15.1. Soil Properties

15.1.1. Properties of Dry Soils

The particle size distribution is the main characteristic of a soil with gravels (2 mm < d_s < 64 mm), sands (0.0625 mm< d_s < 2 mm), silts (2 microns < d_s < 62.5 microns) and clays (d_s < 2 microns). The percentage of sand, silt and clay has been used for the soil classification in Section 14.1.4. The US standard sieve sizes include No. 10 at 2mm separates sands from gravels, No. 60 at 0.25 mm, No. 100 at 0.15 mm and silts and clays pass No. 200 at 0.075 mm. From the particle size distribution in Figure 15.1, it is important to consider the grain size d_{10} for which 10% of the material by weight is finer. Well-graded mixtures include nearly impervious glacial till and hardpans that experienced consolidation under very high pressure.

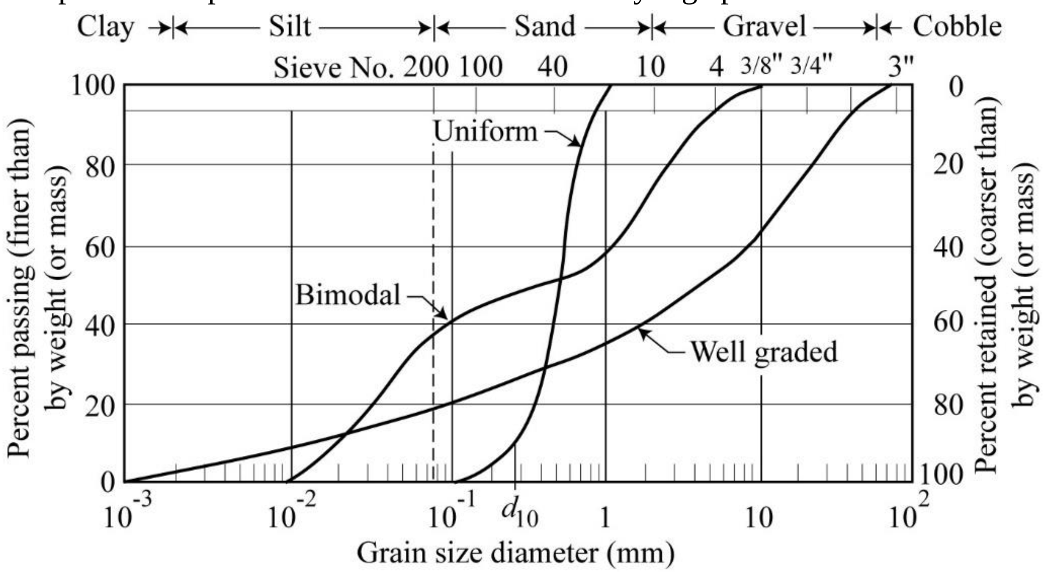

Figure 15.1. Particle size distribution

Clays are very complex given their property to adsorb water. Per Figure 15.2, one basic clay sheet is the tetrahedral silica sheet sketched as a trapezoid with a layer of silicon atoms between a layer of oxygen atoms with one minus charge per silicon atom ($Si_2O_5^{-2}$ structure). The second basic sheet represented by a rectangle is the octahedral sheet or layer of aluminum (or iron/magnesium) atoms between layers of densely packed hydroxyls. Combinations of these basic sheets define the main types of clays. For simplicity, only three types of clay particles are considered: kaolinite, illite and montmorillonite.

Kaolinite (and also serpentine) has a 1:1 structure, meaning that it superposes a silica sheet to an octahedral aluminum sheet to form a structural unit. The thickness of one unit is approximately $7A°$ ($1A°$ = angstrom = 10^{-10} m). The bonds between the oxygens of the silica sheet and the hydroxyls of the aluminum sheet are strong and many units can be stacked up to form very stable minerals that cannot be easily penetrated by water (low swelling). Kaolinite crystals are typically 300-4,000 nm (a nanometer is 1nm = 10^{-9} m) wide, 50-2,000 nm thick, with a low specific surface (surface per unit mass) of 10-20 m^2/g.

