Lecture 21

Compacted soil liners

TOWN OF BOURNE, ISWM DEPARTMENT

LANDFILL LINER SYSTEM, PHASE 3

FALL 2000, View of the placement of the low permeability soil.

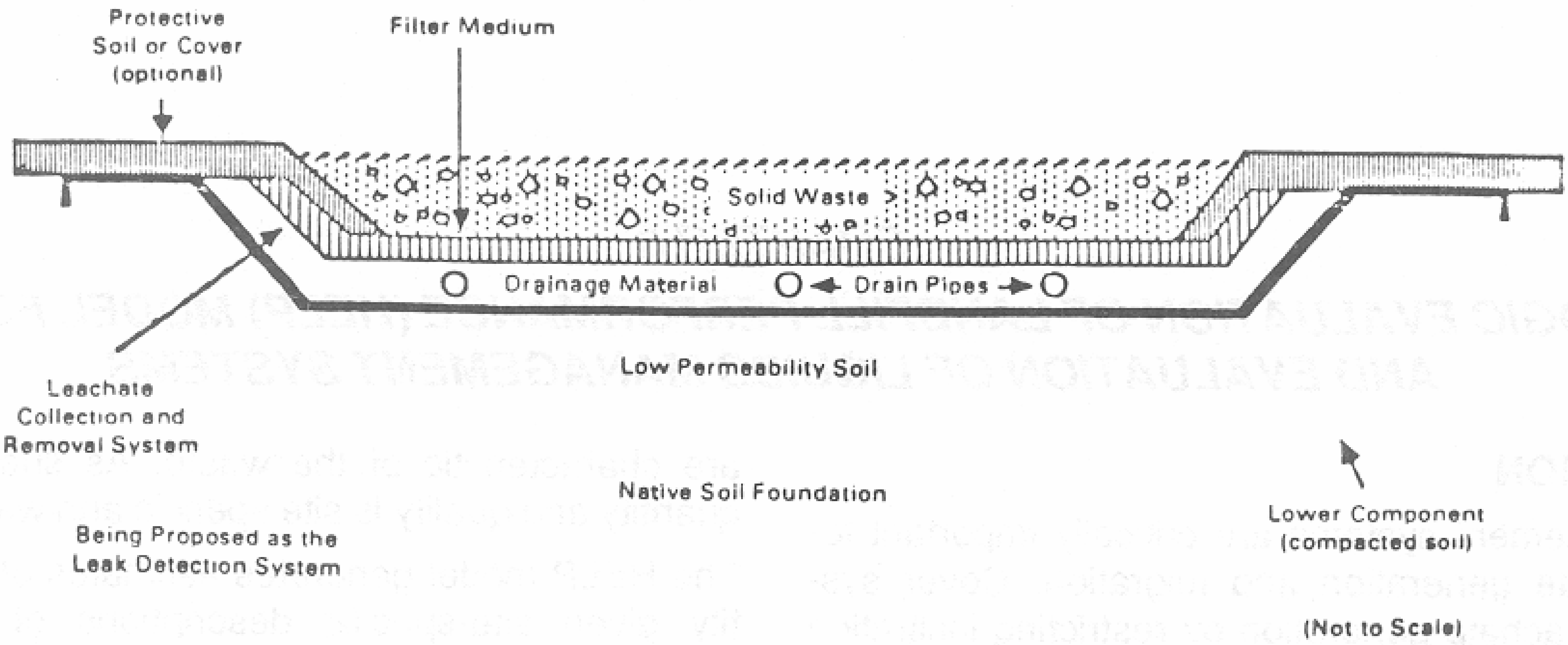
See http://www.townofbourne.com/Town%20Offices/ISWM/Layer2.htm.

Minimal Liner System

1. Leachate collection and removal system (LCRS)
   - Thickness of 1 foot (30 cm)
   - $K > 10^{-2}$ cm/sec
2. Compacted soil liner
   - Thickness of 2 feet (0.6 m) installed in 6-inch (15-cm) lifts
   - Average side slope of 2.5:1 to 3:1 (H:V)
   - Average bottom slope of 2 to 5%
   - $K \leq 10^{-7}$ cm/sec

Not from any specific regulations, but the minimal liner in early landfill liners

Minimal Liner System



Source: U.S. EPA, 1991. Design and Construction of RCRA/CERCLA Final Covers. Report Number EPA/625/4-91/025. U.S. Environmental Protection Agency, Cincinnati, Ohio. May 1991. Figure 8-2, pg. 74.

Design Objectives for Compacted Soil Liner

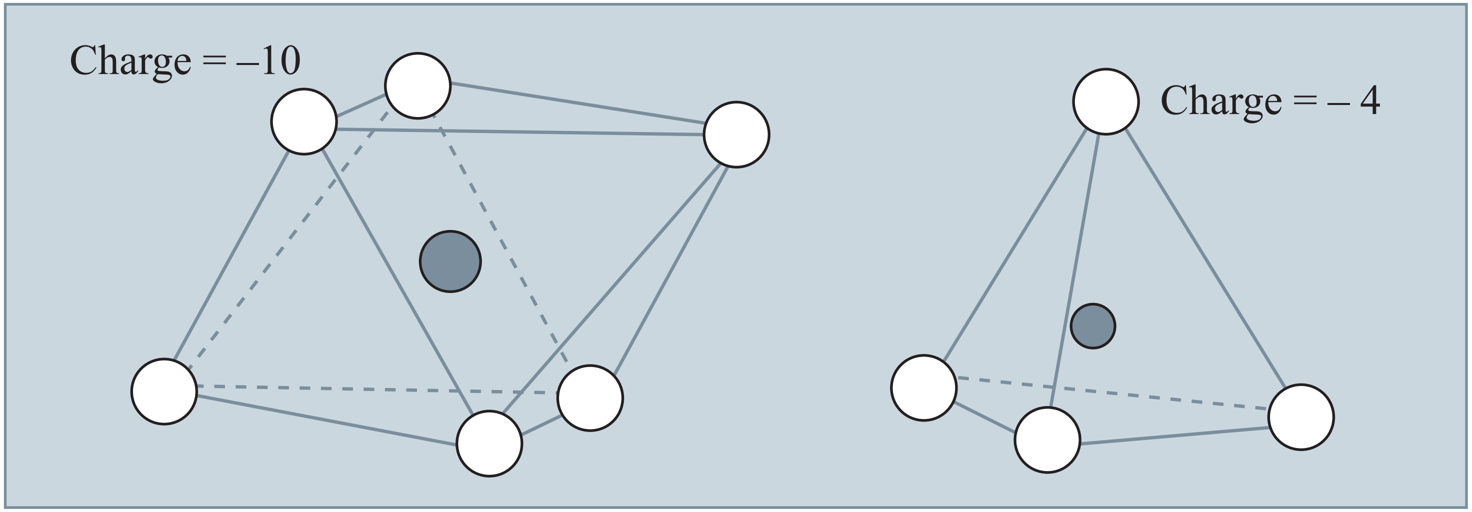
- Low hydraulic conductivity to minimize leakage ($K \leq 10^{-7}$ cm/sec)
- Adequate shear strength to maintain liner stability
- Minimal shrinkage potential to minimize desiccation cracking

Unified Soil Classification System

Major Divisions			Group Symbol	Group Name
Coarse grained soils more than 50% retained on no. 200 sieve	Gravel more than 50% of coarse fraction retained on no. 4 sieve	Clean gravel	GW	Well-graded gravel, fine to coarse gravel
			GP	Poorly-graded gravel
		Gravel with fines	GM	Silty gravel
			GC	Clayey gravel
	Sand more than 50% of coarse fraction passes no. 4 sieve	Clean sand	SW	Well-graded sand, fine to coarse sand
			SP	Poorly-graded sand
		Sand with fines	SM	Silty sand
			SC	Clayey sand
Fine grained soils more than 50% passes no. 200 sieve	Silt and clay liquid limit less than 50	Inorganic	ML	Silt
			CL	Clay
		Organic	OL	Organic silt, organic clay
	Silt and clay liquid limit 50 or more	Inorganic	MH	Silt of high plasticity, elastic silt
			CH	Clay of high plasticity, fat clay
		Organic	OH	Organic clay, organic silt
Highly Organic Soils			PT	Peat

Soil groups in BLUE show materials suitable for clay liner construction

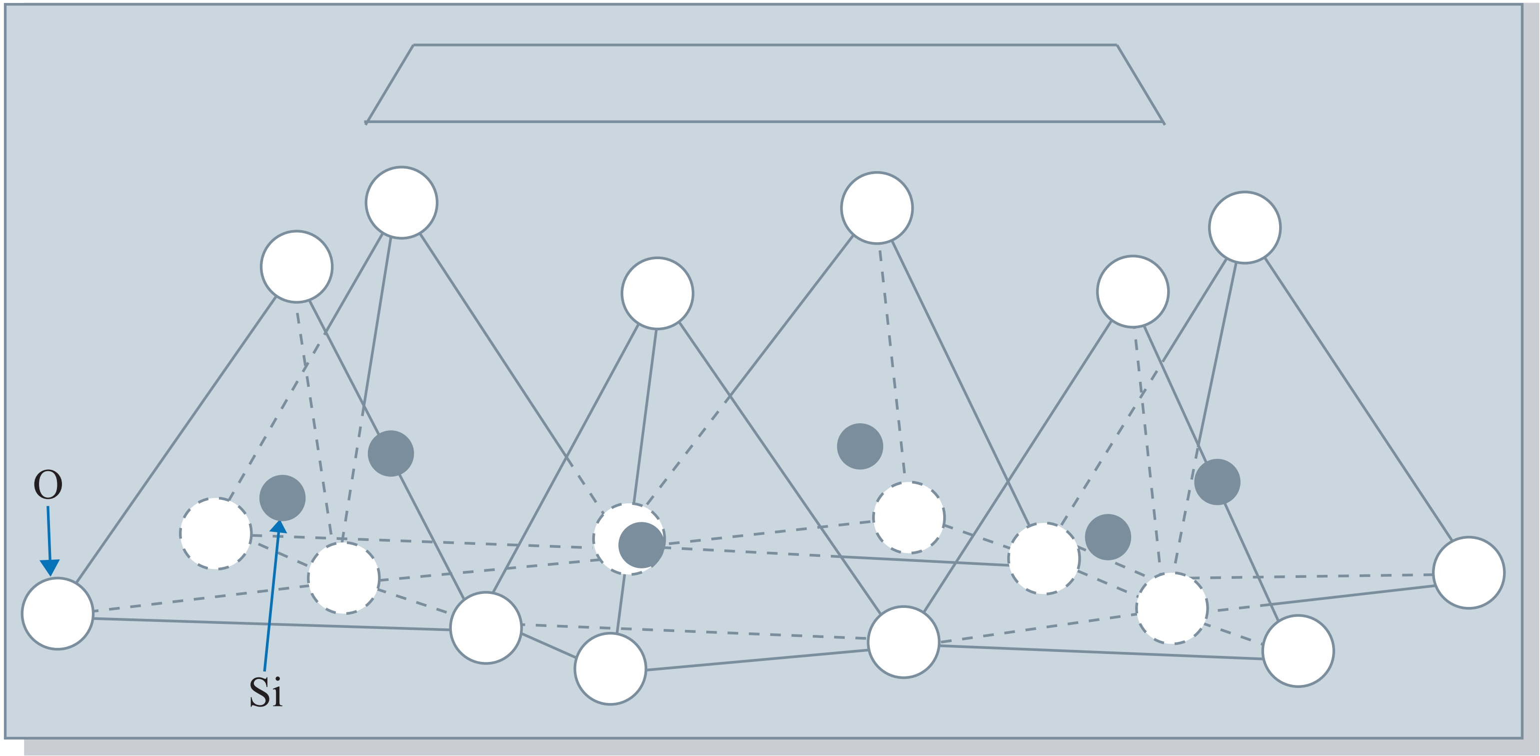
Molecular Structure of Clay



The basic structural units of aluminosilicate clay minerals: a tetrahedron of oxygen atoms surrounding a silicon ion (right), and an octahedron of oxygens or hydroxyls enclosing an aluminum ion (left).

Adapted from: Hillel, D. *Environmental Soil Physics*. San Diego, California: Academic Press, 1998.

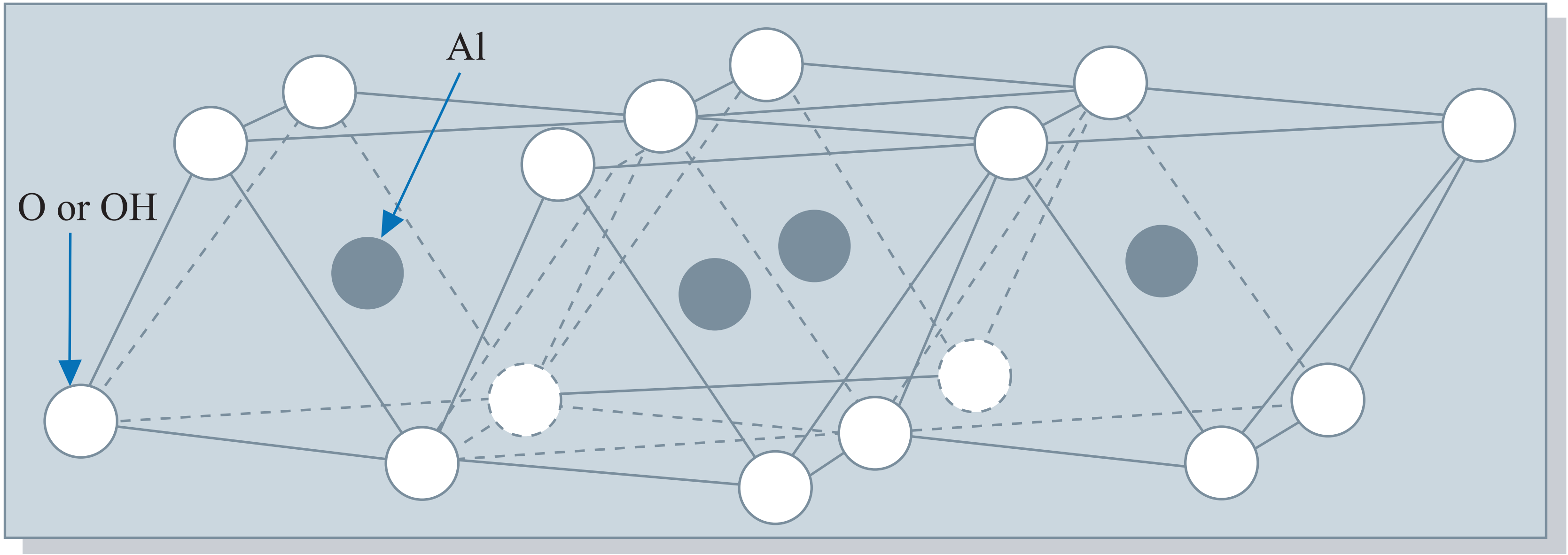
Molecular Structure of Clay



Hexagonal network of tetrahedra forming a silica sheet.

Adapted from: Hillel, D. *Environmental Soil Physics*. San Diego, California: Academic Press, 1998.

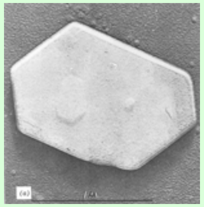
Molecular Structure of Clay

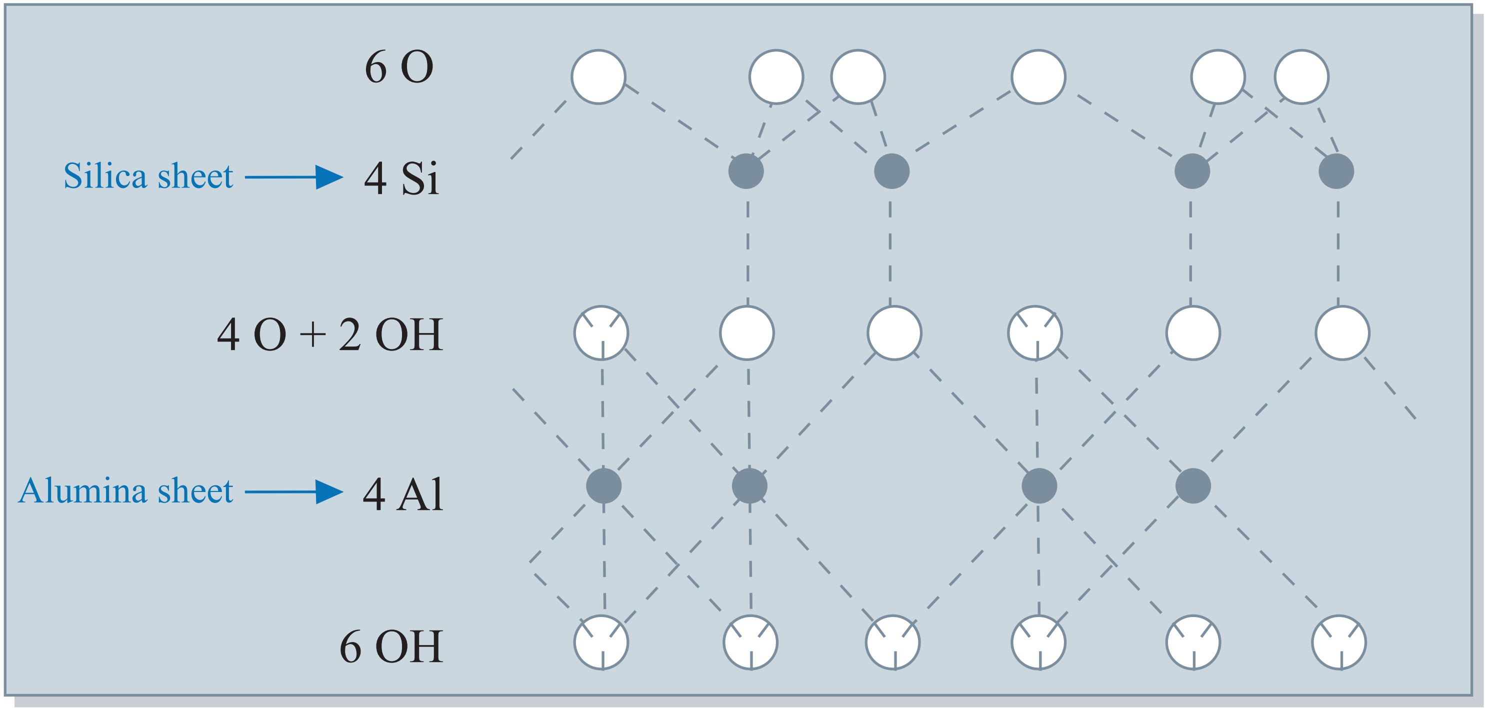


Structural network of octahedra forming an alumina sheet.

