of pore fluid composition, e.g., type, concentration of cations, pH, etc.
      (covered in Part II-2)

3: INDEX PROPERTIES TO GROUP SOILS WITH SIMILAR ENGINEERING PROPERTIES

3.1 Objective

1) Want relatively simple tests in order to determine:
   1st The Soil Type
   2nd Its Relative State

Then can expect similar engineering properties, e.g., Coefficient of permeability, compressibility, strength

2) Will present a simplified approach and distinguish between Granular versus Cohesive soils
3.2 Granular Soils

1) Soil Type: Use particle size distribution ASTM D422

- GR.: SAND
- FINEST (See Section 4.2)

![Particle Size Distribution Diagram]

- Smallest Size (Related to k)
  - $D_{10}$ or % Fines (% No. 200 sieve = 75µm)
- Gradation (Related to Δk range)
  - Coef. of Uniformity, $C_u$
  - $C_u = \frac{D_{60}}{D_{10}}$
  - $\gamma_{5:1}$: well graded
  - $< 2$: uniform

2) Relative State: Use Relative Density, $D_r$ (See Table 3.2.3.3)

- Void Ratio
  - $Q_{\text{max}} (D_r = 100)$
  - $D_r = \frac{Q_{\text{max}} - Q}{Q_{\text{max}} - Q_{\text{min}}}$
  - $Q_{\text{min}}$ (max. density) via ASTM D4253
  - (vibrating in mold with surcharge load)
  - $Q_{\text{min}}$ (D = 100%)
  - $\text{e}_{\text{max}}$ (min. density) via ASTM D4254
  - (pour through funnel into mold)

- $D_r > 70\%$ is "dense"; $D_r < 30\%$ is "loose" (worrisome
  liquefaction during earthquake)

3) Empirical correlations for granular soils

- $K$ (cm/sec) = $[D_{10} (mm)]^2$
  - Very good for loose, fairly uniform sands
- See Sheet C for estimation of initial density & drained friction angle ($\phi'$)

* Sieve No. 4 8 10 16 20 30 40 50 60 100 140 200
- Dia. (mm) 4.75 2.36 2.00 1.18 0.85 0.60 0.425 0.30 0.25 0.15 0.106 0.075
### 3.3 Cohesive Soils

**1) Soil Type: Use Afterberg Limits via ASTM D4318**

- **Tests run on remolded soil passing #40 sieve.**
  - **Note:** Best to start with soil at \( W_s \) because air/oven drying can reduce \( W_s \) & \( I_p \) of soils containing organic matter, smectite, Al/S Fe oxides, etc.
  - \( W_s \) corresponds to low undrained shear strength \( \sigma_u = 20 \text{ kPa} = 40 \text{ psf} \approx 2 \text{ kPa} \) (ide brittle at room temperature)
  - \( W_p \) when soil loses ability to deform plastically (crumbling of 3.2 mm = 1/8 in. thread of nail)
  - \( W_s \) = computed or in 5=100% after oven drying cube of saturated soil
  - **Activity = \( \frac{I_p}{(W_s - W_p)} \)**
  - **Above A-Line = Inorganic Clays**
    - High oven dried strength
    - Very low \( k \) = Tough at \( W_p \)
  - **Below A-Line = Silt & Organic Soils**
    - Very friable as \( W_s \to W_p \)
    - Lower oven dried strength
    - 1. Marine illitic clays (BBC)
    - 2. Baltic smectite clays (full matrix)
    - 3. Arctic soils (Alaska)
    - 4. Mudflat deposits (N.E. Canada)

### Casagrande's Plasticity Chart

- **Ip (%)**
- **WL (%)**

\* 1 atm = 1 kgf/m² = 2000 psf = 1 TSF = 10 TSM = 100 kPa = 1 bar

\* 100 kN/m²
2) Relative State: Use Stress History (current $\sigma'_{vc}$ plus $\sigma'_p$ or OCR)

- Illustrate via 1-D consolidation test starting with soil slurry

Virgin Compression Line (VCL) for Normally Consolidated (NC) Soil
(Large plastic (unrecoverable) deformation)

$\sigma'_{vm} =$ Maximum past vertical stress
($\sigma'_p =$ preconsolidation pressure)

