FABRIC AND STRENGTH OF CLAYS
STABILIZED WITH LIME

by
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VOLUME II

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(a) Principal particle size scales

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<th>Diagrammatic Representation of Structure</th>
<th>Si-O Group and Negative Charge</th>
<th>Oxygen to Silicon Ratio</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Island Independent</td>
<td><img src="image1" alt="Diagram" /></td>
<td>(Si$_4$O$_4$)$_4^-$</td>
<td>4:1</td>
<td>Olivines (Mg, Fe)$_2$Si$_2$O$_4$</td>
</tr>
<tr>
<td>Double</td>
<td><img src="image2" alt="Diagram" /></td>
<td>(Si$_2$O$_3$)$_6^-$</td>
<td>7:2</td>
<td>Amermanite Ca$_2$Mg$_2$Si$_5$O$_9$</td>
</tr>
<tr>
<td>Rings</td>
<td><img src="image3" alt="Diagram" /></td>
<td>(Si$_6$O$_8$)$_6^-$</td>
<td>3:1</td>
<td>Benitoite BaTiSi$_3$O$_8$</td>
</tr>
<tr>
<td>Chains</td>
<td><img src="image4" alt="Diagram" /></td>
<td>(Si$_2$O$_3$)$_4^-$</td>
<td>3:1</td>
<td>Pyroxenes</td>
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<tr>
<td>Bands</td>
<td><img src="image5" alt="Diagram" /></td>
<td>(Si$<em>5$O$</em>{10}$)$_6^-$</td>
<td>11:4</td>
<td>Amphiboles</td>
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Figure 2.2
Crystal chemistry of silicates, after Mitchell [5]
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<th>Si-O Group and Negative Charge</th>
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<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheets</td>
<td><img src="image1" alt="Diagram of Sheets" /></td>
<td>((\text{Si}<em>4\text{O}</em>{10})^2)</td>
<td>5 2</td>
<td>Micas</td>
</tr>
<tr>
<td>Frameworks</td>
<td><img src="image2" alt="Diagram of Frameworks" /></td>
<td>((\text{Si}_2\text{O}_5)^2)</td>
<td>2 1</td>
<td>Quartz</td>
</tr>
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Also feldspars, for example, orthoclase, \(\text{KASi}_3\text{O}_8\).

Figure 2.2
(continued)
Figure 2.3

(a) Diagrammatic sketch of the kaolinite structure

(b) Charge distribution in kaolinite, after Mitchell [5]
Figure 2.4

(a) Diagrammatic sketch of the montmorillonite structure

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(type structure for montmorillonite, after Mitchell [5])
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(a) Diagrammatic sketch of the structure of muscovite

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<th>LL (percent)</th>
<th>PL (percent)</th>
<th>PI (percent)</th>
<th>Passing 200 sieve (percent)</th>
<th>Clay content (percent)</th>
<th>Dry density (lb/ft³)</th>
<th>Moisture content (percent)</th>
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<tr>
<td>Brickearth (1) Harmondsworth</td>
<td>25</td>
<td>17</td>
<td>8</td>
<td>79</td>
<td>24</td>
<td>111</td>
<td>116</td>
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(a) CYCLIC AND CONTINUOUS FREEZING

![Graph showing continuous and cyclic heave](image)

(b) HEAVE FOR CYCLIC FREEZING

![Graph showing heave for cyclic freezing](image)

**Figure 3.4**

Comparison of continuous and cyclic freezing for silty clay soil, after Croney and Jacobs [80]
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Schematic illustration of upward flow of soil moisture towards ice crystal, after Gillott [4]
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States of colloidal dispersions (upper sketch) and settled volumes (lower sketch):

(a) stable dispersion (b) coagulation,
(c) heterocoagulation, (d) flocculation,

after Ottewill [95]
Figure 4.2

Solubility diagrams for alumina, quartz and calcium hydroxide, after Ottewill [95]
Layer lattice element with Ca ions (cubes) in octahedral positions between OH ions, situated 0.147nm above and below the Ca plane. More exact cell size 0.3593nm. Next layer stacked directly on top, at a distance of 0.4909nm.

Figure 4.3
Crystal Structure of calcium hydroxide, after Grudemo [109]
The C-S-H gel structure consists of a layer based on the CH cell. Cubes represent Ca, tetrahedra Si, circles O or OH. Figure 4.4 shows a mosaic of CH-type cells in the C-S-H layer, with a C/S ratio of 1.68.