Adapted from: Hillel, D. *Environmental Soil Physics*. San Diego, California: Academic Press, 1998.

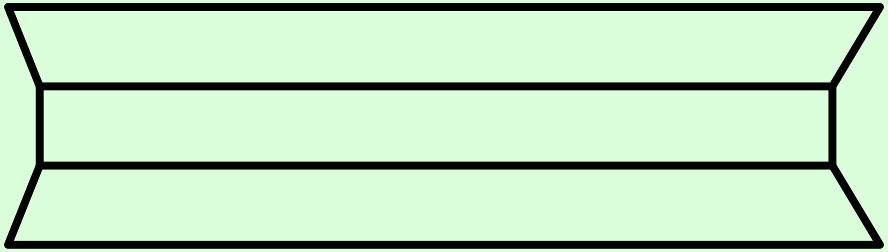
Molecular Structure of Kaolinite

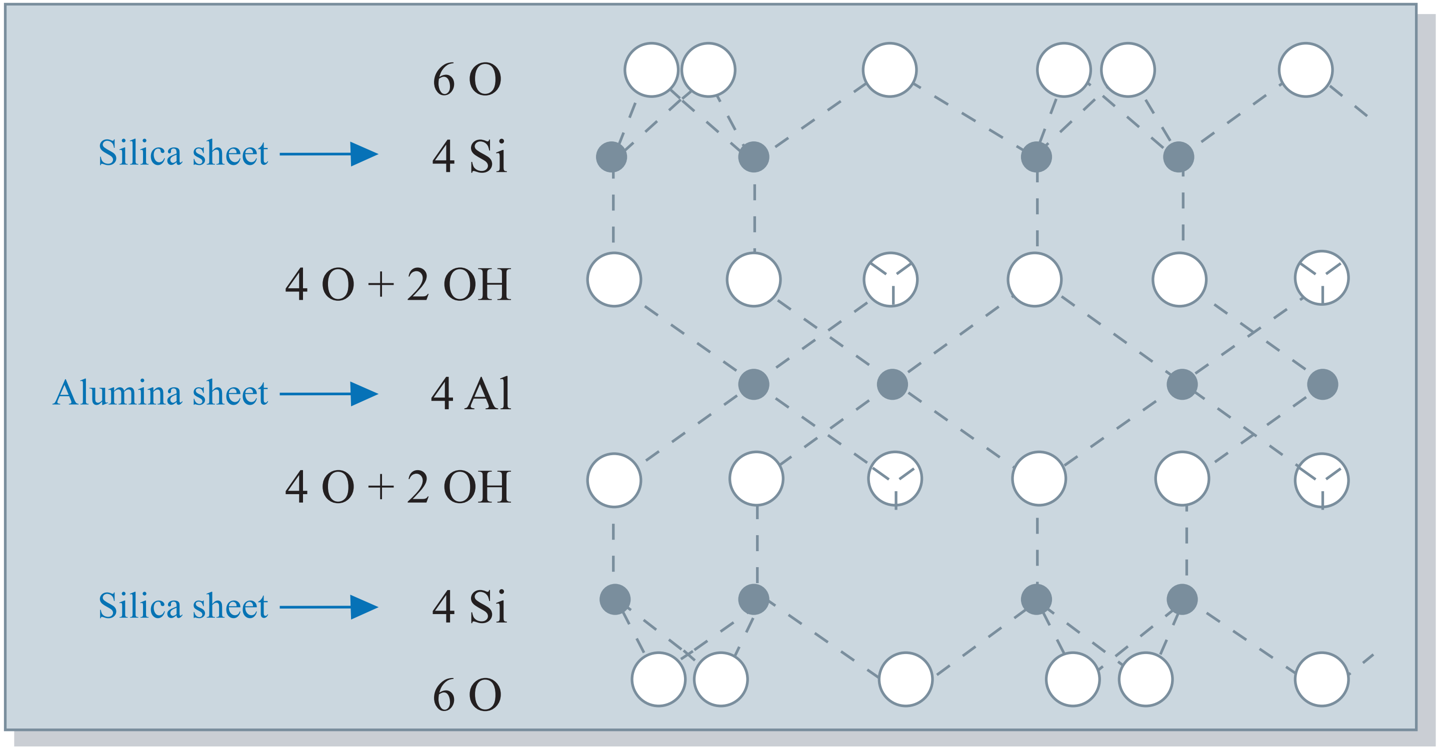




Adapted from: Hillel, D. *Environmental Soil Physics*. San Diego, California: Academic Press, 1998.

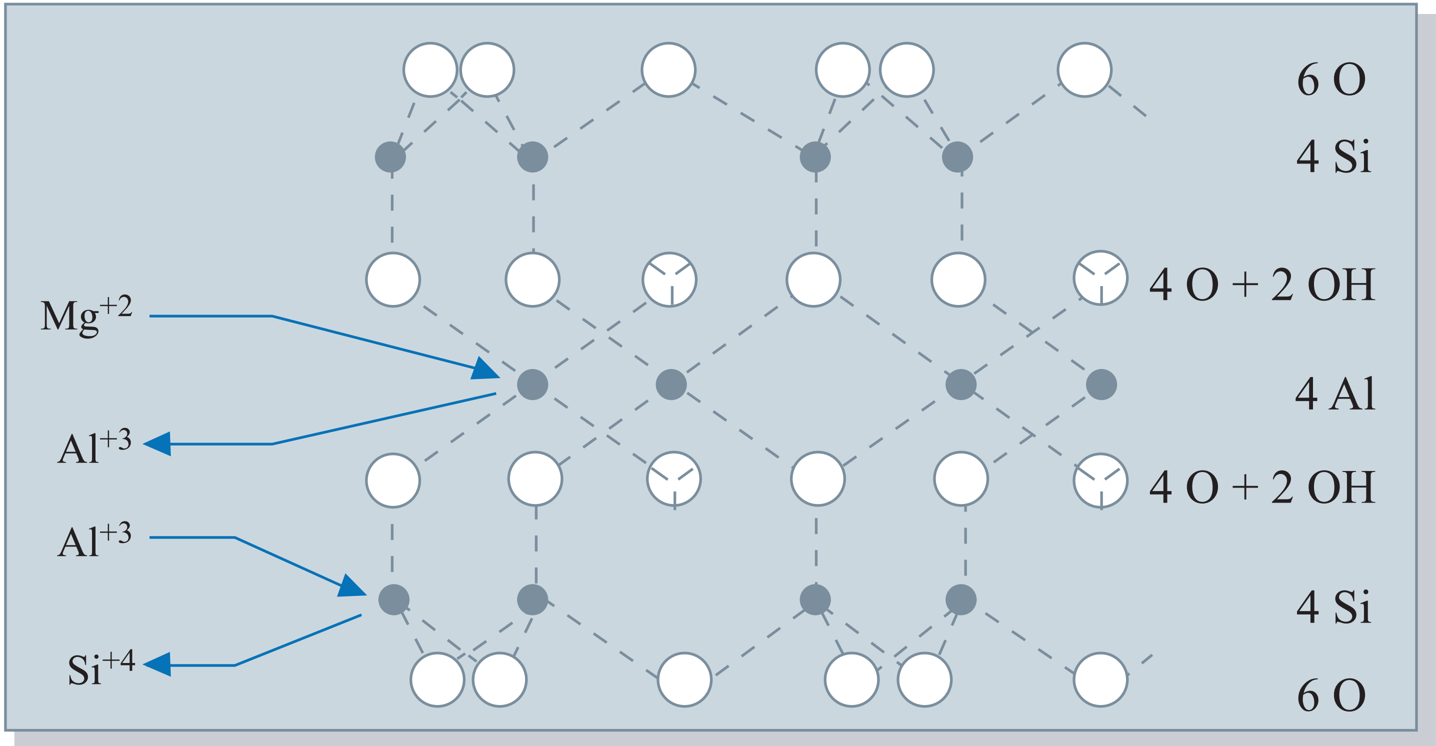
Molecular Structure of Montmorillonite





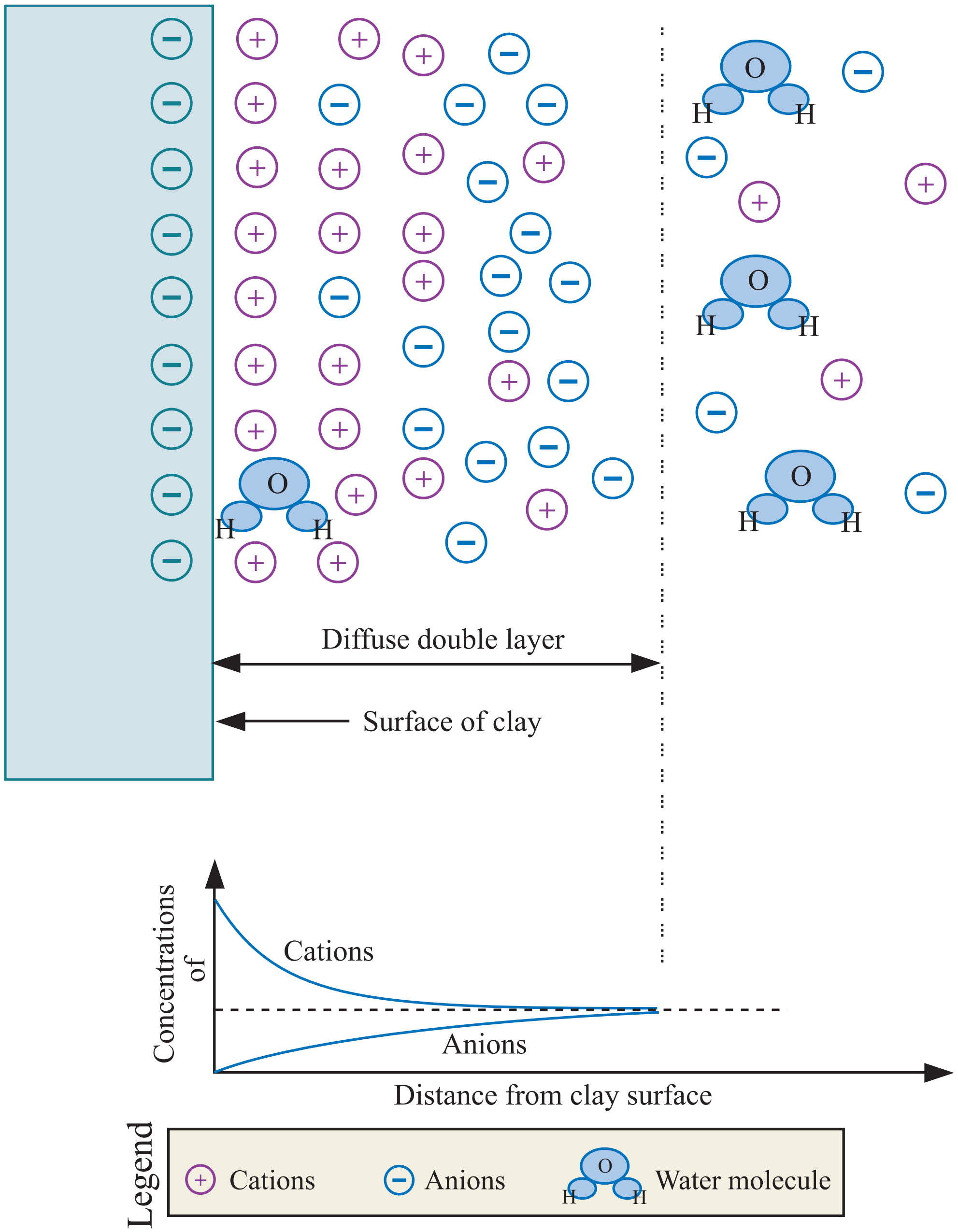
Adapted from: Hillel, D. *Environmental Soil Physics*. San Diego, California: Academic Press, 1998.

Isomorphous Substitution



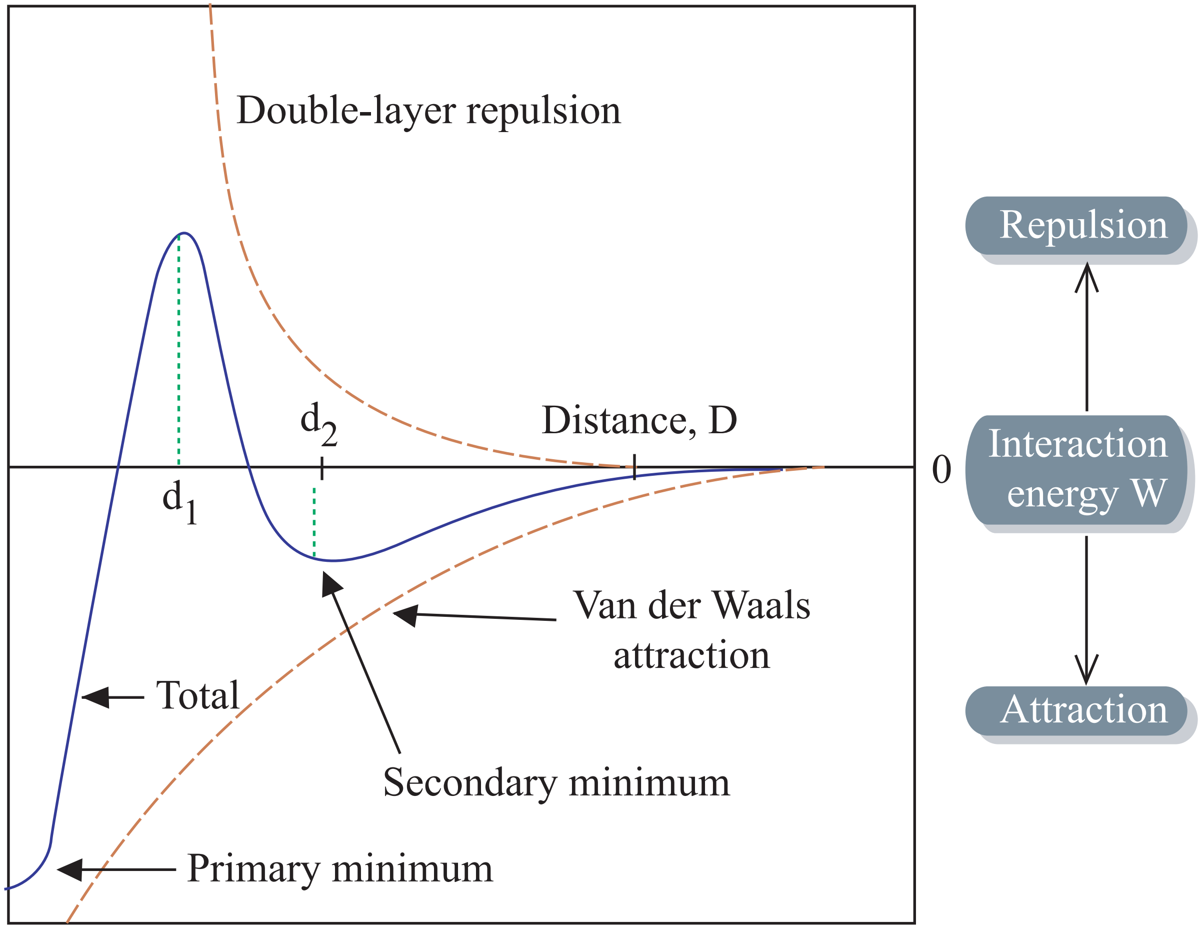
Leads to net negative charge on clay particle.

Charge Structure of Clay



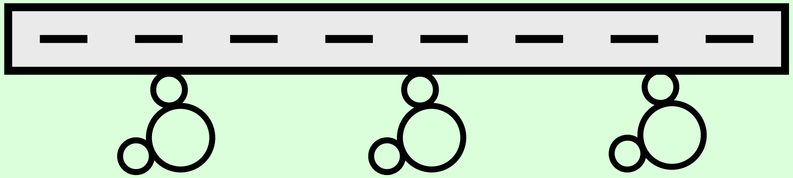
Adapted from: www.bham.ac.uk/CivEng/resproj/ liew/ck2_ht4.gif

Forces between clay particles

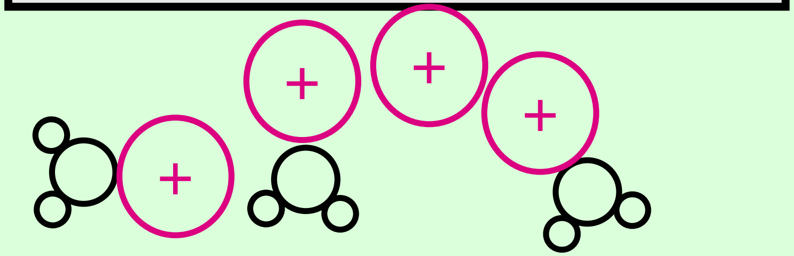


Adapted from: Reddi, L. N., and H. I. Inyang. *Geoenvironmental Engineering*, *Principles and Applications*. New York: Marcel Dekker, Inc., 2000, Figure 2.13, pp. 50.