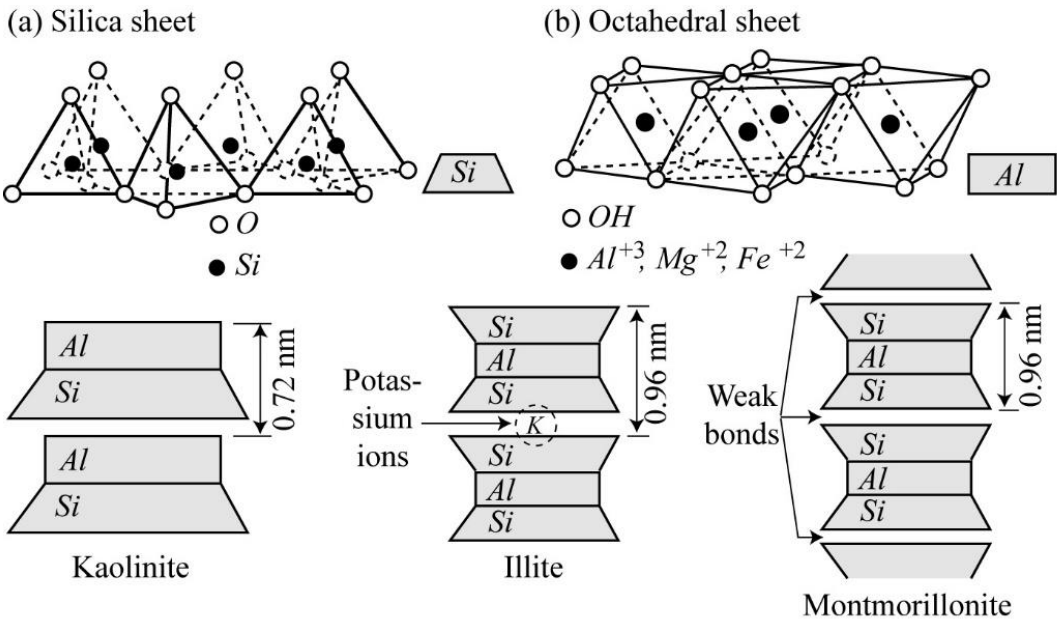

Figure 15.2. Tetrahedral and octahedral sheet, kaolinite, illite and montmorillonite

Illite has a 2:1 structure, meaning that a unit is composed of an octahedral sheet sandwiched between two silica sheets. The unit thickness is about 1 nm $= 10A°$. The units are linked by non-exchangeable potassium and illite will not swell as water cannot easily penetrate between the units. Illite crystals are typically 10,000 nm wide, 30 nm thick with a moderate specific surface (surface per unit mass) of 80-100 m^2/g.

Montmorillonite also has a 2:1 structure, but the bonds between the units are much weaker than the potassium bonds of illite. As a result, water can easily enter between the units and causing rapid swelling and shrinkage of montmorillonite clays. Montmorillonite crystals are typically very small, 100-1,000 nm wide, 3 nm thick with a very high specific surface of 800 m^2/g. Soils with montmorillonite also tend to have higher plasticity.

The cation exchange capacity represents the capacity of a clay to accept cations. Cations in water can be attracted to clay surfaces and higher valence cations can easily replace cations of lower valence. Replacement reactions in soils follow the approximate order

$$Li^+ < Na^+ < H^+ < K^+ < NH_4^+ < Mg^{+2} < Ca^{+2} < Al^{+3} < Zn^{+2} < Fe^{+3} < Ni^{+2} < Cu^{+2}$$

For instance, the swelling of sodium montmorillonite clays can be significantly reduced by the addition of lime ($CaOH$)which replaces Na^+ by stronger Ca^{+2} cations.

Atterberg limits define the water content at certain critical stages of the soil behavior. The water content w is measured as the ratio of the weight of water to the weight of solids in a soil sample. The liquid limit LL is the water content at which the soil behaves like a fluid. The plastic limit PL

is the water content at which a soil reaches the plastic state and the plasticity index $PI = PL - LL$ is the difference in water content between the plastic and liquid limits. Figure 15.3 provides a plasticity chart for different types of clays.