Figure 4.4
Structure of C-S-H gel, after Grudemo [109]
A chain of CaO₆ octahedra sharing O-O edges with each other, and individual oxygen atoms with (a) Si₂O₅ groups; (b) Si₄O₁₄ groups and (c) longer Si-O chains

Figure 4.5
Structure of C-S-H gel, after Taylor [131]
Ca–O sheets with attached anions including $\text{Si}_2\text{O}_7$

- Typical spaces containing $\text{Ca H}_2\text{O}$ and anions including compact polysilicate anions.

Figure 4.6
Suggested structure for C-S-H, after Taylor and Roy [108]
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Suggested C-S-H gel structure, illustrating bonds between and along sheets and polymerization of silicate chains, after Ramachandran et al. [140]
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x: Intracrystallite pore,
o: Intercrystallite pore
•: Mono layer water

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Thermogravimetric results for Red-Marl
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A-talc, B-muscovite, C-sericite, D-pyrophyllite, E-muscovite
F-glauconite, G-fine-ground muscovite, H-illite,
I-illite, Fithian, Illinois, U.S.A., J-illite, South Wales,
K-muscovite, Goshen Massachusetts, U.S.A., after Mackenzie [182]
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Scanning electron micrographs of the Red-Marl

(a) X2000, (b) X5000
Figure 7.6

EDAX results from TEM studies of soil particles showing illite and chlorite compositions
Illite

\[ \text{K}_0.6 \text{Ca}_{0.12} (\text{Al}_{1.76} \text{Fe}_{0.17}) (\text{Al}_{0.63} \text{Si}_{3.37}) \]

Chlorite

\[ \text{K}_0.71 \text{Ca}_{0.27} (\text{Al}_{1.79} \text{Fe}_{0.01}) (\text{Al}_{0.98} \text{Si}_{3.02}) \]
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Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in a moist environment at 25°C
Figure 7.21

Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in a moist environment at 50°C
Figure 7.22
Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in a moist environment at 75°C.
Figure 7.23

Variation in compressive strength with lime content for 24 week moist-cured soil-lime cylinders at different temperatures.
Figure 7.24

Plot of unconfined compressive strength against lime content for soil-lime cylinders cured for 12 weeks in a moist environment at 50°C
Figure 7.25

Relationship between pH values and lime content for slurries of Red-Marl after 1 hour at room temperature
Figure 7.26
Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in an unsealed environment at room temperature (\(\sim 20^\circ C\))
Figure 7.27
Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in an unsealed environment at 25°C
Figure 7.28
Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in an unsealed environment at 50°C
Figure 7.29

Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in an unsealed environment at 75°C
Figure 7.30

Variation in moisture content with curing time for the specimens cured at different temperatures in unsealed environments.
Figure 7.31

Plot of unconfined compressive strength against moisture content for untreated Red-Marl cylinders.
Figure 7.32

Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in a nitrogen environment at room temperature (~20°C)
Figure 7.33
Plot of unconfined compressive strength against curing time for soil-lime cylinders of various compositions cured in a carbon dioxide environment at room temperature (~20°C)
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Variation in moisture content with curing period for soil-14 wt% lime specimens cured in nitrogen and carbon dioxide environments.
Variation in weight during curing period for specimens of various compositions cured in a carbon dioxide environment.
Figure 7.36

Effect of delay between mixing and compacting on the unconfined compressive strength of soil - 6 wt% lime cylinders cured for 12 weeks in a moist environment at 25, 50 and 75°C
Figure 7.37

Effect of soil particle size on the unconfined compressive strength for soil-6 wt% lime cylinders cured for 12 weeks in a moist environment at 50°C
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Plot of unconfined compressive strength against curing time for soil-lime - 1 wt% sodium chloride cylinders cured in a moist environment at 25°C
Figure 7.39
Plot of unconfined compressive strength against curing time for soil-lime - 1 wt% sodium chloride cylinders cured in a moist environment at 50°C
Figure 7.40

Plot of unconfined compressive strength against curing time for soil-lime-1 wt% sodium chloride cylinders cured in a moist environment at 75°C
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Figure 7.42 Cumulative pore volume against pore radius for soil - 2 wt% lime specimens cured for 75°C for 1 and 24 weeks.
Figure 7.43 Cumulative pore volume against pore radius for soil - 6 wt% lime specimens cured at 75°C for 1 and 24 weeks
Figure 7.44 Cumulative pore volume against pore radius for soil - 10 wt% lime specimens cured at 75°C for 1 and 24 weeks.
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Figure 7.47
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Figure 7.48

Permeability against lime content for specimens cured at 25°C for 1 and 24 weeks.
Figure 7.49

Permeability against lime content for specimens cured at 50°C for 1 and 24 weeks.
Figure 7.50

Permeability against lime content for specimens cured at 75°C for 1 and 24 weeks
Figure 7.51

Permeability against curing temperature for soil-lime specimens of various compositions cured for 24 weeks
Figure 7.52