Attraction of Water to Clay



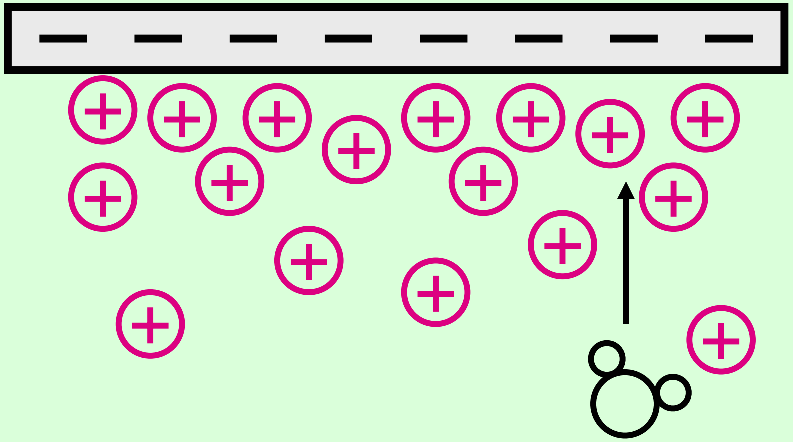
1. Hydrogen bonding



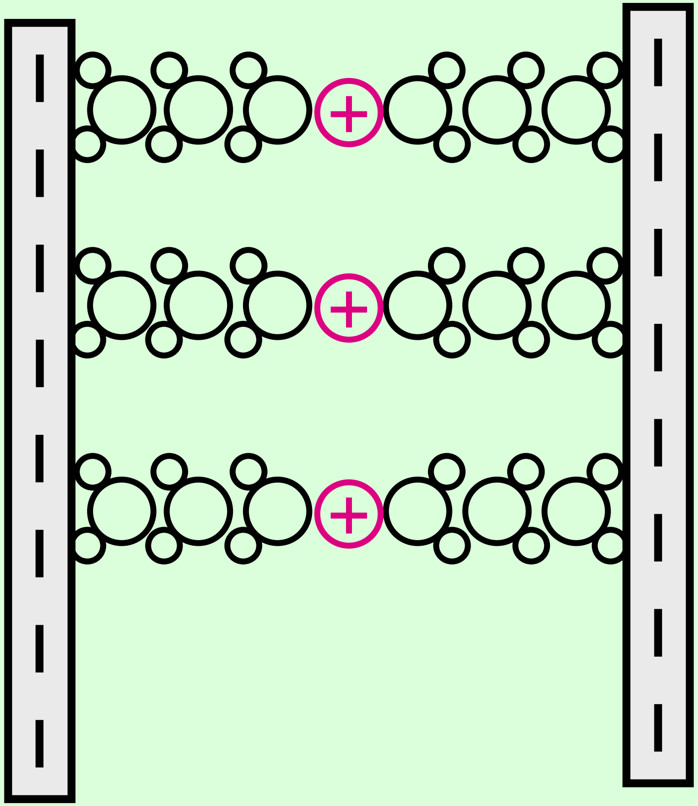
2. Ion hydration

Based on: Reddi, L. N., and H. I. Inyang, 2000. *Geoenvironmental Engineering, Principles and Applications.* Marcel Dekker, Inc., New York, New York. Figure 2.9, pg. 41.

Attraction of Water to Clay



3. Osmosis
(inward diffusion against ion
concentration gradient)

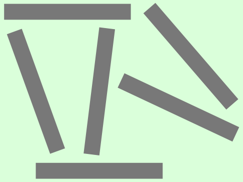


4. Dipole attraction

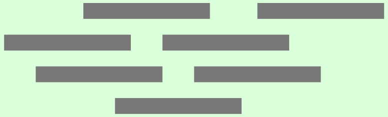
Based on: Reddi, L. N., and H. I. Inyang, 2000. *Geoenvironmental Engineering, Principles and Applications.* Marcel Dekker, Inc., New York, New York. Figure 2.9, pg. 41.

Why does clay have low K?

- Small particle size
- Compact soil fabric (i.e., configuration of clay plates)



Flocculated



Dispersed

Dispersed particles create more tortuous paths and lower K. Flocculated particles creates large channels for flow.

Why does clay have low K?

- Clay chemistry

  Large sodium molecules between clay particles cause clay to swell and plates to disperse – high sodium clays have lowest K

- Double layer holds water which reduces K

Information on clay chemistry from:

The Basics of Salinity and Sodicity Effects on Soil Physical Properties, Information Highlight For The General Public

Adapted by Krista E. Pearson from a paper by Nikos J. Warrence, Krista E. Pearson, and James W. Bauder

Water Quality and Irrigation Management, Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, Montana. Accessed April 25, 2004.

http://waterquality.montana.edu/docs/methane/basics_highlight.shtml

Properties of Low Conductivity Soils

Soil Symbol	Dry Strength	Dilatancy	Plasticity	Toughness
ML – Silt	None to Low	Slow to Rapid	None to Low	Low or thread cannot be formed
CL – Lean Clay	Medium to High	None to Slow	Low to Medium	Medium
MH – Elastic Silt	Low to Medium	None to Slow	Medium	Low to medium
CH – Fat Clay	High to Very High	None	High	High

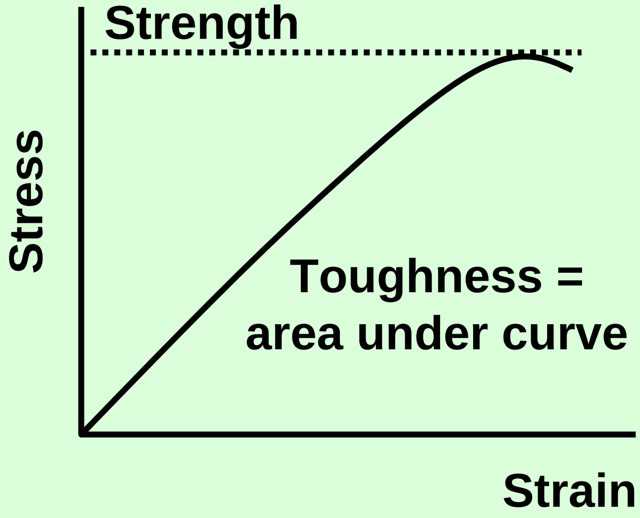
lean clay is only slightly plastic,
whereas **fat clay is** highly plastic

Dilatancy is increase in volume when soil is compressed

Toughness

Strength: Measure of stress needed to break clay

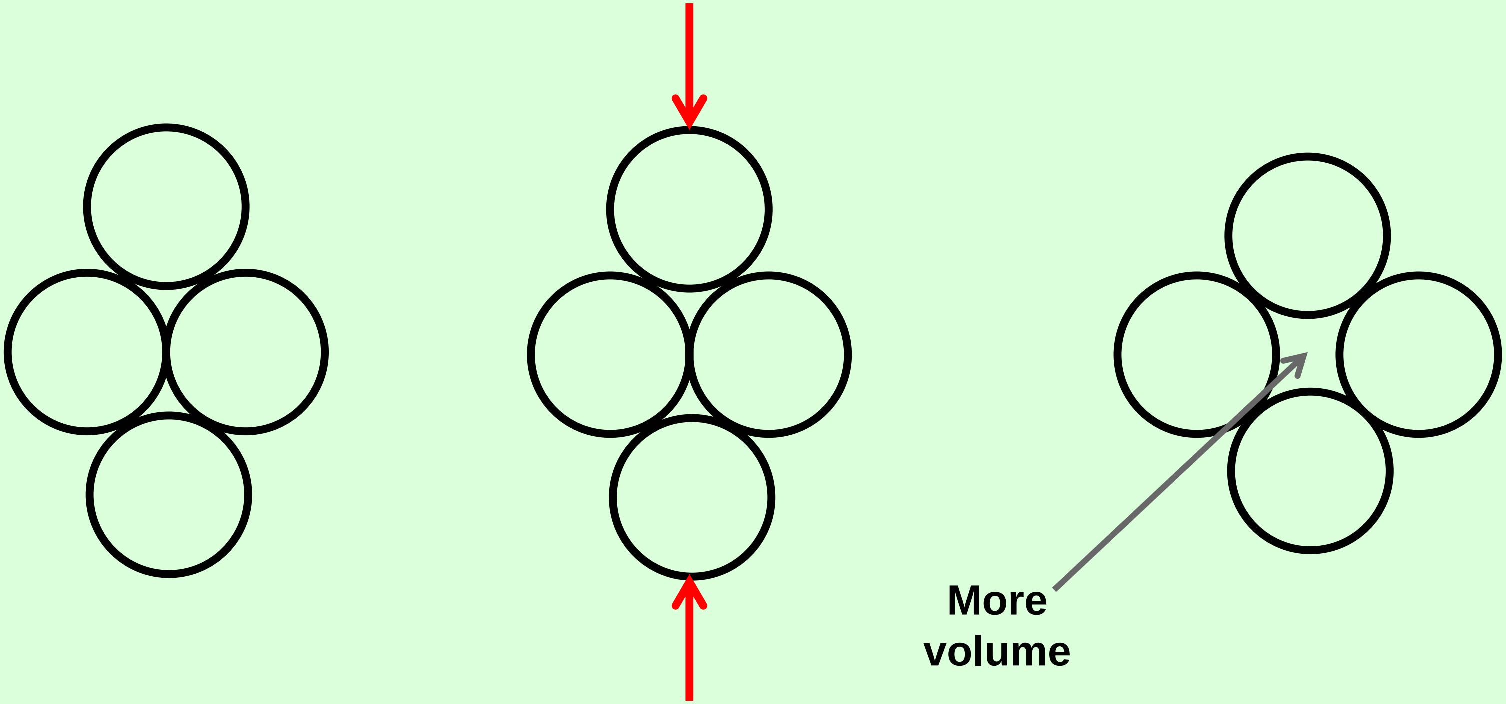
Toughness: Measure of energy needed to break clay



Definitions from: Koehler, K.R., 1996. Stress and strain. Mathematics, Physics and Computer Science, Raymond Walters College, University of Cincinnati, Cincinnati, Ohio. http://www.rwc.uc.edu/koehler/biophys/2f.html. Accessed April 25, 2004.

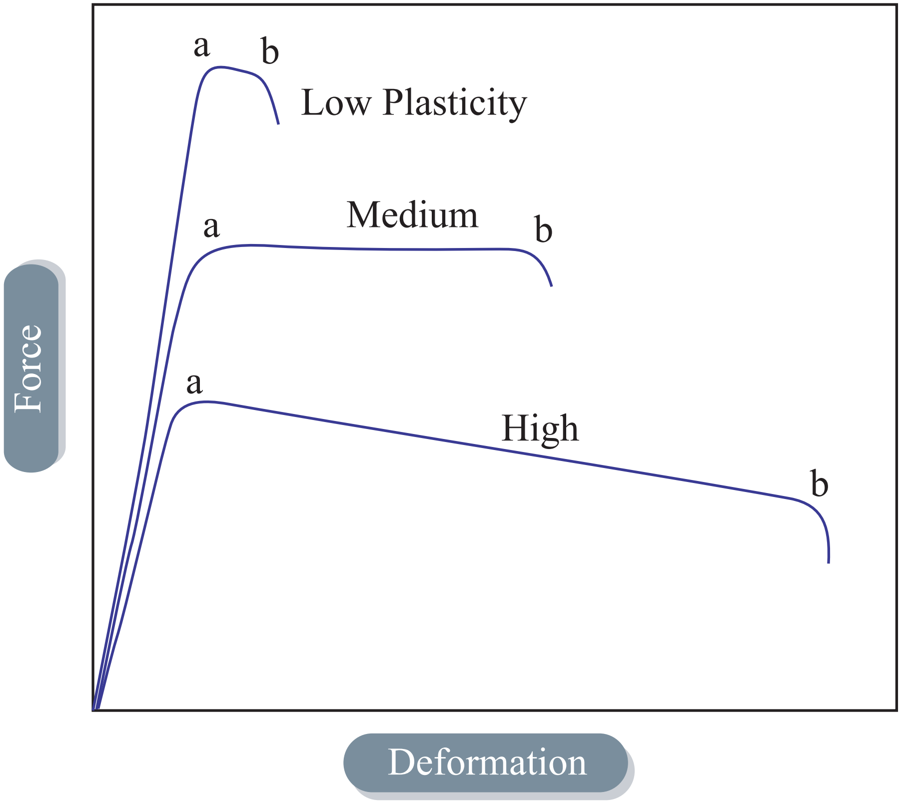
Dilatancy

Dilatancy = increase in volume as result of applied stress



Plasticity

Plasticity is a property of the fine-grained portion of a soil that allows it to be deformed beyond the point of recovery without cracking or changing volume appreciably.



Adapted from: Norton, F. H. "Clay: Why it Acts the Way it Does."
Studio Potter 4, no. 2 (Winter 1975/76).
http://www.studiopotter.org/articles/?art=art0019

Plasticity

Plasticity is a property of the fine-grained portion of a soil that allows it to be deformed beyond the point of recovery without cracking or changing volume appreciably. Some minerals, such as quartz powder, cannot be made plastic no matter how fine the particles or how much water is added. All clay minerals, on the other hand, are plastic and can be rolled into thin threads at a certain moisture content without crumbling. Since practically all fine-grained soils contain some clay, most of them are plastic. The degree of plasticity is a general index to the clay content of a soil.

The term *fat* and *lean* are sometimes used to distinguish between highly plastic and slightly plastic soils. For example, lean clay is only slightly plastic, whereas fat clay is highly plastic. In engineering practice, soil plasticity is determined by observing the different physical states that a plastic soil passes through as the moisture conditions change. The boundaries between the different states, as described by the moisture content at the time of change, are called consistency limits or Atterberg limits.

The liquid limit (LL) is the moisture content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil. Above this value, the soil is presumed to be a liquid and behaves as such by flowing freely under its own weight. Below this value, it deforms under pressure without crumbling, provided the soil exhibits a plastic state.

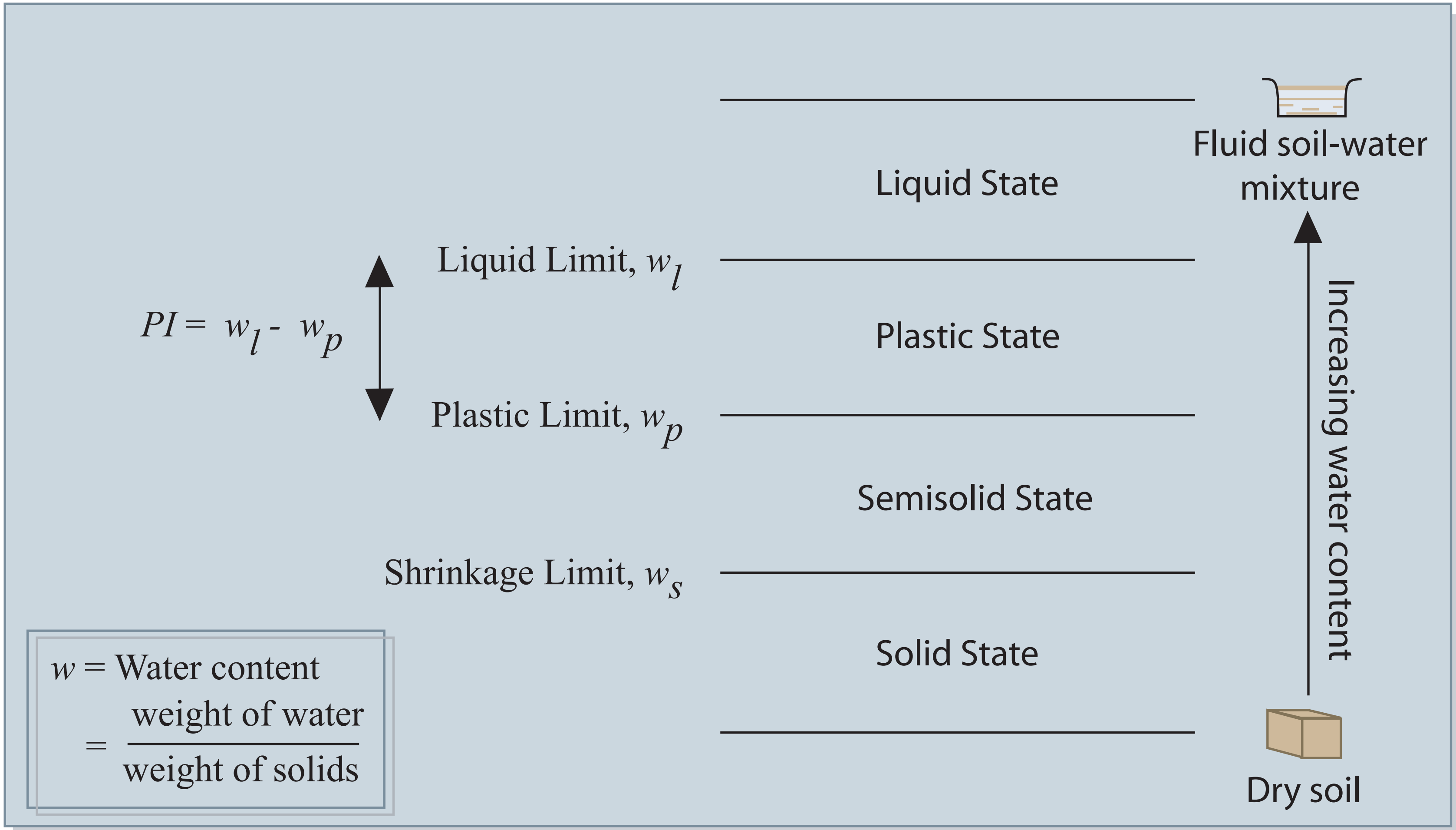
The plastic limit (PL) is the moisture content at an arbitrary limit between the plastic and semisolid state. It is reached when the soil is no longer pliable and crumbles under pressure. Between the liquid and plastic limits is the plastic range. The numerical difference in moisture content between the two limits is called the plasticity index (PI). The equation is $PI = LL - PL$. It defines the range of moisture content within which the soil is in a plastic state.