Overconsolidation Ratio =

$OCR = \sigma'_{vm} / \sigma'_{vc}$

NOTE: $\sigma' = \bar{\sigma} = \sigma - u =$ effective stress

Consolidation Stress, $\sigma'_{vc}$ (log scale)

3) Empirical Correlations for Cohesive Soils

a) Coefficient of consolidation, $c_v$: See Sheet D1 (excellent correlation)

b) Virgin compression index, $C_c = -dq/d\log \sigma'_{vc} =$ slope of VCL

$C_c = 0.009 (\mu_s - 10\%)$ (Terzaghi & Peck 1967)

c) Remolded undrained shear strength [$at \mu_s = 16 kPa = 33 psf$]

$S_u (kPa) = 1/(I_2 - 0.2)^2$ (Kerrouci et al 1983, CGJ '80(4))

d) SHANSEP equation for design $S_u$ of homogeneous sedimentary cohesive soils

$S_u/\sigma'_{vo} = S (OCR)^m$

$CL$ and $CH$ clays $S = 0.22 \pm 0.03 \text{ SD}$

$S_a$ and $A$-line $S = 0.25 \pm 0.05 \text{ SD}$

$m = 0.8 \pm 0.1$

a) Drained shear strength (value of $c' \& \phi'$)

See Sheet D2

log $S_u/
\sigma'_{vo}$

$S$

$\log OCR$
4. **UNIFIED SOIL CLASSIFICATION SYSTEM (USCS)**

4.1 **Overview of USCS** (ASTM D 2487)

- # = Sieve size
- % fines = % passing #200 (75μm)

<table>
<thead>
<tr>
<th>Six Main Soil Types</th>
<th>&lt; 5% Fines Gradation</th>
<th>Between Dual</th>
<th>&gt; 12% Fines Plasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 50% passing #200</td>
<td>W = Well graded</td>
<td>Use Both</td>
<td>M = Silt</td>
</tr>
<tr>
<td>G = Gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S = Sand</td>
<td>P = Poorly graded</td>
<td>C = Clayey</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M = Silt</td>
<td>Below A-Line</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 50% passing #200</td>
<td>C = Clay On/Above A-Line</td>
<td>Plasticity Chart</td>
<td></td>
</tr>
<tr>
<td>O = Organic L\text{(\overline{L})} dried \text{(\overline{L})} not dried &lt; 0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pт = Peat Mostly organic matter</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**A-Line**: $PI = 0.73 (LL - 20)$  
**U-Line**: $PI = 0.9 (LL - 8)$

[Plasticity Chart Diagram]

- CH\(_3\)OH
- CL, OL
- ML, OL
- CL-ML
- MH\(_2\)OH
- LL = w\(_L\) (%)
4.2 Details of USC5

See sheet E

4.3 Remarks & Examples

1) Coarse Grained (Granular)
   - Well vs. Poorly graded
     \[ \frac{D_{60}}{D_{10}} > 4 \text{ or } 6 \text{ requires a wide range in particle sizes} \]
     \[ 1 \leq C_c = \frac{(D_{60})^2}{D_{10} \cdot D_{60}} \leq 3 \text{ permits gap grading} \]
     \[ C_c = \text{Coeff of Curvature} \]
   - < 5% Finer, e.g., GW, GP = Well, Poorly graded Gravel
   - > 12% Finer, e.g., SM, SC = Silty, Clayey Sand
   - 5% Finer ≤ 12% = Dual classification for both Gradation & Plascity
     e.g., GW-GM = Well graded Gravel with Silt
     e.g., SP-SC = Poorly graded Sand with Clay

2) Fine Grained (Cohesive)
   - On a Above A-Line
     CL, CH = Lean, Fat Clay
     OL, OH = Organic Clay (CCL = lean, fat Organic Clay)
   - Below A-Line
     ML, MH = Silt, Plastic Silt (CCL = lean, plastic Silt)
     OL, OH = Organic Silt (CCL = lean, plastic Organic Silt)
   - For Both
     if > 30% #200; add "sandy" or "gravelly" before the name
     if 15-29% #200; add "with sand" or "with gravel" after the name
     e.g., Sandy, lean Clay
       \[ \rightarrow \text{e.g., lean Silt with gravel} \]
Composition of Soil

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Dept. of Civil Engr. - M.I.T.