Permeability against the percentage porosity contributed by pores of radius greater than 40 nm
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Frost heave against curing time for soil-lime cylinders of various compositions cured at 25°C
Figure 7.54
Frost heave against curing time for soil-lime cylinders of various compositions cured at 50°C
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Frost heave against curing time for soil-lime cylinders of various compositions cured at 75°C
Figure 7.56
Frost heave against lime content for soil-lime cylinders cured for 1 and 24 weeks at 25°C
Figure 7.57
Frost heave against lime content for soil-lime cylinders cured for 1 and 12 weeks at 50°C
Figure 7.58
Frost heave and formation of ice lenses in soil-lime cylinders
(a) soil-2 wt% lime cured for 1 week at 75°C
(b) soil-6 wt% lime cured for 6 weeks at 25°C
(c) soil-10 wt% lime cured for 6 weeks at 50°C
Figure 7.59
Thermogravimetric results for soil and cured soil-lime samples, cured for 24 weeks at 50°C, (A) soil, (B) soil and 6 wt% lime, (C) soil and 10 wt% lime and (D) soil and 14 wt% lime.
Figure 7.60

Plot of the wt% "consumed lime" against the wt% loss of "gel water" in the temperature region 100–250°C
Figure 7.61

Plot of unconfined compressive strength against wt% "consumed lime" for soil-lime specimens cured at 50°C for various times.
Figure 7.62

Scanning electron micrograph of the fracture surface of a 24 week (50°C) cured soil–14 wt% lime sample, X5000
Figure 7.63

Part of the X-ray diffractometer of soil-10 wt% lime sample cured for 1.5 years at 75°C
Figure 7.64

Scanning electron micrographs of the fracture surface of a 1 day (75°C) cured soil-10 wt% lime sample

(a) X2000, (b) X5000
Figure 7.65

Scanning electron micrographs of the fracture surface of a 3 week \(75^\circ\mathrm{C}\) cured soil-10 wt% lime sample

(a) X2000, (b) X5000
Figure 7.66

Scanning electron micrographs of the fracture surface of a 6 week (75°C) cured soil-10 wt% lime sample

(a) X2000, (b) X5000
Figure 7.67

(a) fracture surface of a 6 week (75°C) cured soil - 10 wt% lime sample, X2000

(b) 4 week cured Portland cement, X5000
SEM and EDAX results of the platelets particles formed in a soil - 10 wt% lime sample, cured for 6 weeks at 75°C
Figure 7.69

Scanning electron micrographs of the fracture surface of 12 week (75°C) cured soil-10 wt% lime sample
(a) X5000, (b) X10000
Figure 7.70

Scanning electron micrographs of the fracture surface of 6 month (75°C) cured soil-10 wt% lime sample
(a) X5000, (b) X10000
Figure 7.71

Scanning electron micrographs of the fracture surface of 1 year (75°C) cured soil-10 wt% lime sample
(a) X10000, (b) X20000
Figure 7.72
Scanning electron micrographs of the fracture surface of 18 month (75°C) cured soil-10 wt% lime sample
(a) X10000, (b) X10000
Figure 7.73

Scanning electron micrographs of the fracture surface of 2 year (75°C) cured soil-10 wt% lime sample

(a) X5000, (b) X10000
Figure 7.74

Typical transmission electron micrographs showing gel morphology after one year at 75°C for a soil-10 wt% lime sample
Figure 7.75

(a) Transmission electron micrograph of gel formed in soil 10 wt% lime composite cured in a moist environment at 75°C for one year, (b) EDAX analysis of gel
Figure 7.76
Transmission electron micrograph of typical gel particle together with its electron diffraction pattern

d = 0.293 ± 0.01 nm
Figure 7.77

(a) TEM micrograph of gel formed in soil-10 wt% lime composite cured in a moist environment at 75°C for 1 year

(b) EDAX analysis of gel at point X
Figure 7.78

(a) TEM micrograph of gel formed in soil-10 wt% lime composite cured in a moist environment at 75°C for 1 year

(b) EDAX analysis of gel at point X
Figure 7.79

(a) TEM micrograph of gel formed in a soil-10 wt% lime composite cured in a moist environment at 75°C for six weeks

(b) EDAX analysis of gel at point X
Figure 7.80

(a) TEM micrograph of gel formed on the borders of a quartz particle in a soil-10 wt% lime composite cured at 75°C for 1 year
(b) EDAX analysis at point "A"
(c) EDAX analysis at point "B"
(d) EDAX analysis at point "C"
Figure 7.81

Scanning electron micrographs of the fracture surface of a 12 week (75°C) cured refined Marl-20 wt% lime sample
(a) X5000, (b) X10000
Figure 7.82