The shrinkage limit is the boundary in moisture content between the solid and the semisolid states. The solid state is reached when the soil sample, upon being dried, finally reaches a limiting or minimum volume. Beyond this point, further drying does not reduce the volume but may cause cracking. The limit tests are described later in this chapter.

Criteria for Describing Plasticity

Description	Criteria
Nonplastic	A 3 mm (1/8 in.) thread cannot be rolled at any water content.
Low (Lean)	The thread can barely be rolled and the lump cannot be formed when drier than the plastic limit.
Medium	The lump crumbles when drier than the plastic limit. The thread is easy to roll and not much time is required to reach the plastic limit. The thread cannot be rolled after reaching the plastic limit.
High (Fat)	Considerable amount of time is required for rolling and kneading to reach the plastic limit. The thread can be re-rolled several times after reaching the plastic limit. The lump can be formed without crumbling when drier than the plastic limit.

Plasticity



Fluid soil-water mixture

Liquid State

Liquid Limit, w_l

$PI = w_l - w_p$

Plastic State

Plastic Limit, w_p

Semisolid State

Shrinkage Limit, w_s

Solid State

Dry soil

Increasing water content

w = Water content

$$= \frac{\text{weight of water}}{\text{weight of solids}}$$

Atterberg limits and related indices.

Adapted from: Lambe, T. W., and R. V. Whitman. *Soil Mechanics*. New York: John Wiley & Sons, 1969.

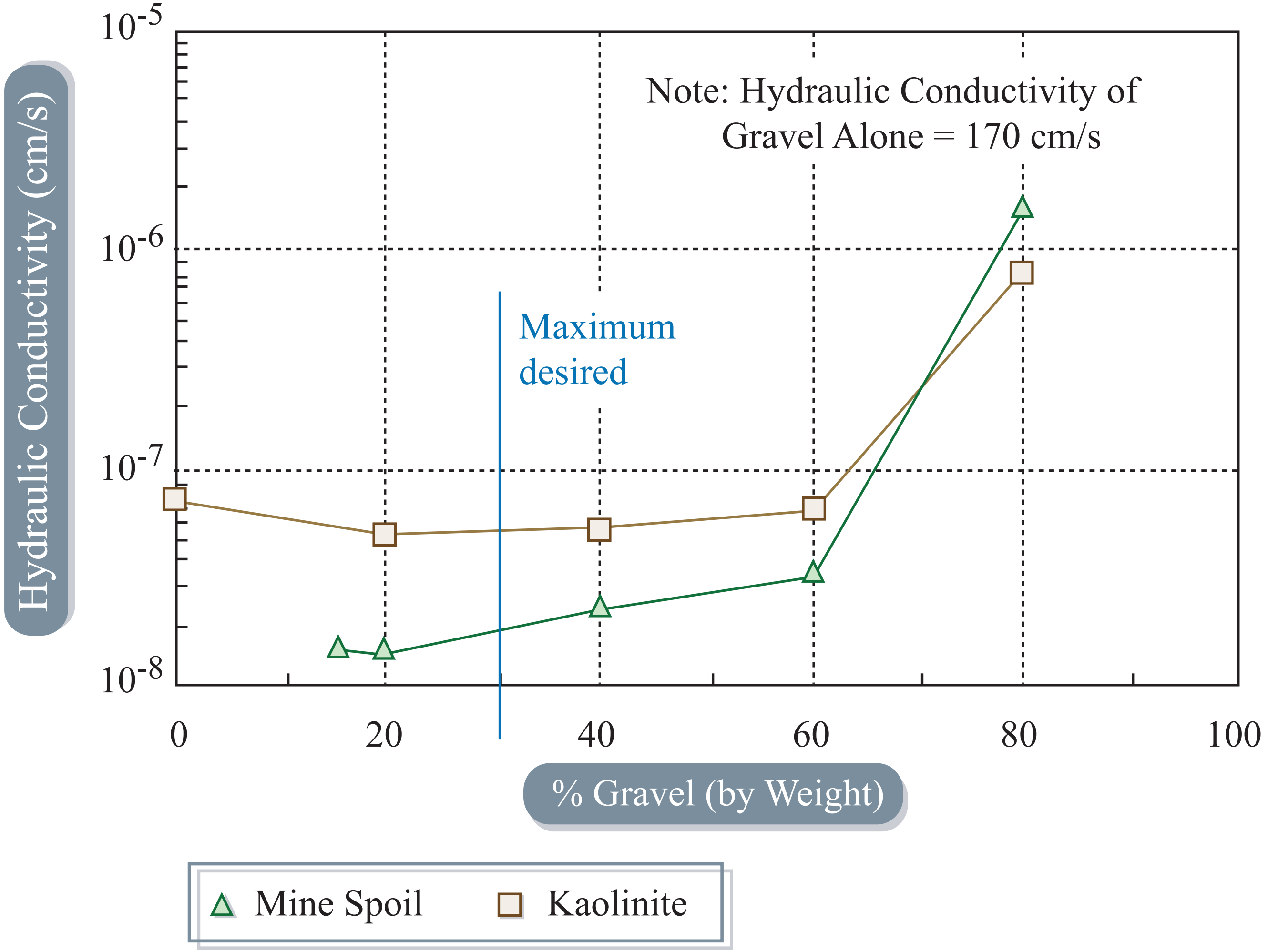
Minimum specifications to reach $K \leq 10^{-7}$

Fines (<75 μm)	20 to 30%
Gravel (≥ 4.76 mm)	≤ 30%
Plasticity index*	7 to 10%
Maximum particle size	25 to 50 mm

* Soils with high plasticity (30 to 40%) are undesirable:

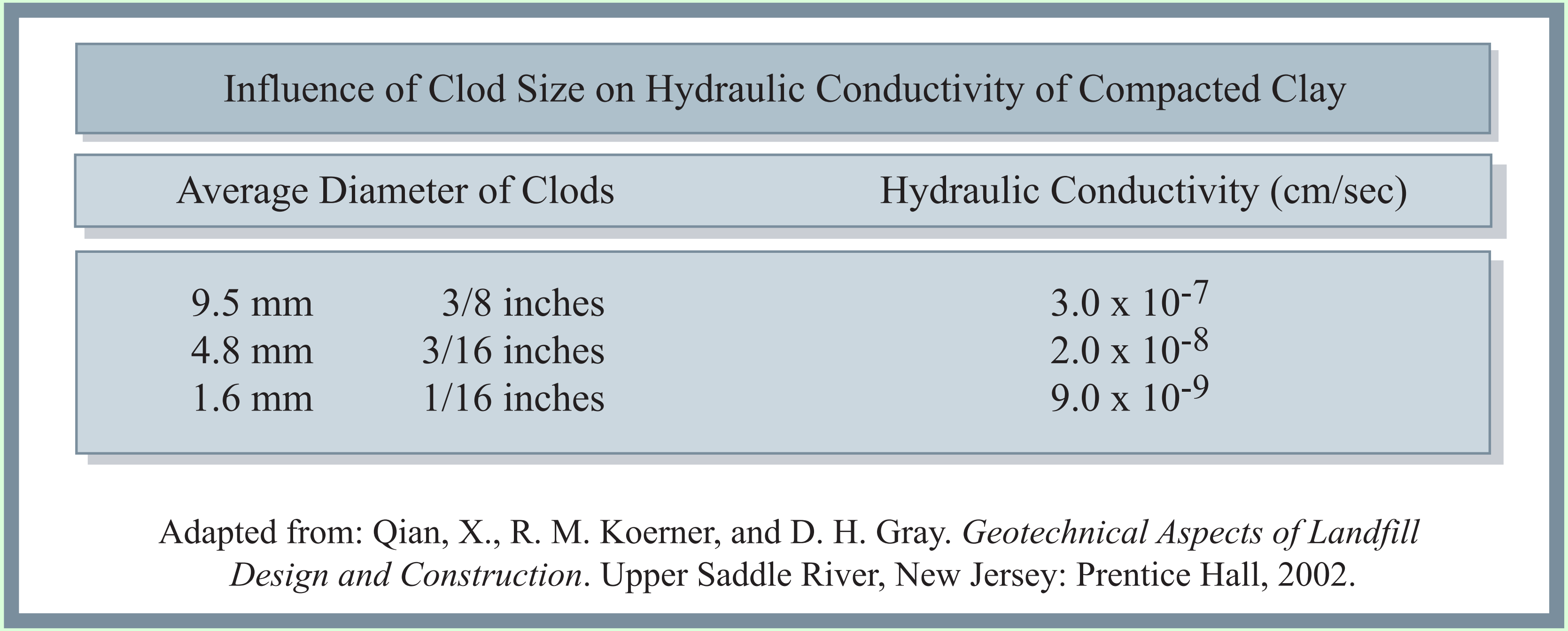
- Form hard clods when dry
- Are too sticky when wet

Effect of gravel on K



Adapted from: Daniel, D. E. "Clay Liners." *Geotechnical Practice for Waste Disposal.* Edited by D. E. Daniel. New York: Chapman & Hall, 1993, pp. 137-163.

Soil clods



Influence of Clod Size on Hydraulic Conductivity of Compacted Clay

Average Diameter of Clods		Hydraulic Conductivity (cm/sec)
9.5 mm	3/8 inches	3.0×10^{-7}
4.8 mm	3/16 inches	2.0×10^{-8}
1.6 mm	1/16 inches	9.0×10^{-9}

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

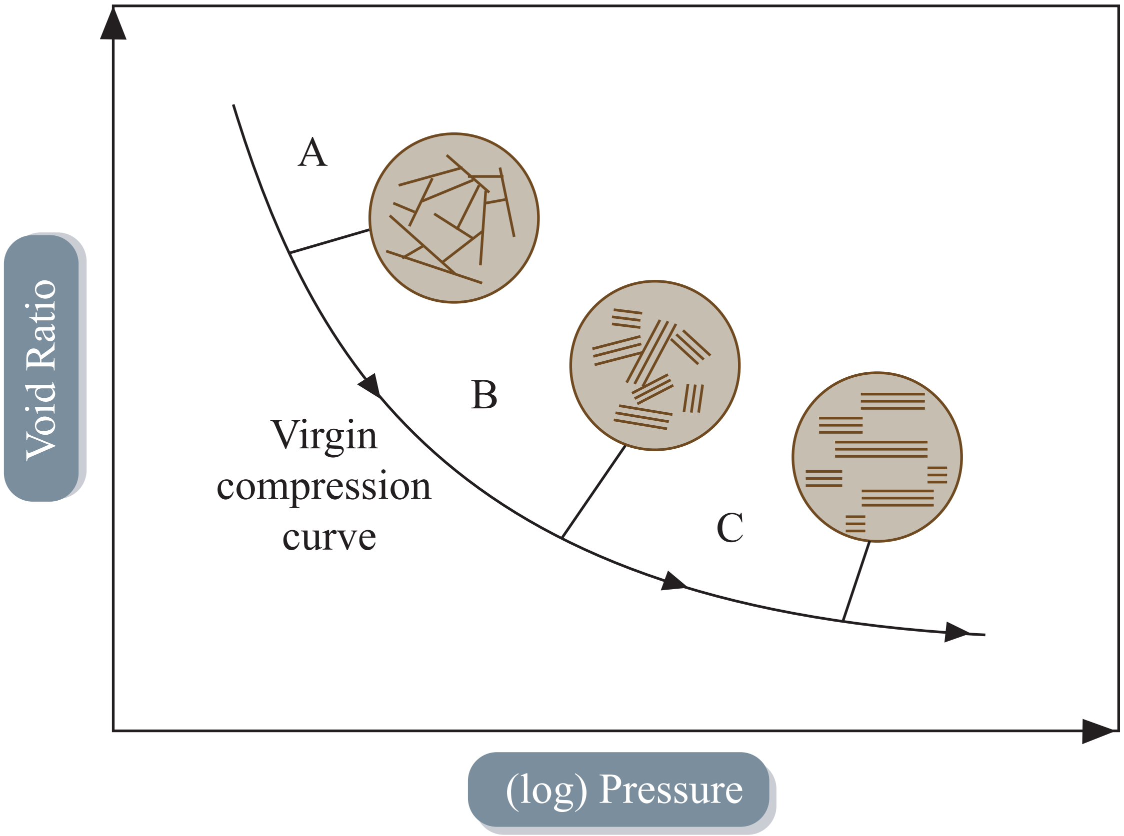
Soil Compaction

Remolding of soil to remove clods and create homogeneous mass of void-free soil

Factors affecting resulting hydraulic conductivity

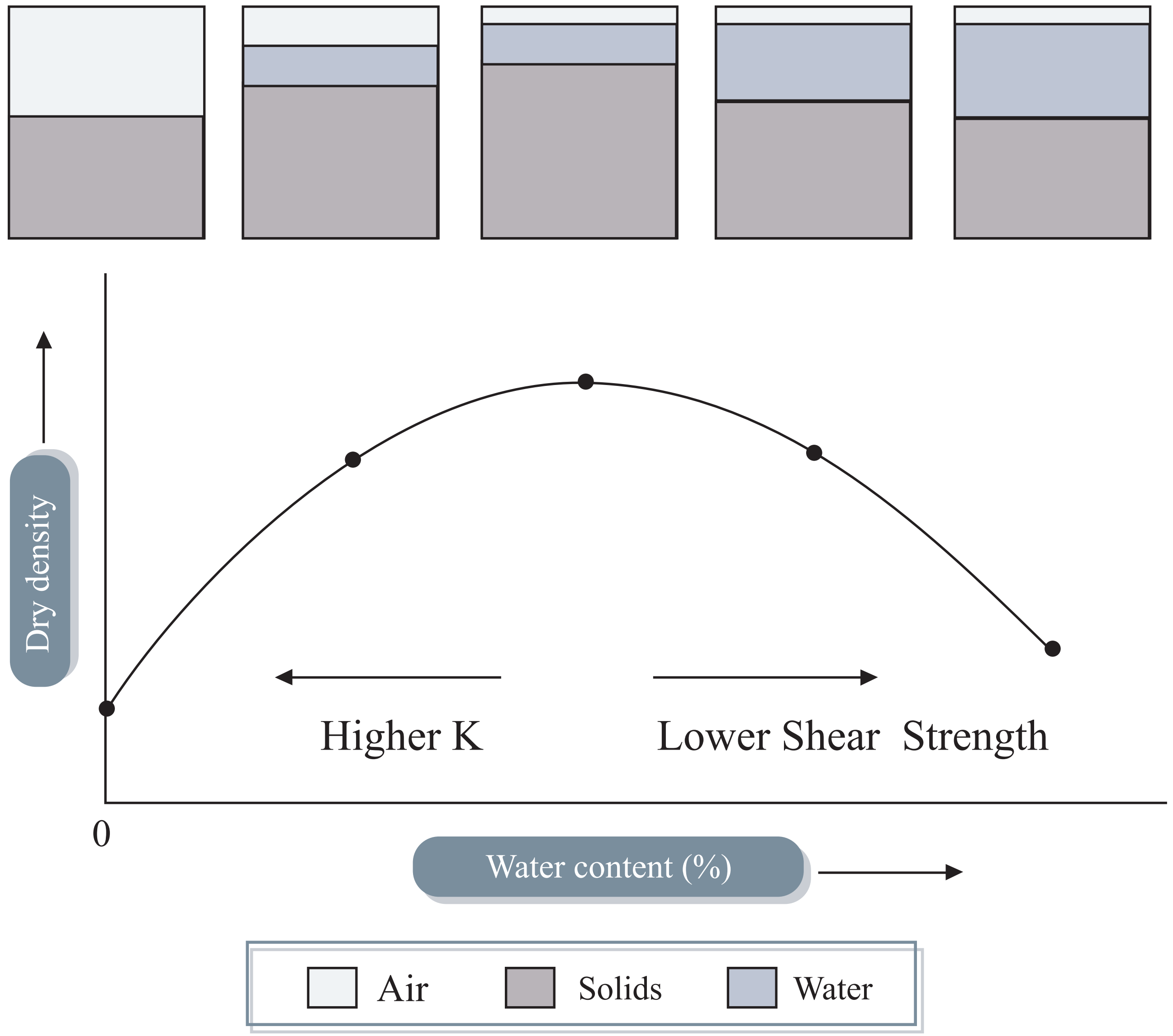
- Compaction method (kneading, dynamic, static)
- Compactive effort
- Moisture content of soil

Effect of soil compaction on clay



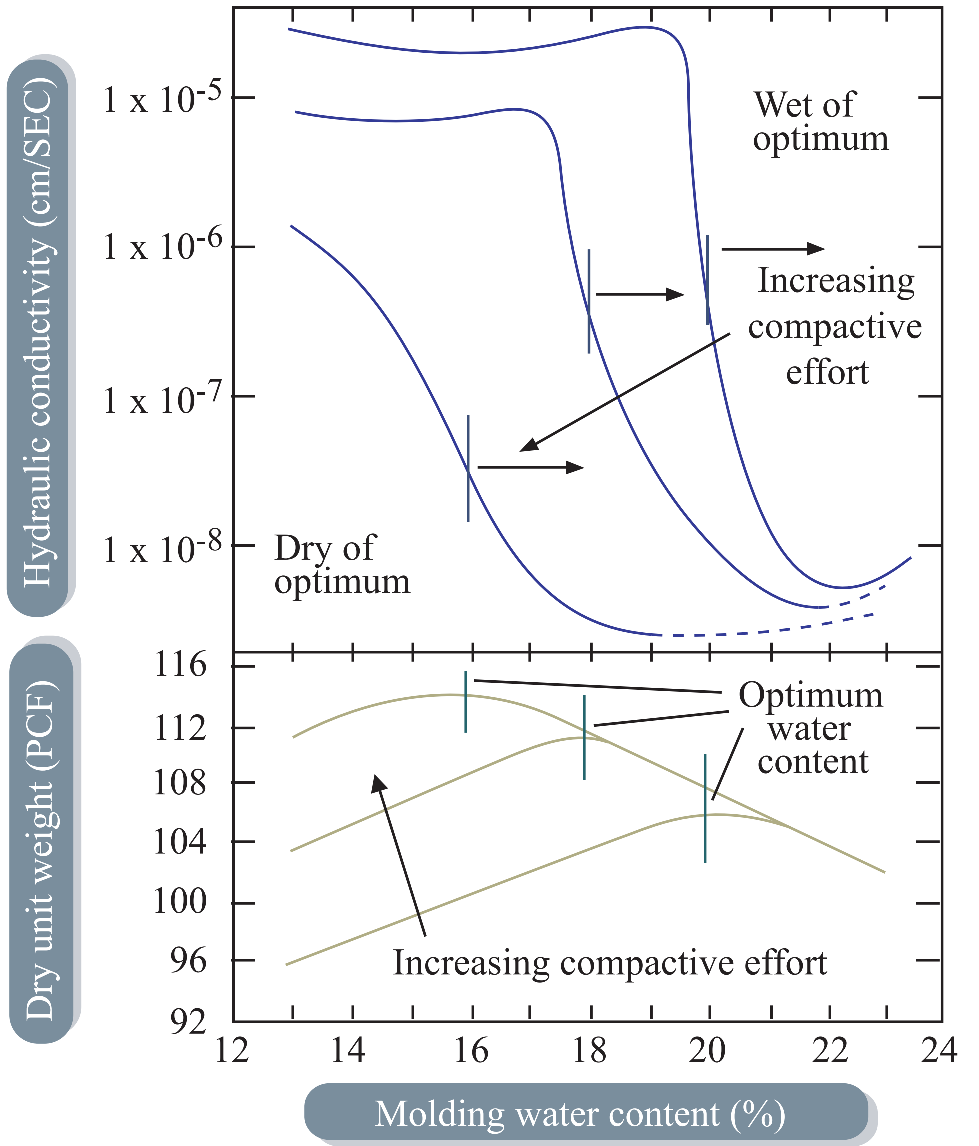
Structure changes during consolidation process.