INDEPENDENT TETRAHEDRONS
- Olivine - (Mg, Fe)₂ Si₂O₆
- Sillimanite - Al₂ Si₂O₅
- Zircon - Zr Si₄O₁₂
- Staurolite
- Garnet
- Sphene - Ca Ti Si O₅

DOUBLE TETRAHEDRONS
- Lawsonite
- Tourmaline
- Pyroxene (single)
- Augite
- Amphibole (double)
- Hornblende Polygonalite (Atapulgite)
- Halloysite - Three Sheet
- Talc - Mg₆ Si₈ O₂₀ (OH)₄
- Pyrophyllite - Al₄ Si₄ O₂₀ (OH)₄
- Muscovite - K₂ Al₄ (Al₂ Si₄ O₂₀) (OH)₄
- Biotite Vermiculite
- Illite - K (Al, Mg, Fe)₄ O₆ (Si₈ Al₈ O₂₆) (OH)₄
- Montmorillonite - (Al₃ Mg₆) (Si₈ O₂₆) (OH)₄

RINGS
- Chains
- Sheets
- Frameworks
- Quartz - Si₄ O₈
- K Feldspar - K₂ Si₃ O₈
- Plagioclase - NaAlSi₃ O₈ - Ca Al₂ Si₂ O₈

INORGANIC
- AMORPHOUS
  - Opal
  - Hydrous oxides of Si, Fe, Al

CRYSSTALLINE
- CARBONATES
  - Calcite - CaCO₃
  - Dolomite - CaMg(CO₃)₂
- OXIDES
  - Rutile - TiO₂
  - Magnetite - Fe₃ O₄
- HYDROXIC OXIDES
  - Goethite
  - Gibbsite - Al₆ (OH)₂³
  - Brucite - Mg₆ (OH)₂³
- PHOSPHATES
  - Apophite - Ca₅ (F, Cl, OH) (PO₄)₃
- SILICATES

Numbers refer to order of abundance in sands and silts
(Chayes & Clay Technology, Bulletin 169, 1955)
# Data on Common Clay Minerals

1.322 Soil Technology  
Dept. of Civil Engineering  
M.I.T.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Unit Cell Formula</th>
<th>Structural Symbol</th>
<th>Isomorphous Substitution</th>
<th>Charge Density (meg/lhg)</th>
<th>Interlayer Bonding</th>
<th>Typical Particle Shape</th>
<th>Size</th>
<th>CEC (charge/100g)</th>
<th>SSA (m²/g)</th>
<th>σ (surface charge density)</th>
<th>Var. d(00)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaoalinite</td>
<td>(Al)₄[Si₄]O₁₀(OH)₈</td>
<td></td>
<td>Al for Si, Mg for Al (~1 in 400)</td>
<td>~2</td>
<td>Secondary valence + H-bonding strong</td>
<td>Hexagonal sheets d=3.49µm t=2/3µm</td>
<td>~3</td>
<td>10-15</td>
<td>1.2</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hydrated</td>
<td></td>
<td></td>
<td>As above</td>
<td>~8</td>
<td>As above except weak if larger spacing</td>
<td>Hollow tubes d=0.06µm l=0.05µm</td>
<td>~12</td>
<td>30-50</td>
<td>1.8</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Dehydrated</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscovite</td>
<td>K₂(Al₂Si₃)O₇(OH)₂</td>
<td></td>
<td>As above</td>
<td>~2</td>
<td>K-bonding + sec. vol. very strong</td>
<td>Platy Very large</td>
<td>3-10</td>
<td>1-10</td>
<td>2.2</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>(Mica)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vermiculite</td>
<td>(Mg,Al,Fe)₆[Si₄]O₉·[Si₂,Al₈]O₄(OH)₂·1.5H₂O</td>
<td></td>
<td>Mainly Al for Si (~3/11) Also Mg, Fe for Mg</td>
<td>150±20</td>
<td>Weak primary val. (Ca, Mg) + sec. val. weak</td>
<td>Sheets Variable</td>
<td>150</td>
<td>700-1000 when expanded</td>
<td>2.2</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Illite</td>
<td>K₆(Al₃Mg₃)O₁₀(OH)₆</td>
<td></td>
<td>Mainly Al for Si (~3/11) Also Mg, Fe for Mg</td>
<td>~150</td>
<td>K-bonding + sec. vol. Fairly strong</td>
<td>Flakes d=1.2µm t=0.1µm</td>
<td>25</td>
<td>80-100</td>
<td>1.5</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>(Hydrous mica)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>(Al₂₃Mg₀.₃)[Si₄]O₂₀(OH)₄</td>
<td></td>
<td>Mainly Mg for Al (~1 in 4)</td>
<td>100</td>
<td>Weak secondary valence</td>
<td>Sheets d=1.1µm t=0.1µm</td>
<td>95</td>
<td>700-800</td>
<td>0.75</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Montmorillonite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td>(Mg,Al,Fe)₆[Si₄]O₉·[Si₂,Al₈]O₄(OH)₂·1.5H₂O</td>
<td></td>
<td>Al for Si, Mg for Al, Fe for Mg in B⁺</td>
<td>200-250</td>
<td>Primary valence via B⁺ sheet Very strong</td>
<td>Platy Variable</td>
<td>2-40</td>
<td>5-30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Charge density = charge/formula A10⁺  
(2) CEC = cation exchange capacity  
(3) SSA = specific surface area  
(4) σ = surface charge density  