DTG traces for refined Marl - 20 wt% lime samples cured for 1 day to 24 weeks at 75°C
Figure 7.83

TG traces for refined Marl-20 wt% lime samples cured for 1 day to 24 weeks at 75°C
Figure 7.84

Plot of reacted lime against curing time for refined Marl - 20 wt% lime samples cured at 75°C
Figure 7.85

(a) TEM micrograph of gel formed in a refined Marl - 20 wt% lime composite, cured for 6 weeks at 75°C

(b) Electron diffraction at Point X, (c) EDAX analysis at point X
Figure 7.86

(a) TEM micrograph of gel formed in a refined Marl - 20 wt% lime composite, cured for 24 weeks at 75°C

(b) Electron diffraction at point "A"

(c) EDAX analysis at point "A"

(d) EDAX analysis at point "B"

(e) EDAX analysis at point "C"
Figure 7.87

Part of the X-ray diffractometer of montmorillonite - 20 wt% lime sample cured for 12 weeks at 75°C

1 Å = 10 nm
Figure 7.88

Thermogravimetric results for montmorillonite - 20 wt% lime sample, cured at 75°C for 12 weeks
Figure 7.89

(a) TEM micrograph of gel formed in a montmorillonite - 20 wt% lime composite cured for 12 weeks at 75°C

(b) Electron diffraction at point X

(c) EDAX analysis at point X
Figure 7.90

(a) TEM micrograph of gel formed in a montmorillonite - 20 wt% lime composite cured for 12 weeks at 75°C

(b) EDAX analysis at point X
Figure 7.91

Parts of the X-ray diffractometer of kaolinite - 20 wt% lime sample, cured for 12 weeks at 75°C
Figure 7.92
Thermogravimetric results for untreated kaolinite and kaolinite-20 wt% lime sample, cured for 12 weeks at 75°C
Figure 7.93

(a) TEM micrograph of gel formed in a kaolinite - 20 wt% lime composite cured for 12 weeks at 75°C (b) Electron diffraction at point X (c) EDAX analysis at point X
Figure 7.94

(a) TEM micrograph of gel formed in a kaolinite-20 wt% lime composite cured for 12 weeks at 75°C

(b) EDAX analysis at point X
Figure 7.95
(a) TEM micrograph of gel formed in a kaolinite - 20 wt% lime composite cured for 12 weeks at 75°C
(b) EDAX analysis at point X
Figure 7.96

Part of the X-ray diffractometer of illite - 20 wt% lime sample cured at 75°C for 12 weeks
Figure 7.97

Thermogravimetric results for illite - 20 wt% lime sample cured at 75°C for 12 weeks
Figure 7.98
Scanning electron micrographs of the fracture surface of illite - 20 wt% lime sample cured for 12 weeks at 75°C
(a) X 5000, (b) X 10000
Figure 7.99

Typical TEM-EDAX analysis of gel formed in illite - 20 wt% lime sample cured for 12 weeks at 75°C

(major composition : Ca$_{1.58}$ Si$_{1.00}$ Al$_{0.15}$)
Crystal structure of Ca(OH)$_2$; arrangement of linked Ca(OH)$_6$ octahedra within a single layer. Parts of three rows of octahedra are shown. The lightly dotted faces of the octahedra are lying flat, with their points away from the observer. Each octahedron has a Ca$^{2+}$ ion at its centre and OH$^-$ ions at each of its six apices; each OH$^-$ ion is shared between three octahedra.

Crystal structure of a single layer of calcium hydroxide. Full circles represent calcium atoms, and large circles, represent oxygen atoms; hydrogen atoms are not shown.

Figure 8.1

Crystal structure of Ca(OH)$_2$, after Taylor [131]
Ideal 2-dimensional Si\textsubscript{2}O\textsubscript{5} net
- Si
- O

For Si-O = 0.16 nm
b = 0.905 nm

Ideal 2-dimensional dioctahedral sheet

For • = Al, Al-O = 0.189 nm
b = 0.801 nm

For • = Al (in Gibbsite)

b = 0.864 nm

Figure 8.2

Representation of an idealized Si\textsubscript{2}O\textsubscript{5} sheet and the idealized dioctahedral sheet
Figure 8.3
SEM micrographs of a 24 week cured soil-10 wt% lime sample at 75°C showing exfoliation and breakdown of the clay layers
(a) X 5000, (b) X 10000
Figure 8.4

SEM-EDAX analysis at point "X"

in Figure 8.3(a)
Figure 8.5

Representation of illite structure
Figure 8.6

Phase development in the system CaO-SiO$_2$-H$_2$O showing the course of cement-pozzolana-water reactions, after Glasser and Marr [192]