Adapted from: Reddi, L. N., and H. I. Inyang. *Geoenvironmental Engineering, Principles and Applications*. New York, NY: Marcel Dekker, Inc., 2000.



Variation of dry density with water content.

From Culligan notes: Atkins, 1983.

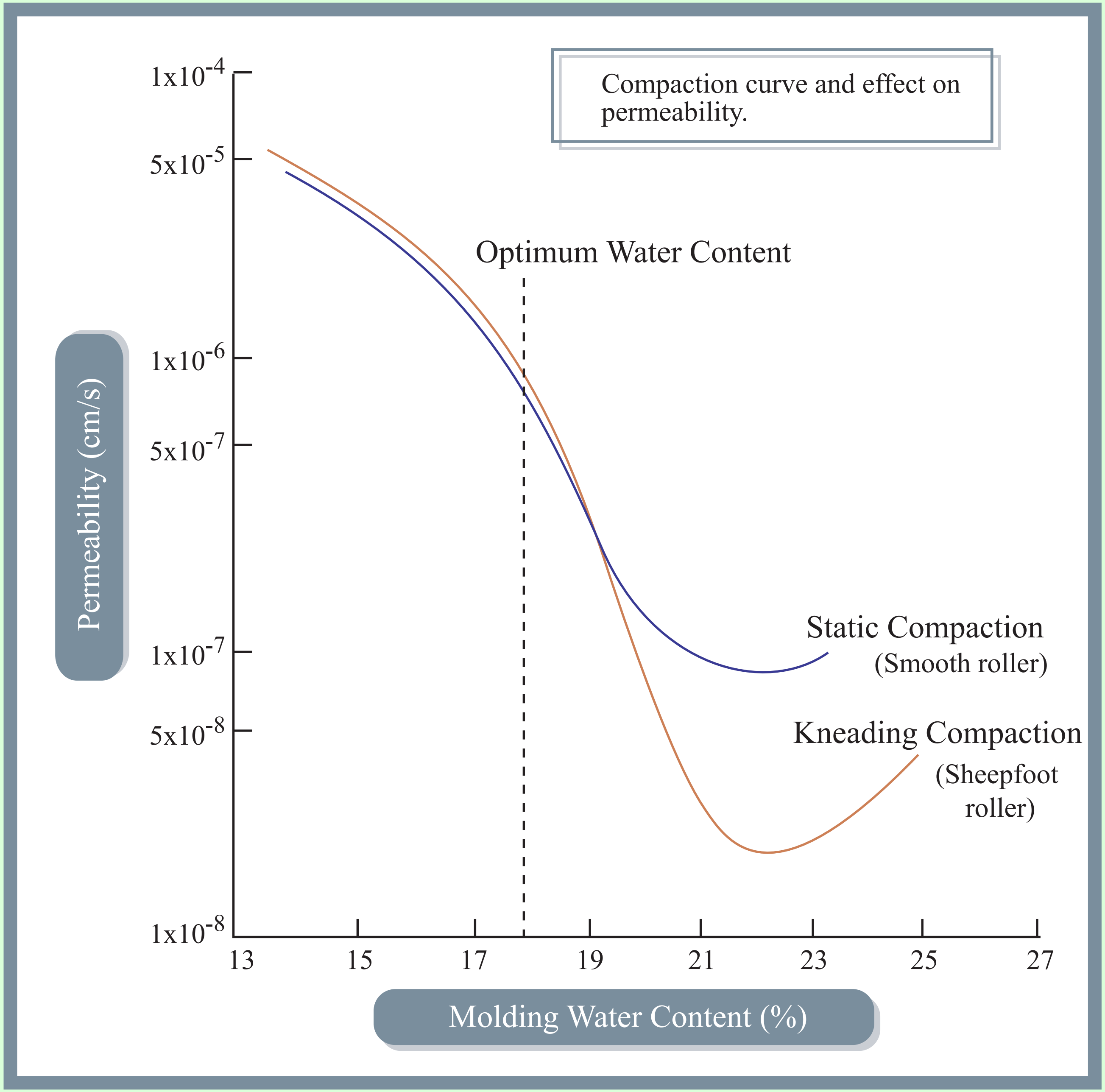


Effect of molding water content and compactive energy on hydraulic conductivity.

Adapted from: Daniel, D. E. "Clay Liners." *Geotechnical Practice for Waste Disposal.* Edited by D. E. Daniel. New York: Chapman & Hall, 1993, pp. 137-163.

Lowest K achieved by compacting wet of optimum

Compactive effort = energy delivered to soil



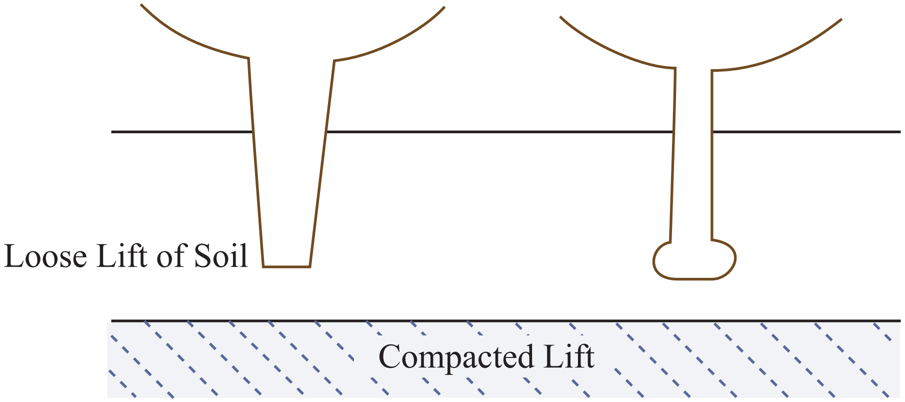
From Culligan notes: Oweis and Khera, 1998

Compaction practice for liners

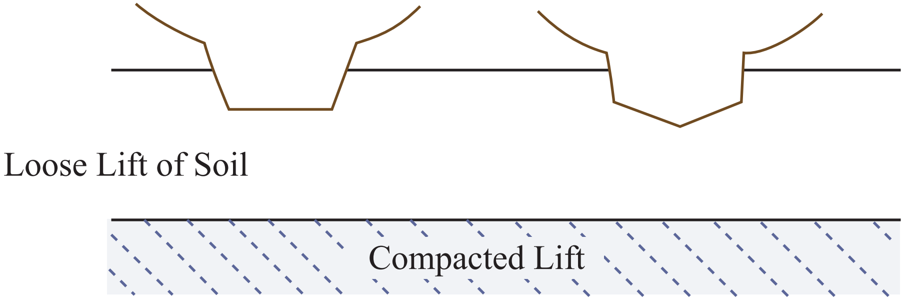
- Compact with clay wet of optimum to minimize hydraulic conductivity
- Select borrow area (material source) carefully
    - Too wet – difficult to dry out by normal aeration
    - Too dry – difficult to break up clods and compact
- Use high degree of kneading-type compactive energy
- Construct lifts carefully
- Protect from freeze-thaw

Footed rollers

Compact until roller feet “walk out” of clay



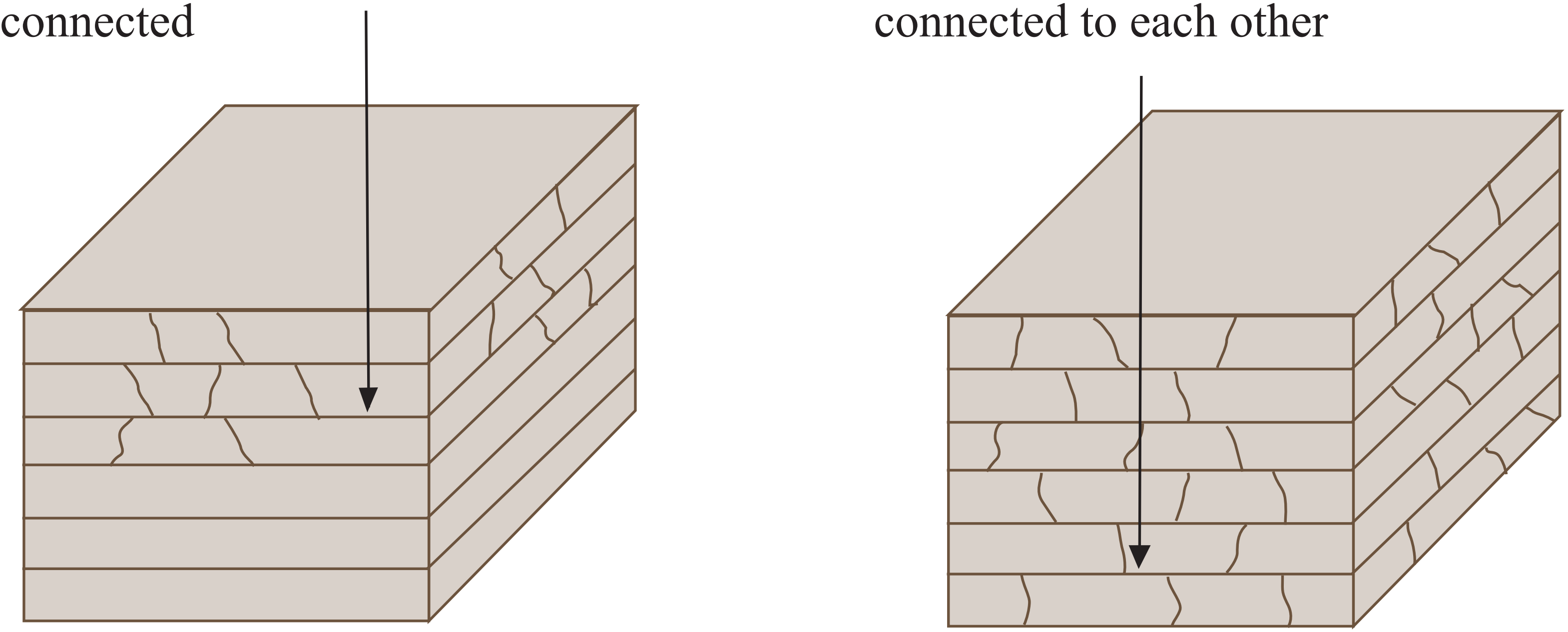
Fully penetrating feet on a footed roller.



Partly penetrating feet on a footed roller.

Adapted from: Daniel, D. E. "Clay Liners." *Geotechnical Practice for Waste Disposal.* Edited by D. E. Daniel. New York: Chapman & Hall, 1993, pp. 137-163.

See images at: Warren Power Attachments, 2003. Sheeps Foot Roller: Wedge Foot™ Pull Type Static Roller. http://www.warrenattachments.com/sheepsfoot_roller.htm.



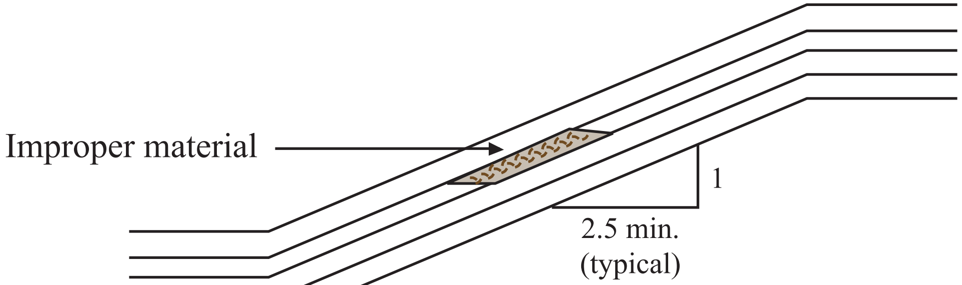
Good bonding of lifts causes hydraulic defects in adjacent lifts to be hydraulically unconnected

Poor bonding of lifts causes hydraulic defects in adjacent lifts to be hydraulically connected to each other

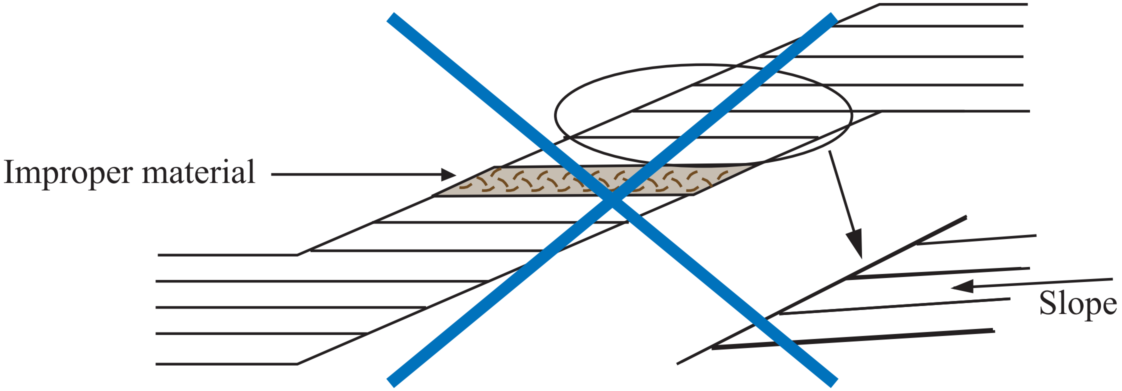
Effect of good and poor bonding of lifts on the performance of a compacted clay liner.

Adapted from: Daniel, D. E. "Clay Liners." *Geotechnical Practice for Waste Disposal.* Edited by D. E. Daniel. New York: Chapman & Hall, 1993, pp. 137-163.

Clay lift placement



Side slopes constructed with parallel lifts.



Side slopes constructed with horizontal lifts.

Adapted from: Daniel, D. E. "Clay Liners." *Geotechnical Practice for Waste Disposal*. Edited by D. E. Daniel. New York: Chapman & Hall, 1993, pp. 137-163.