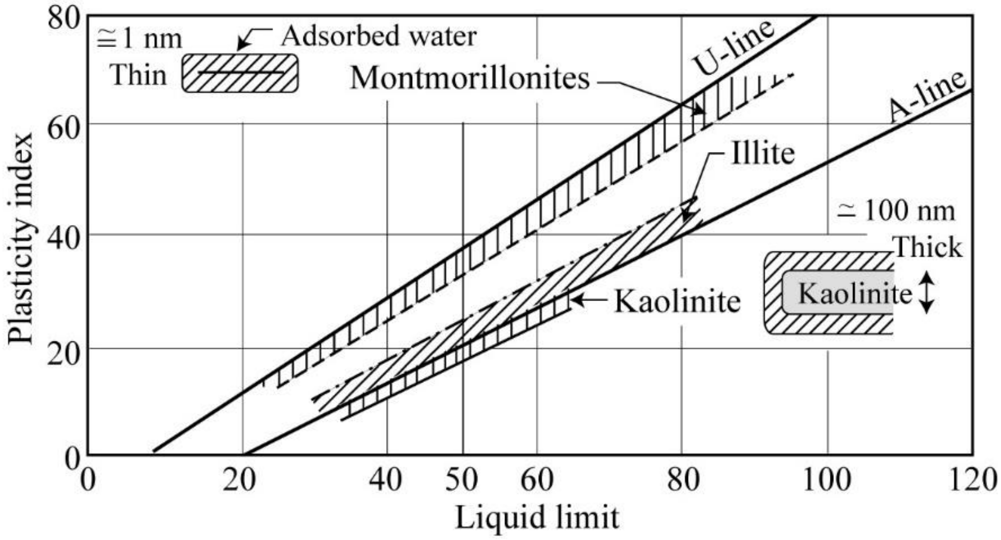

Figure 15.3. Plasticity index chart for different clays (after Holtz and Kovacs, 1981)

The activity of a clay $A = PI / clay\ \ fraction$ is the ratio of the plasticity index to the clay fraction of a soil. Clays are considered inactive when $A < 0.75$ (like kaolinite), normal when $0.75 < A < 1.25$ (e.g. illite), and active when $A > 1.25$ (e.g. montmorillonite). It is important to understand that calcium montmorillonite is active ($A = 1.5$), while sodium montmorillonite is very active ($4 < A < 7$). This means that with only 5% montmorillonite, a soil would have a very high plasticity index (e.g. $20 < PI < 35$). Montmorillonite increases swelling, shrinkage and plasticity of soils. Table 15.1 provides a comparison of the main characteristics of clays.

Table 15.1. Typical properties of clays and saturated soils

	specific gravity	thickness nm	diameter nm	specific surface m^2/g	exchange capacity Meq/100g	cation	liquid limit %	plastic limit %	plasticity index %	activity A	shrinkage limit %
kaolinite	2.62-2.68	50-2,000	100-1,000	10-20	3-8		38-60	27-37	11-23	0.4	25-29
illite	2.60-2.86	30	10,000	80-100	25-40		95-120	45-60	50-70	0.9	14-18
montmorillonite	2.75-2.78	3	300-4,000	800-1,000	80-100		290-710	55-100	215-650	7.2	9.3-15
						Na	710	55	650		
						K	660	100	560		
						Ca	510	80	430		
						Mg	410	60	350		
						Fe	290	75	215		

	porosity n %	void ratio e %	water content w %	ρ_d dry kg/m^3	ρ_t total kg/m^3	γ_d dry lb/ft^3	γ_t total lb/ft^3
Glacial till	20	25	9	2,120	2,320	132	145
Dense mixed sand	30	43	16	1,860	2,160	116	135
Dense sand	34	51	19	1,750	2,090	109	130
Stiff glacial clay	37	60	22	1,700	2,070	106	129
Loose mixed sand	40	67	25	1,590	1,990	99	124
Loose sand	46	85	32	1,430	1,890	90	118
Soft glacial clay	55	120	45	1,220	1,770	76	110
Lightly organic clay	66	190	70	930	1,580	58	98
Very organic clay	75	300	110	680	1,430	42	89
soft bentonite	84	520	194	430	1,270	27	80

* Compiled from Lambe and Whitman (1969) and Holtz and Kovacs (1981)