- Octahedral / Tetrahedral Sheets  
- Unit Layer = 2 or 3 sheets  
- Particle = Σ layers

Mineral Formula Wet:  
Kaoalinite 517  
Talc 750  
Pyrophyllite 710
**Correlations Of Strength Characteristics For Granular Soils**

Adapted from NAVFAC DM-7.1 (5/82) p 7.1 - 149

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**Friction Angle (Schmertmann, 1975)**

Coarse, Angular, Well-graded

Fine, Rounded, Uniform

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**Angle of Internal Friction Vs Density (For Coarse Grained Soils)**

Φ° Obtained from effective stress failure envelopes approximate correlation is for cohesionless materials without plastic fines

ML
SM and SP
GW
GP
SW

Relative Density 100%
55%
50%
25%
0
ML
SM and SP
GW

Dry Unit Weight (γ_d), PCF

(G = 2.68)

Void Ratio, e

Porosity, n

---

Correlations Of Strength Characteristics For Granular Soils

Adapted from NAVFAC DM-7.1 (5/82) p 7.1 - 149
Coefficient of Consolidation Vs Liquid Limit

Adapted from NAVFAC DM-7.1 (1982)

Undisturbed Samples:
- \( C_v \) in Range of Virgin Compression
- \( C_v \) in Range of Recompression Lies Above this Lower Limit

Completely Remolded Samples:
- \( C_v \) Lies Below this Upper Limit

Comparison of field and laboratory undrained strength ratios for nonvarved sedimentary soils (OCR = 1 for laboratory \( CK_o U \) testing)

Adapted from Ladd (1991), JGE, ASCE, 117(4)
Peak Strength against Effective Normal Stress Relationship of London Clay Sample from 35 m Depth (Data from Bishop et al. 1965)

Relationship between Cohesion Intercept and Preconsolidation Pressure

Adapted from Mesri & Adel - Ghaffar (1993), JGE, ASCE, 119(8)
TABLE 1 Soil Classification Chart

<table>
<thead>
<tr>
<th>Coarse-Grained Soils</th>
<th>Finer Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravels (85+50%)</td>
<td>Clean Gravels (CL)</td>
</tr>
<tr>
<td>LCM (40+25%)</td>
<td>Fines classify as ML or MH</td>
</tr>
<tr>
<td>CLM (40+20%)</td>
<td>Fines classify as CL or CH</td>
</tr>
<tr>
<td>Silt (60+20%)</td>
<td>Clean Sands (CL)</td>
</tr>
<tr>
<td>LCM (30+10%)</td>
<td>Fines classify as ML or MH</td>
</tr>
<tr>
<td>CLM (30+5)</td>
<td>Fines classify as CL or CH</td>
</tr>
</tbody>
</table>

For classification of fine-grained soils and fine-grained fraction of coarse-grained soils.

Equation of "A"-line
Horizontal at PI = 4 to LL = 25.5,
then PI = 0.73 (LL-20)

Equation of "U"-line
Vertical at LL = 16 to
PI = 7, then PI = 0.9(LL-8)