Testing procedure for clay liners

Determine compaction vs. water content

Determine K vs. water content

Determine shear strength vs. water content

Determine shrinkage vs. water content

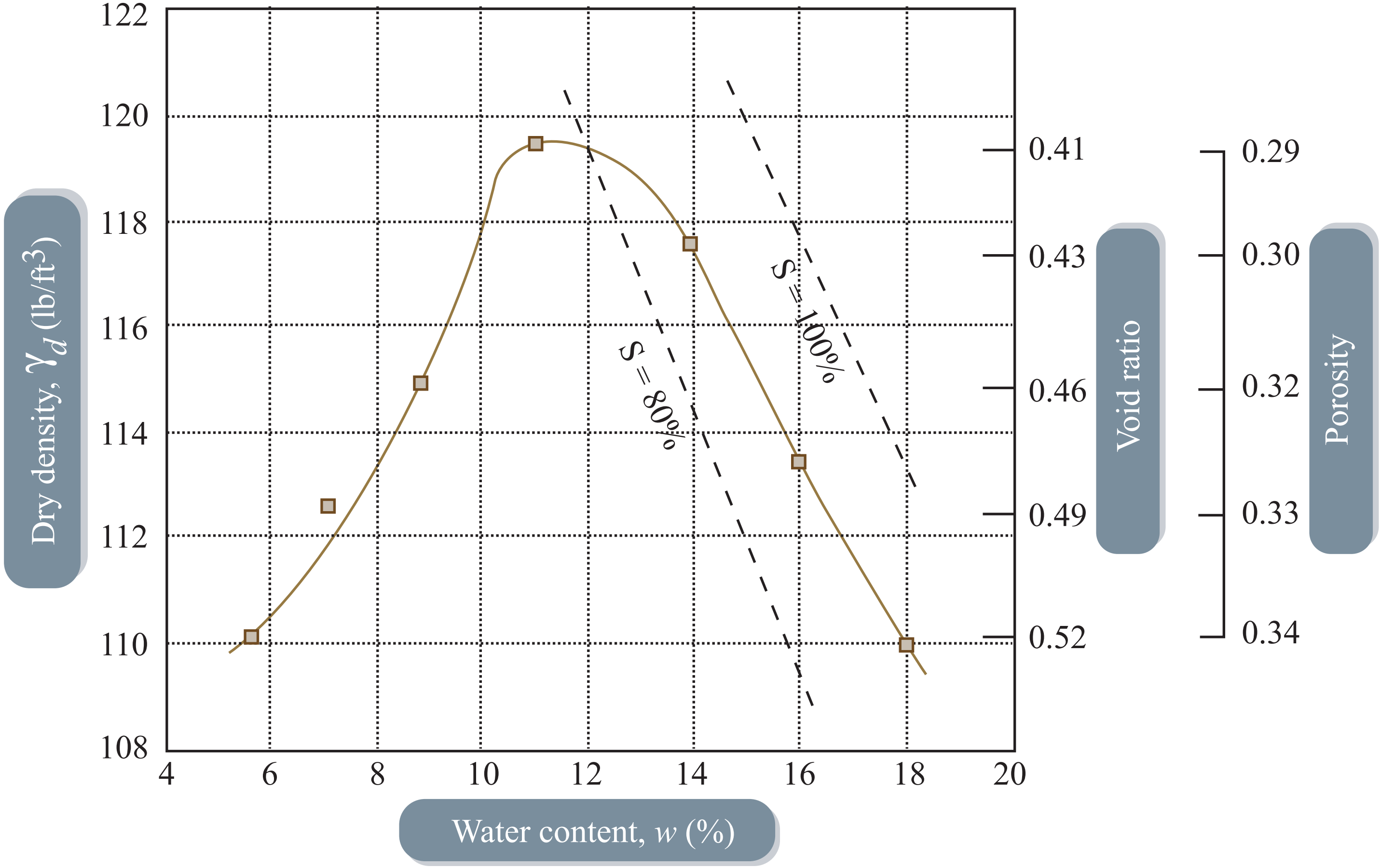
Allowable ranges of K, shear strength, shrinkage to find water content and compaction

Proctor compaction test

To determine the optimum moisture content (OMC) and the maximum dry density of a cohesive soil. Proctor developed a compaction test procedure to determine the maximum dry unit weight of compaction of soils. The OMC can be done by two tests: Standard Proctor Test and Modified Proctor Test. The different between the two tests is the amount of energy of compaction. In the Standard Proctor Test, the moist soil is poured into the mold in three equal layers. Each layer is compacted by the standard Proctor hammer with 25 blows per layer. In the Modified Proctor Test, the moist soil is poured into the mold in five equal layers. Each layer is compacted by the modified Proctor hammer with 25 blows per layer.

See http://saluki.civl.citadel.edu/civl402/lab5/purpose.htm.

Proctor test results



Standard proctor compaction test.

Adapted from: Lambe, T. W., and R. V. Whitman. *Soil Mechanics*. New York: John Wiley & Sons, 1969.

Proctor test variations

Test	Hammer Weight (N) (lb)	Drop Distance (mm) (in)	Layers	Blows per Layer
Modified Proctor	45 10	450 18	5	25
Standard Proctor	24 5.4	300 12	3	25
Reduced Proctor	24 5.4	300 12	3	15

Proctor test samples

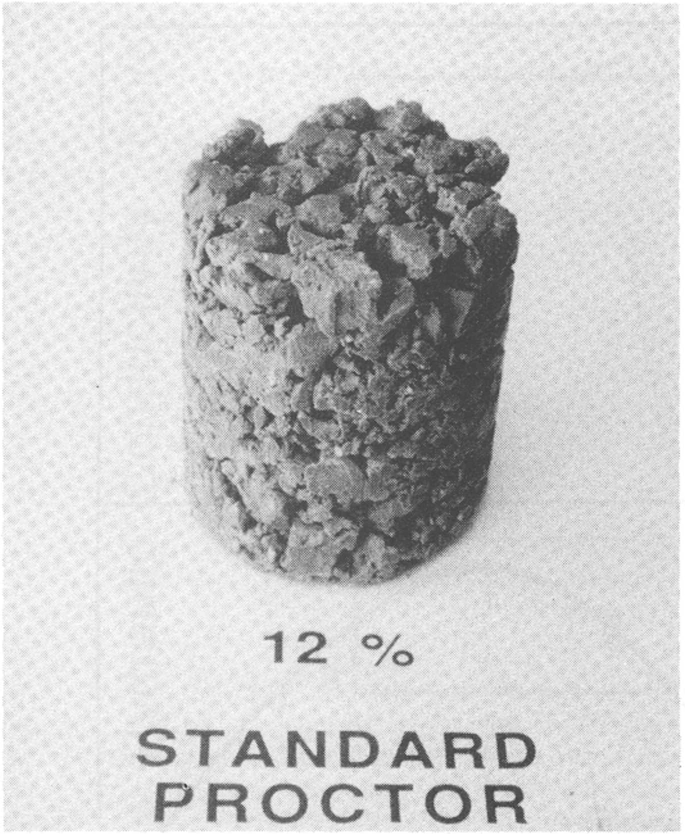


Figure 2-5. Highly plastic soil compacted with standard Proctor procedures at a water content of 12%.

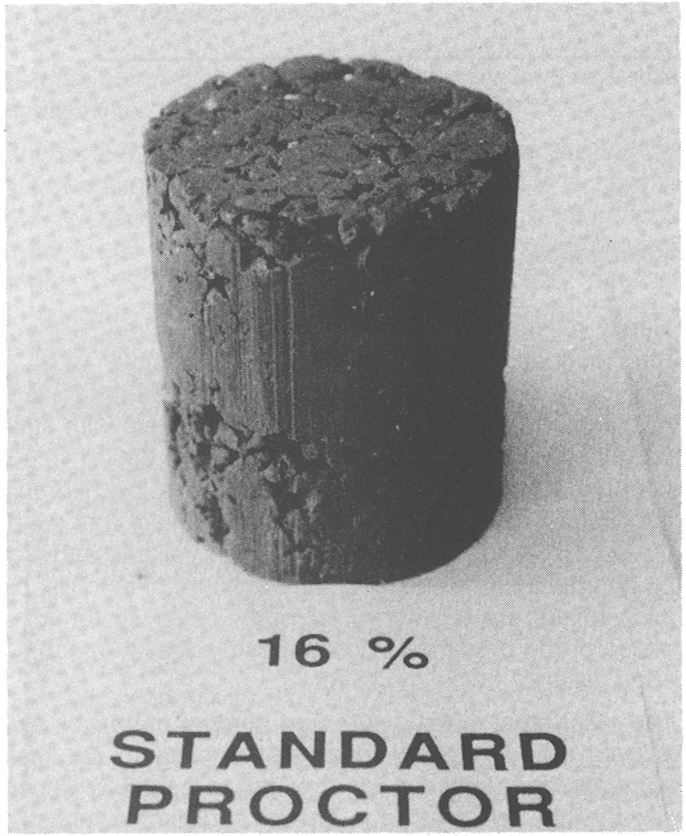


Figure 2-6. Highly plastic soil compacted with standard Proctor procedures at a water content of 16%.

Figure 2-7. Highly plastic soil compacted with standard Proctor procedures at a water content of 20%.

Source: U.S. EPA, 1991. Design and Construction of RCRA/CERCLA Final Covers. Report Number EPA/625/4-91/025. U.S. Environmental Protection Agency, Cincinnati, Ohio. May 1991. Pg. 16.

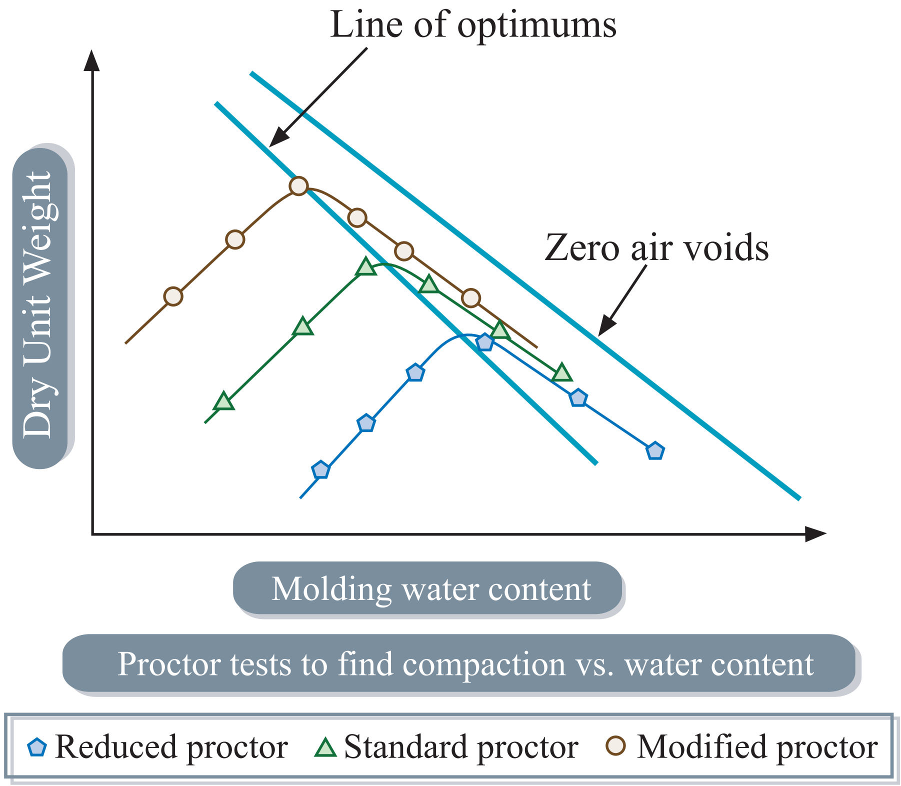
Permeameter to measure K

See Figure 3.4 in: Todd, D. K., 1980. *Groundwater Hydrology*, 2nd Edition. John Wiley & Sons, New York, New York.

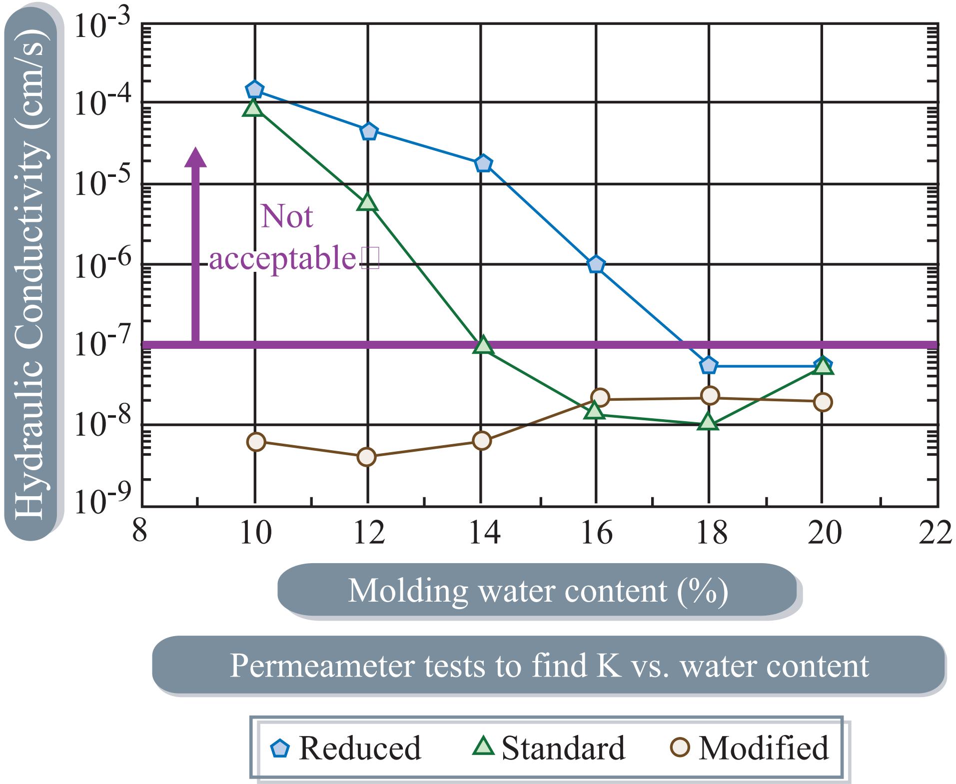
Triaxial test to measure stress-strain

See Figures 9.4 and 9.5 in: Lambe, T. W., and R. V. Whitman, 1969. *Soil Mechanics*. John Wiley & Sons, New York, New York.

Procedure for finding water content



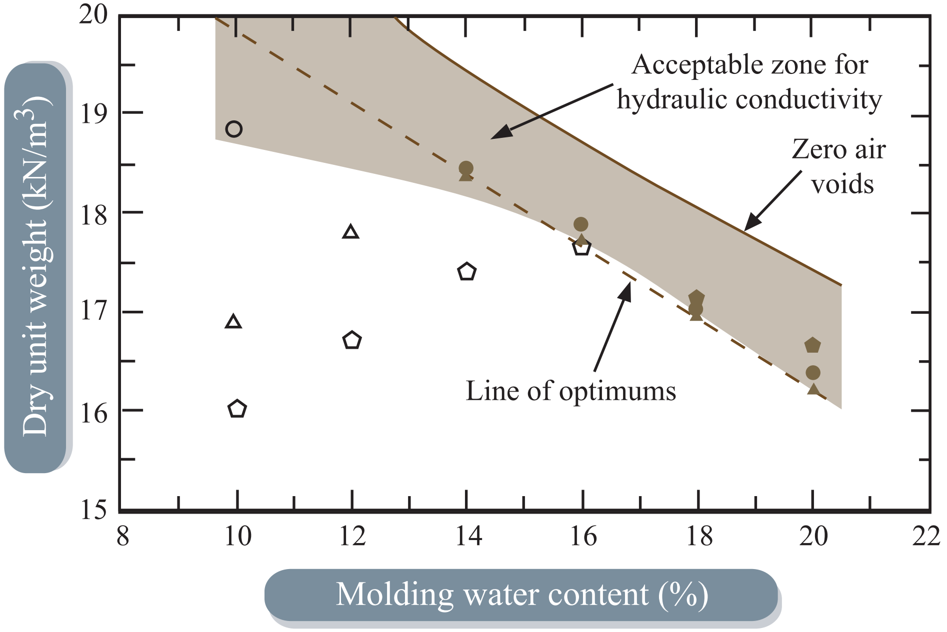
Proctor tests to find compaction vs. water content



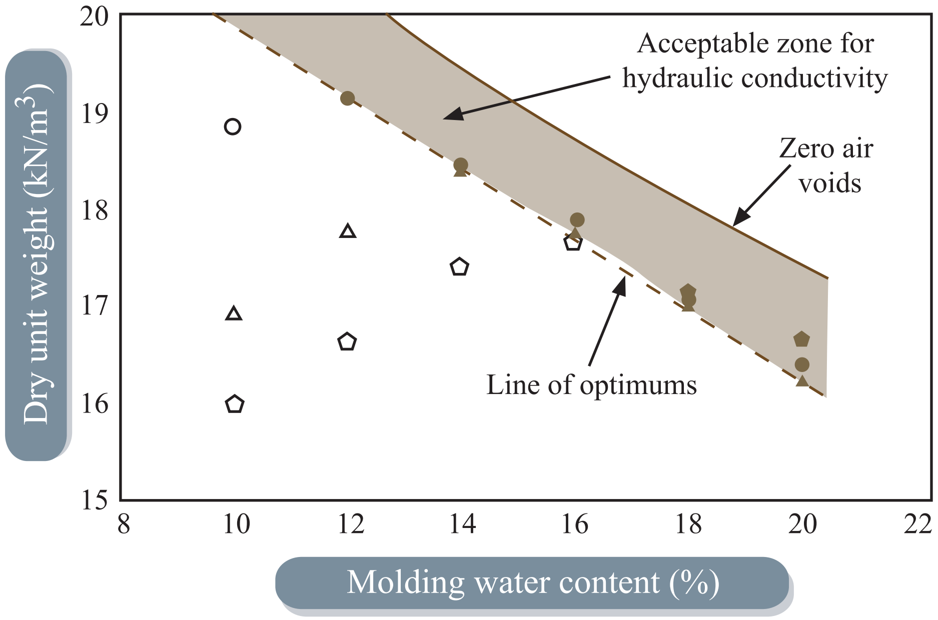
Permeameter tests to find K vs. water content

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Procedure for finding water content



Acceptable moisture content based lab hydraulic conductivity

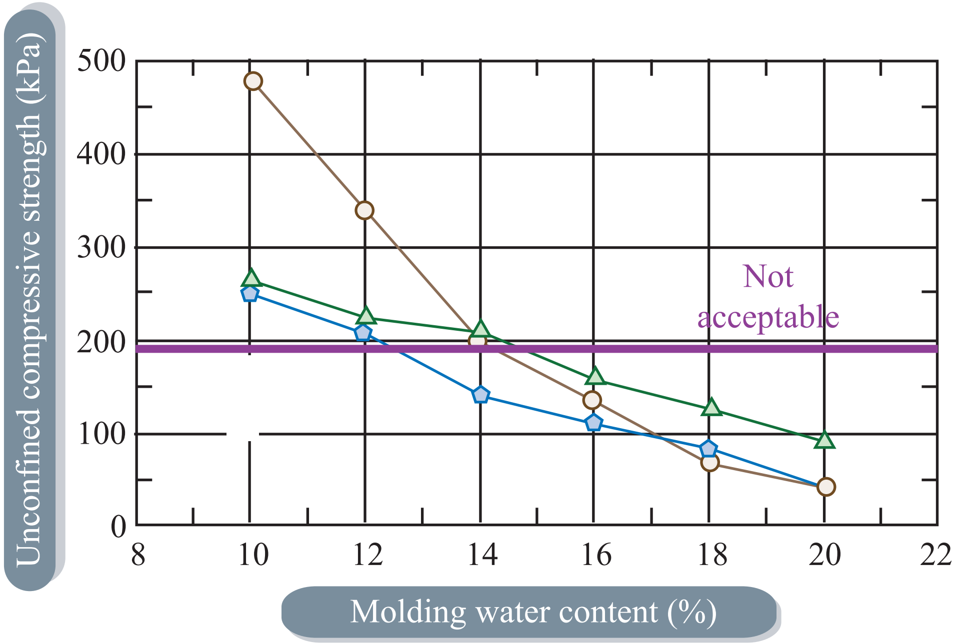


Acceptable moisture content adjusted for field experience

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

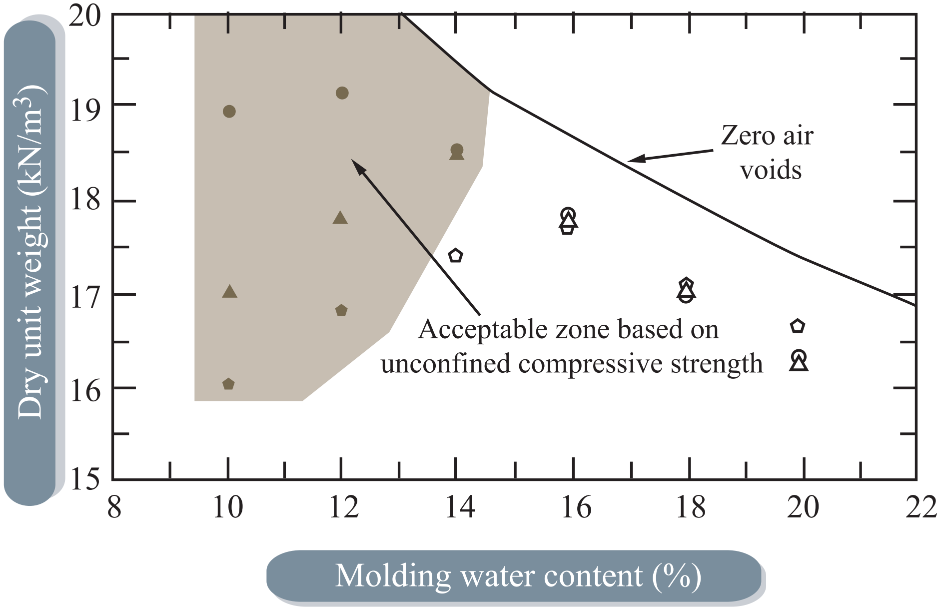
Reference: Qian et al. 2002 – field experience showed that K often exceeded 10-7 cm/sec despite good lab tests if soil was not wet of optimum

Procedure for finding water content



Run triaxial tests to find shear strength vs. water content

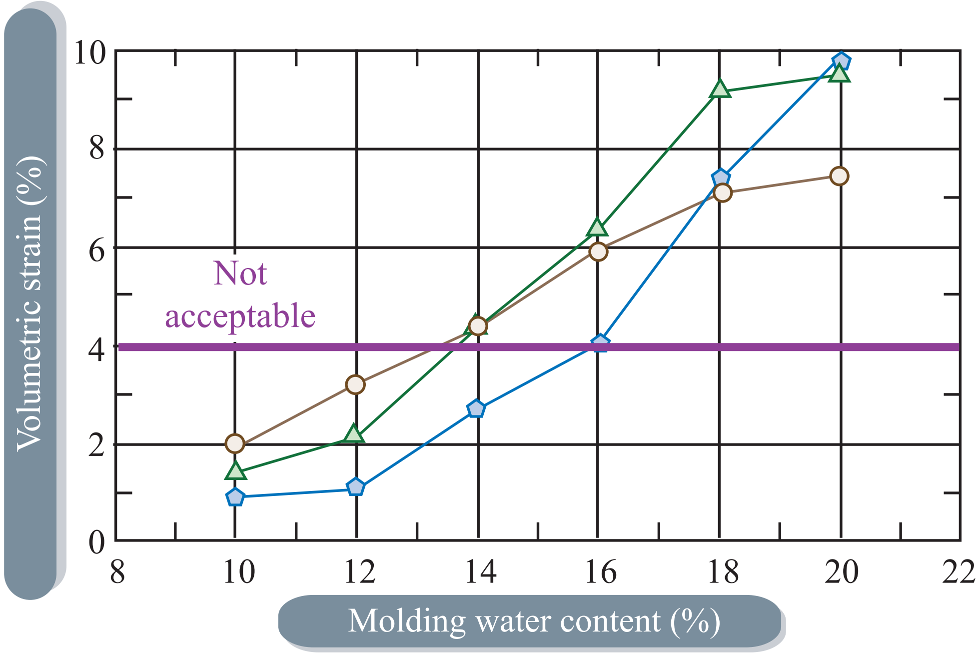
△ Standard ⬠ Reduced ○ Modified



Acceptable moisture content based on shear strength

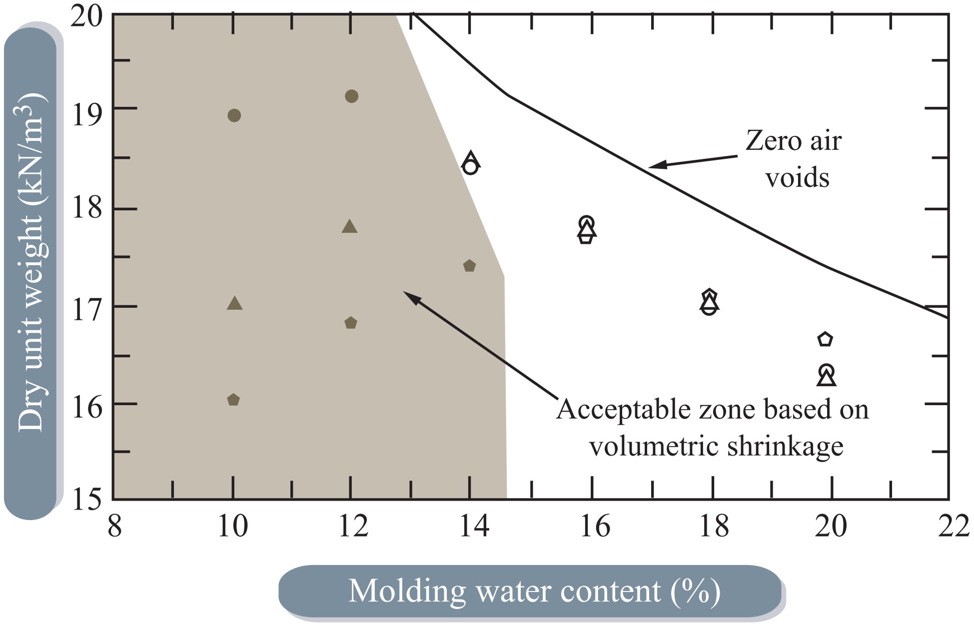
Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*.
Upper Saddle River, New Jersey: Prentice Hall, 2002.

Procedure for finding water content



Run volumetric strain tests to find shrinkage vs. water content (for sites where desiccation is a potential concern)

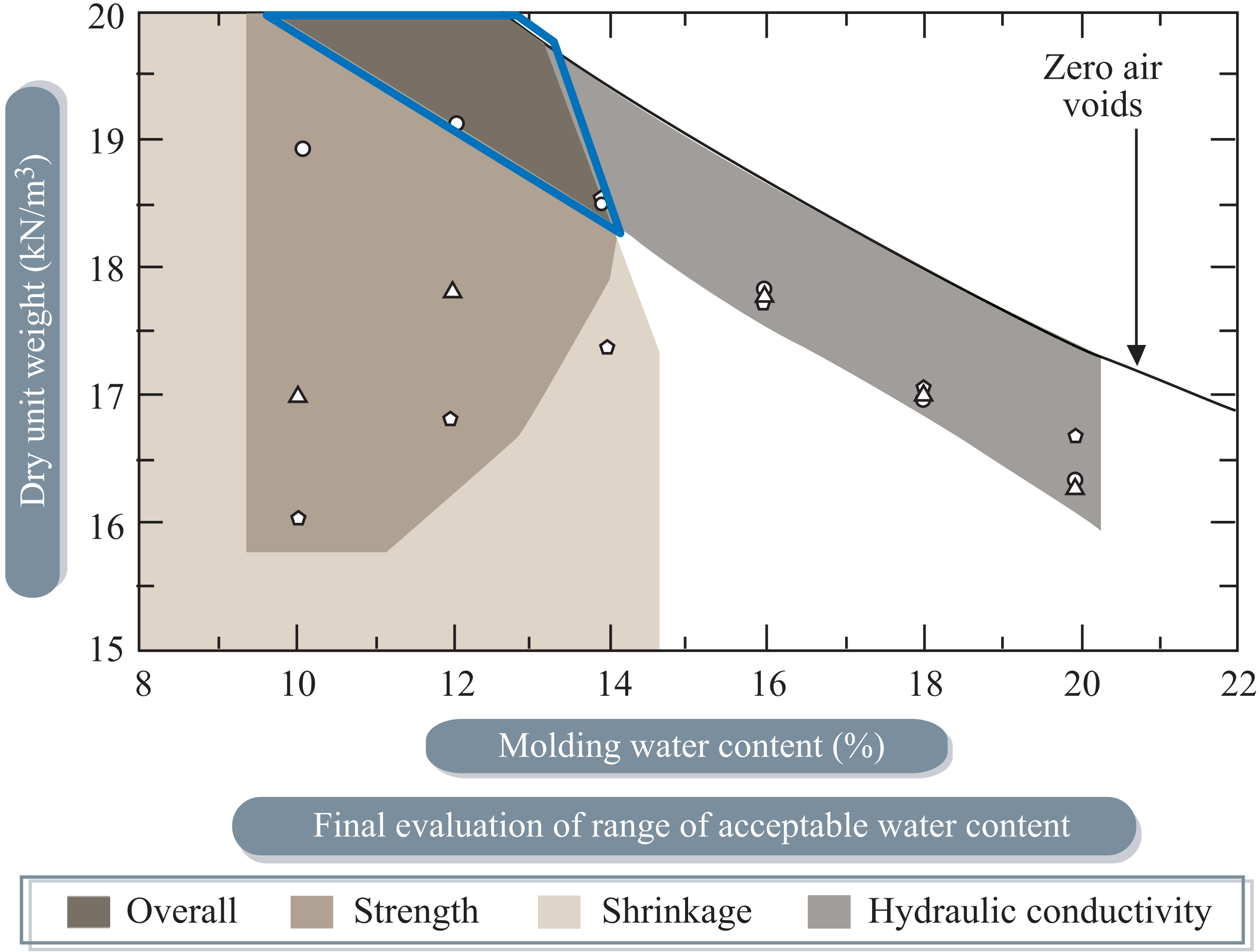
△ Standard ⬠ Reduced ○ Modified



Acceptable moisture content based on allowable shrinkage

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*.
Upper Saddle River, New Jersey: Prentice Hall, 2002.

Procedure for finding water content



Final evaluation of range of acceptable water content

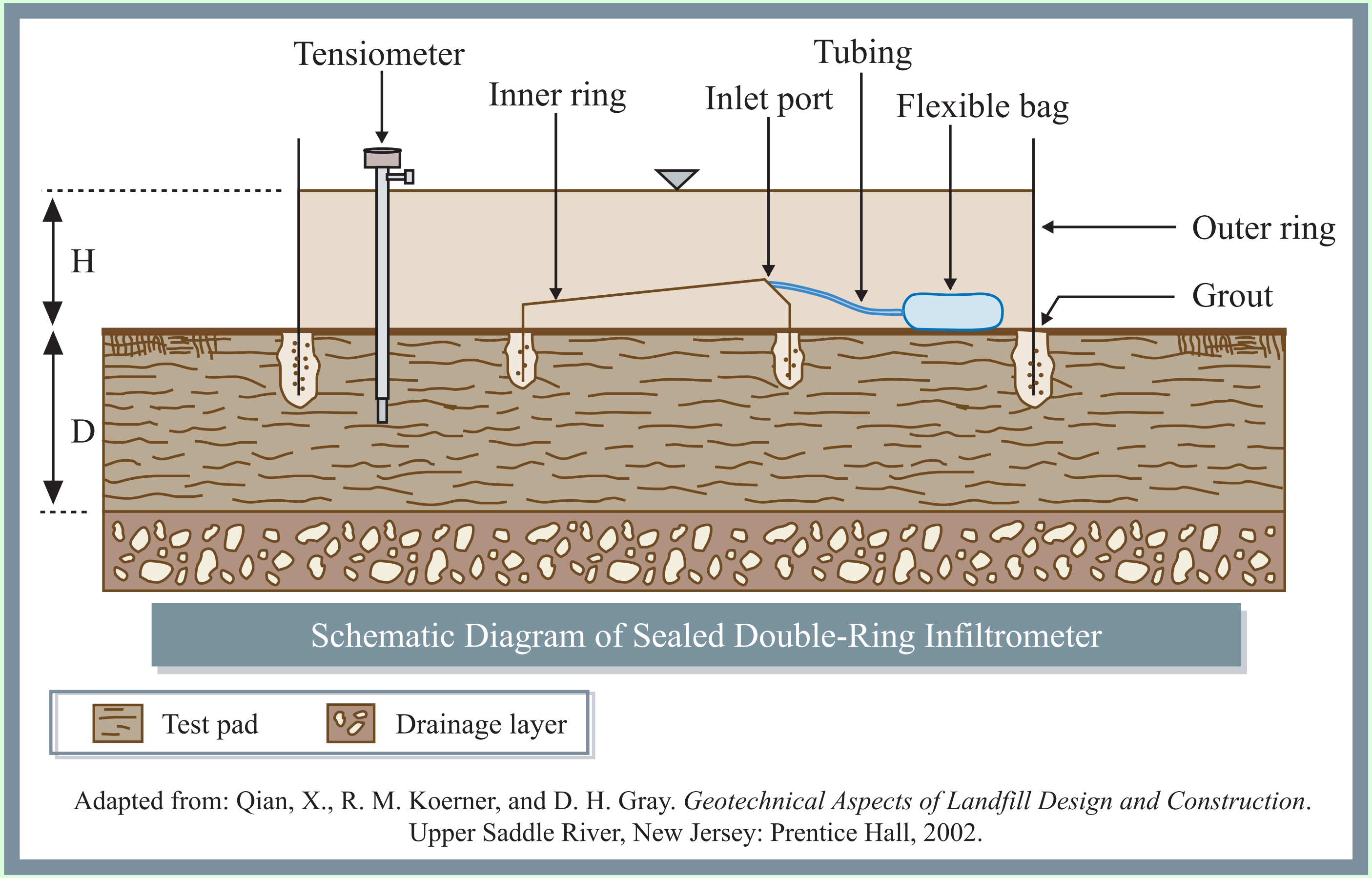
Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Open double-ring infiltrometer

See image at: Rickly Hydrological Company, 2004. Columbus, Ohio. http://www.rickly.com/MI/Infiltrometer.htm. Accessed April 25, 2004.

See image at: Southern Africa Geoconsultants (Pty) Ltd, undated. Engineering Geology. http://www.geocon.co.za/html/engineering.html Accessed April 25, 2004.

Field testing K



Schematic Diagram of Sealed Double-Ring Infiltrometer

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

Double ring problem of lateral flow away from inner ring

Inner ring has area A

Covered inner ring has no evaporation

Infiltration into soil empties bag: amount of water loss, Q, is measured over time period of test, t

Q/At = Infiltration rate

K = I/I

i is computed assuming:

i = (H+D) / D

i = (H+D’) / D’ where is wetting front determined when tensiometer measures atmospheric pressure

i = (H+D+HS) / D similar to 2 except using measured suction head at tensiometer

Tensiometer

See image at: Grissino-Mayer, H.D., 1999. Geology 3710, Introduction to Soil Science, Laboratory 8, Soil Water Content along a Soil Profile. Geology Department, Valdosta State University, Valdosta, Georgia. October 31, 1999. http://www.valdosta.edu/~grissino/geol3710/lab8.htm. Accessed April 25, 2004.

See image at: Smajstrla, A.G. and D.S. Harrison, 1998. Tensiometers for Soil Moisture Measurement and Irrigation Scheduling. Circular 487, Agricultural & Biological Engineering Dept., Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. April 1998. http://edis.ifas.ufl.edu/AE146. Accessed April 25, 2004.

Calculation of K from double-ring test

Inner ring has area A (covered inner ring has no evaporation)

Infiltration into soil empties bag: amount of water loss, Q, is measured over time period of test, t

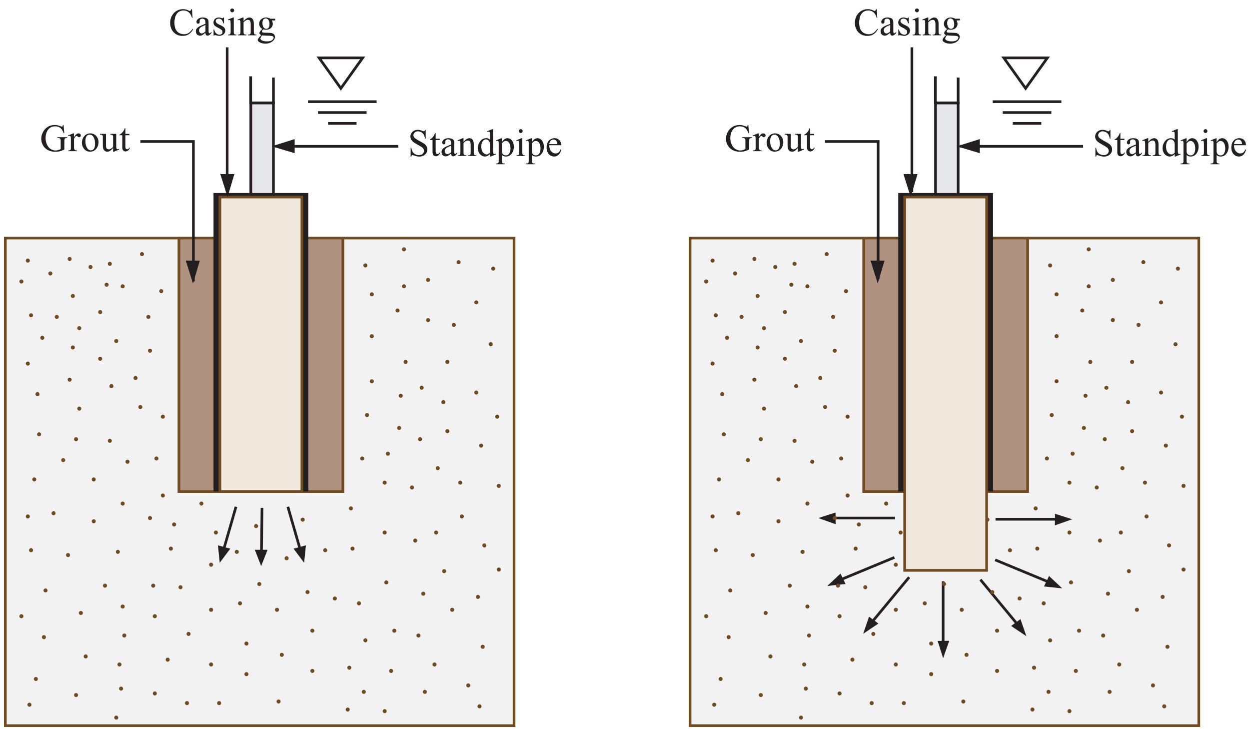
$Q / At = q =$ Infiltration rate

$K = q / i$

i is computed as:

1) $i = (H+D) / D$ where D is thickness of liner
   (most conservative – gives lowest i and highest k)
2) $i = (H+D') / D'$ where D' is wetting front depth determined when tensiometer measures atmospheric pressure
   (most commonly used)
3) $i = (H+D+H_S) / D$ where H_S is measured suction head at tensiometer
   (used infrequently)

Field testing K



Stage I

Stage II

Boutwell two-stage field permeability test

Adapted from: Qian, X., R. M. Koerner, and D. H. Gray. *Geotechnical Aspects of Landfill Design and Construction*. Upper Saddle River, New Jersey: Prentice Hall, 2002.

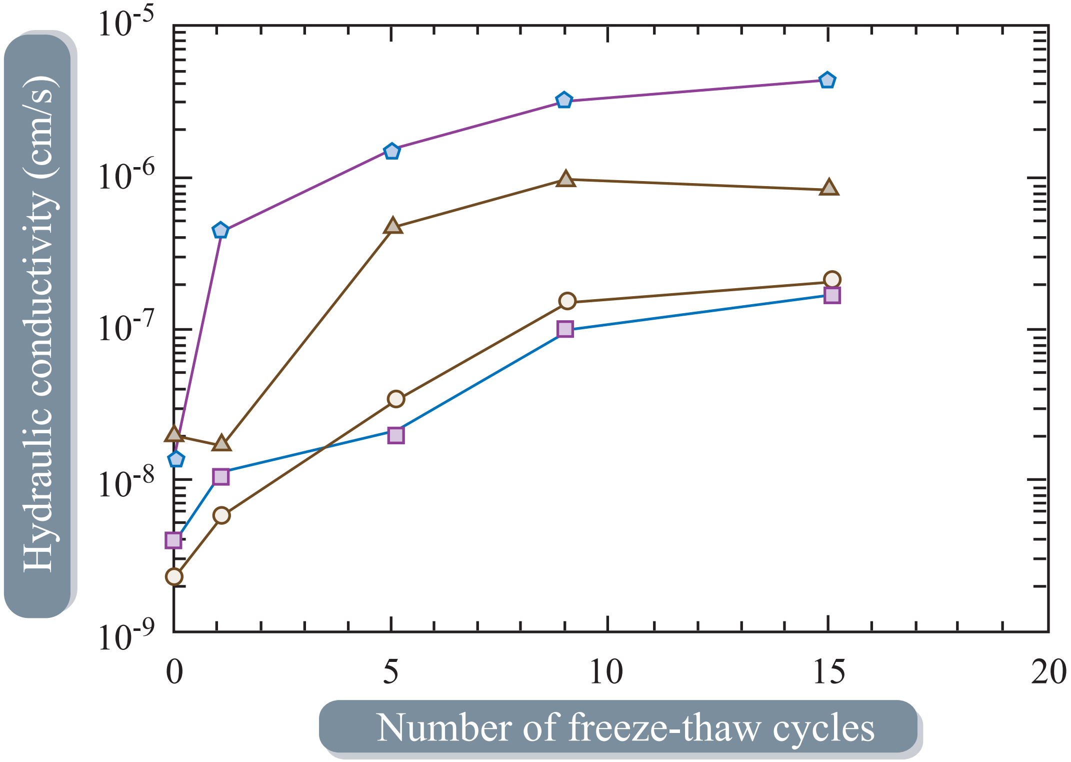
Determine K1 and K2 during Stage I and Stage II respectively

Can be used to compute KH and KV

Potential compromises of clay

- Drying out
  - Causes desiccation cracks
- Freeze-thaw cycles
  - Ice lenses create network of cracks
- Organic liquids
  - Modifies clay chemistry

Protection from freezing



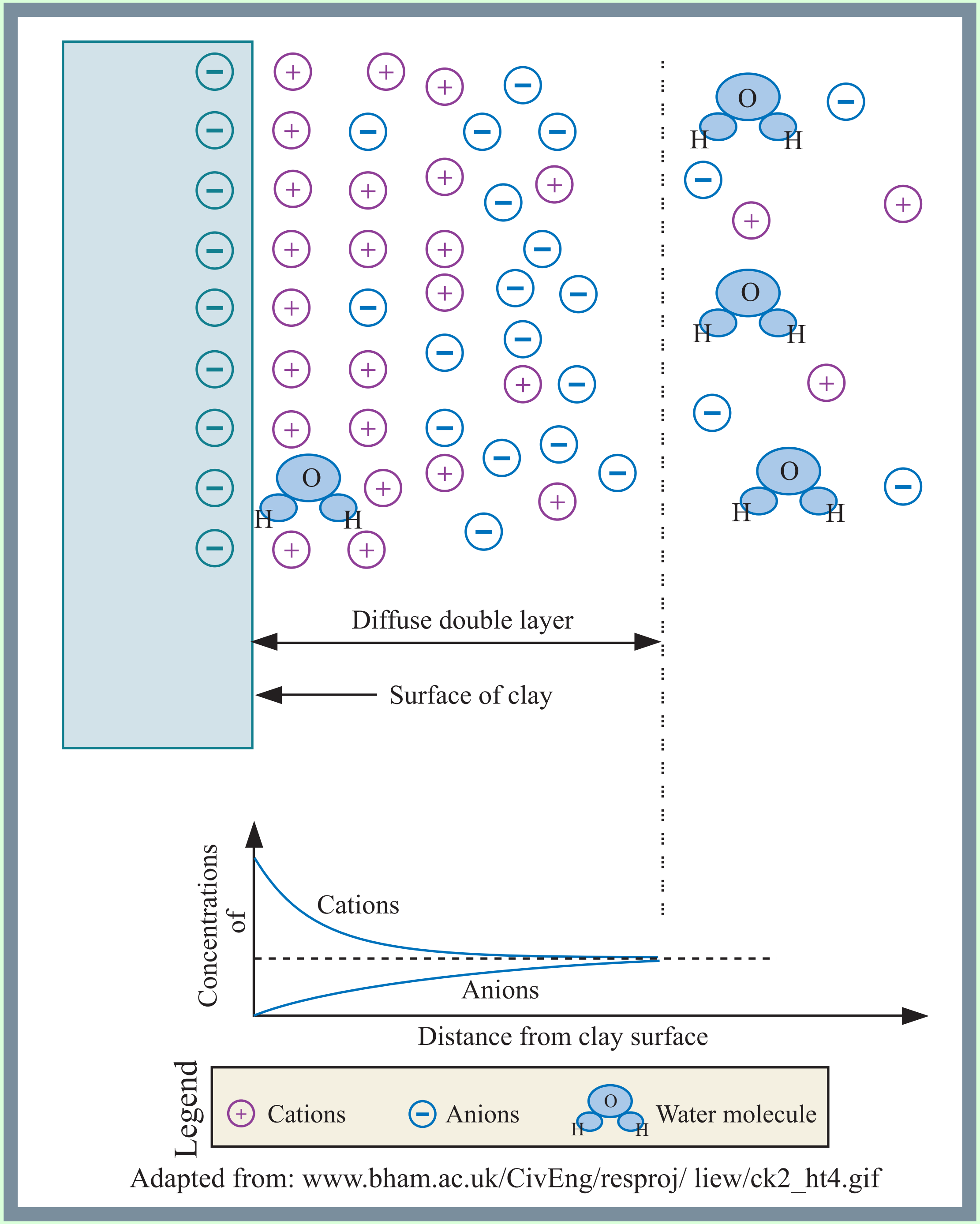
Effect of freeze-thaw on hydraulic conductivity of compacted clay.

Adapted from: Daniel, D. E. "Clay Liners." *Geotechnical Practice for Waste Disposal*. Edited by D. E. Daniel. New York: Chapman & Hall, 1993, pp. 137-163.

Charge Structure of Clay

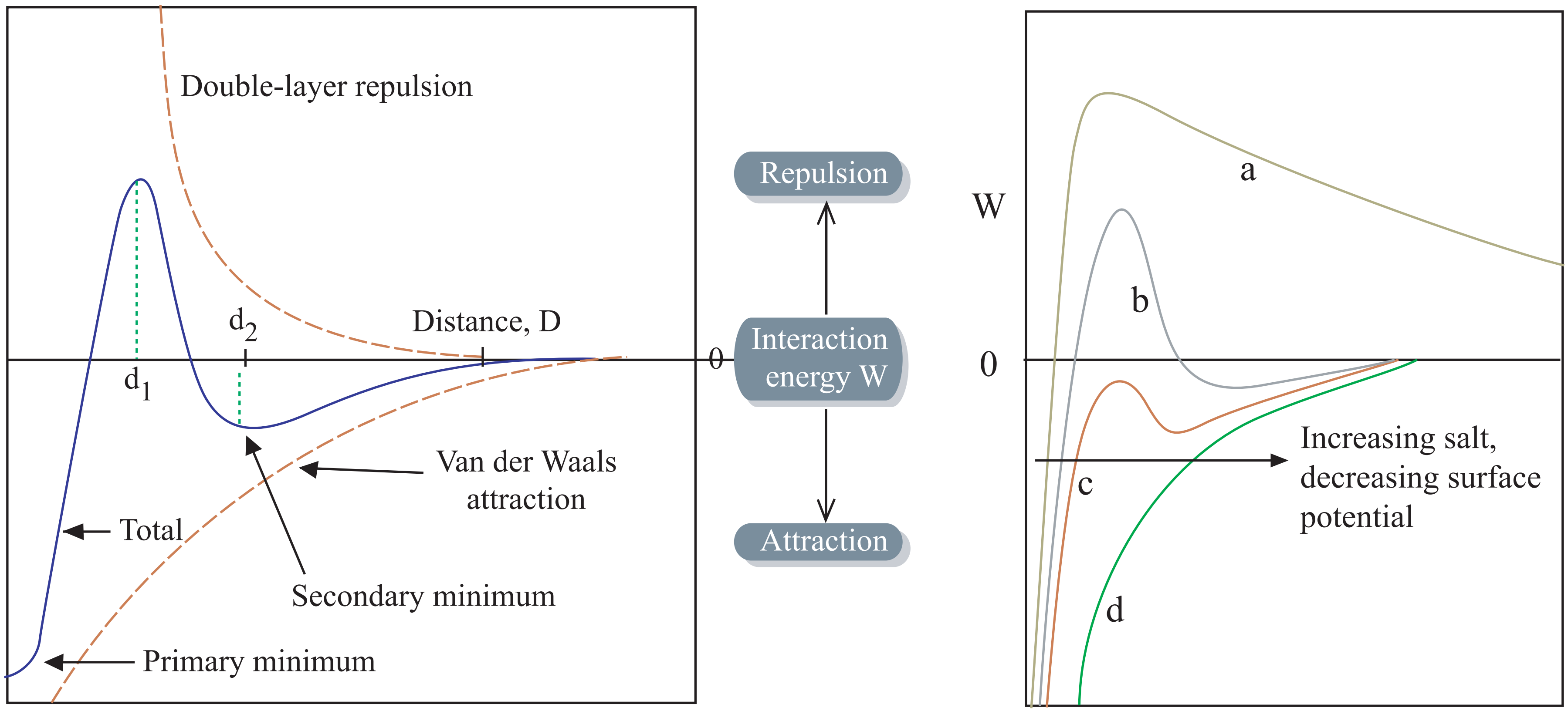
Diffuse double layer affects K

Depends on:
Cations in solution
Pore fluid dielectric constant
Strength of negative mineral charge



Adapted from: www.bham.ac.uk/CivEng/resproj/ liew/ck2_ht4.gif

Effect of ion content on double layer



Adapted from: Reddi, L. N., and H. I. Inyang. *Geoenvironmental Engineering, Principles and Applications*. New York: Marcel Dekker, Inc., 2000, Figure 2.13, pp. 50.

Double-layer shrinkage effects on K

Smaller double layer implies more “free” liquid and greater K

Moderate double-layer shrinkage due to cation concentration increases (e.g. from leachate)

Acute double-layer shrinkage due to organic molecules changing dielectric constant – can increase K by several orders of magnitude

Double-layer swelling effects on K

Larger double layer implies less “free” liquid and lower K - beneficial

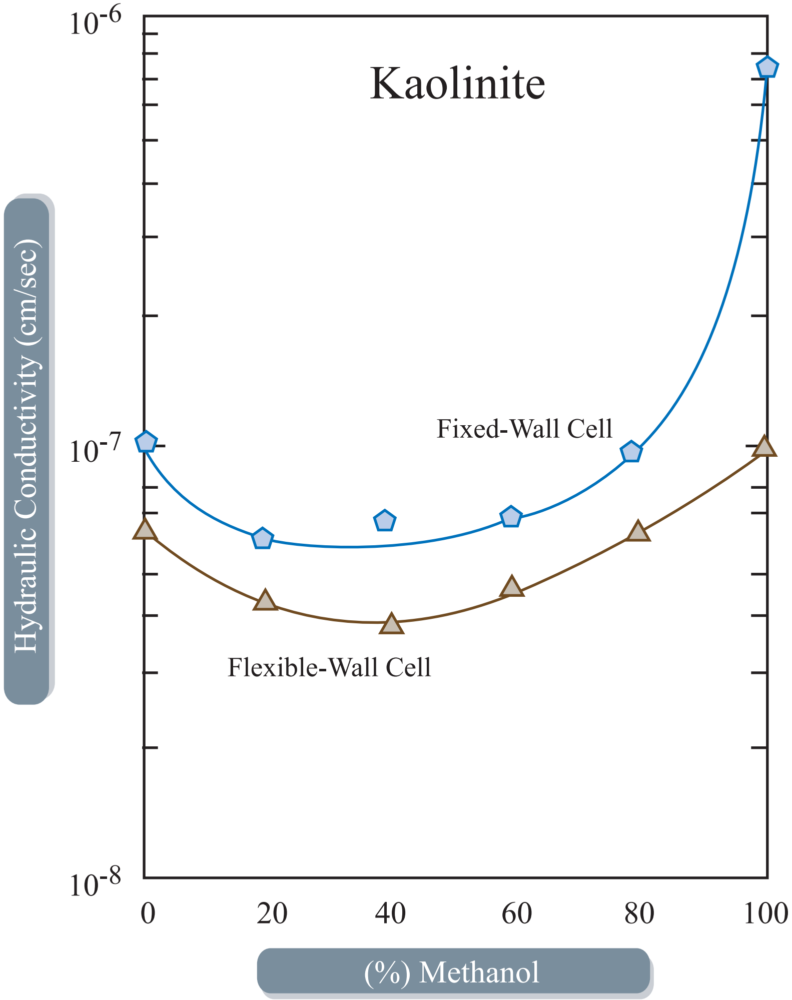
Double-layer swells when cation concentration is reduced

NAPL Effects on Clay

See Fig. 6 in: McCaulou, D. R. and S. G. Huling, 1999. "Compatibility of Bentonite and DNAPLs." *Ground Water Monitoring and Remediation*, Vol. 19, No. 2, Pp. 78.

Organic chemical effect on K

Generally not a problem except for pure solvents and chemicals or very strong solutions



Adapted from: Mitchell, J. K., and F. T. Madsen. "Chemical Effects on Clay Hydraulic Conductivity." In *Geotechnical Practice for Waste Disposal '87*. Edited by Richard D. Woods. New York: American Society of Civil Engineers, 1987, pp. 87-116.