

MODULE 5.1

Soil formation

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MODULE 5.1

Soil formation

Introduction:

Soils are the fundamental resource supporting agriculture and forestry, as well as contributing to the aesthetics of a green planet. They are also a base from which minerals are extracted and to which solid wastes are disposed. In addition, soils act as a medium and filter for collection and movement of water. By supporting plant growth, soil becomes a major determinant of atmospheric composition and therefore earth's climate.

Particle size is the primary physical property of the soil and it is arbitrarily defined as a material with particle size less than 2mm. Within the material defined as soil, there three primary size categories-inorder of decreasing particle size, sand, silt and clay. Since colloids are defined as particles with diameter smaller than 10mm, soil particles in the clay and small silt fractions belong to this category. Soils that are desirable from agricultural perspective are (intermediate between clay and silt) clay loam. Such soils have beneficial physical properties of lighter soils, and chemical reactivity due to the contribution of clay-sized minerals.

The density of the soil reflects that of the minerals or organic contents that make up its composition .

Another physical property of the soil is structure. Structure is a term used to describe the way in which individual particles are aggregated together to form larger units. Organic matter acts as cementing agent and plays a key role in developing soil structure.

In any given volume of a mineral soil, there is an approximately equal proportion of solids and pore space. The former consists of 45% minerals and 5% organic matter and the latter consists of water and air. For waste treatment, as well as for crop production, the proportion of air and water should be approximately equal so as to create favourable conditions for biological activity (both microbial and plant).

Air and moisture movement through the soil are important factors in the decomposition of organic matter and crop growth. The relative ease with which water moves into and through the soil also influences the extent to which leaching (N losses) and run off (P losses) occur, and thereby the potential for ground and surface water pollution respectively. Soil texture and soil structure are key determinants affecting the movement of both air and water through the soil profile.

Soil texture refers to the proportion of minerals of varying sizes that comprise the solid fraction of the soil. Soil structure refers to the way in which individual primary soil particles (sand, silt and clay) are arranged and held together as more or less distinct recognisable units. At one end of the structural spectrum are single grains (such as sand particles) and at the other extreme are groups of particles that have been packed tightly together into a seemingly continuous mass (massive structure). In the former, air and water move freely; in the latter, air and water movement is severely restricted. Within this spectrum are soils with more or less well-defined segregations of soil particles and pore spaces that afford varying degrees of air and water movement characteristics.

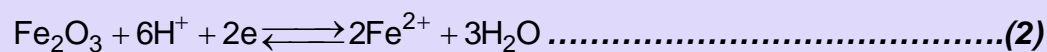
Structure is also a major determinant affecting the permeability, especially in the case of clays. Soils with well developed structure are more permeable than

structureless ones. The volume of space created by structural boundaries may be small compared with the total pore volume of the soil, but it can be a major route for water transport.

Permeability is probably the most significant single factor in influencing the environmental behaviour of the soil. Soils with low permeability can become waterlogged.

When the soil becomes water logged, its physical and chemical properties undergo drastic change. O_2 in such soils is used up by the microorganisms that degrade the soil organic matter. In such soils bonds holding the soil colloidal particles are broken, which causes disruption of soil structure. The soil does not contain the air required by most plant roots and thus it is detrimental to plant growth. Most useful crops with the exception of rice cannot grow on water logged soils.

As a consequence of water logging there is reduction of pE by the action of organic reducing agents acting through bacterial catalysts. Thus the soil becomes more reducing and MnO_2 and Fe_2O_3 are reduced to soluble Mn(II) and Fe(II); the latter being toxic to plants at high levels:



The oxygen content of the air in the soil may be decreased to around 15% and CO_2 content may be several percent higher due to the decay of organic matter. The equilibrium of the process by which roots absorb metals ions from the soil is shifted by the presence of CO_2 .

Kinds of rocks:

Rocks can be broadly recognised into three groups namely igneous, sedimentary and metamorphic. Igneous rocks are formed by the cooling of earth liquid magma. A variety of igneous rocks is formed according to the chemical composition of magma and its rate of cooling. Granite for example are formed by slow cooling of magma and it is high in silica; they contain large proportions of quartz and feldspars which are present as large crystals. In contrast, basalts formed from magma is low in silica; they contain minerals such as amphiboles, pyroxenes and olivines and the crystal size is small because the magma cooled rapidly. Sedimentary rocks are the product of weathering and erosion and has therefore gone through atleast one weathering cycle. They can be described as sand stones, siltstones or clays.

The third group is called metamorphic rocks. High temperatures and pressures cause some degree of recrystallisation of sedimentary rocks, converting sand stones into quartzite and clays into slate.

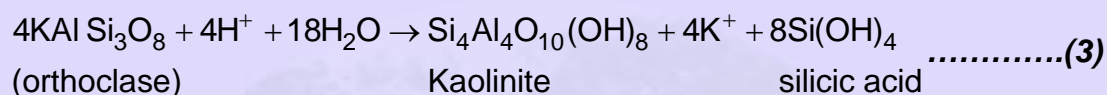
Soils are formed from the three group of rocks and also from deposits that are left by glaciers, from loess, alluvium in valley bottoms and colluvium on the lower slopes of hills.

Weathering process:

Physical weathering causes rocks and minerals to disintegrate. The processes, depending on the climate to which the rock is exposed, include differential thermal expansion and contraction of different minerals, expansion of cracks when water freezes, and abrasion by glaciers and wind-borne sand. Disintegration increases the surface area of the rock and its minerals, allowing chemical decomposition to proceed more quickly.

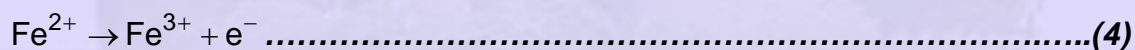
Several processes can be involved in chemical decomposition; in the soil and some of them are shown below.

(a) Hydrolysis: one example for this is the hydrolysis of orthoclase as shown by the equation.



In the reaction, potassium ions and silicic acid are removed leaving kaolinite as residue. Other clay minerals can be formed as shown below.

(b) Oxidation:- The example for this is the oxidation of ferrous iron (Fe^{2+}) to ferric ion (Fe^{3+}) in Biotite.



A member of the mica group of minerals Biotite, contains Fe^{2+} as a constituent of its mineral lattice. During weathering Fe^{2+} is oxidised and forms a coating of $\text{Fe}(\text{OH})_3$, on the surfaces of the weathering products.

Nitrification and denitrification reactions which are example of oxidative and reductive reactions are carried out by soil microorganism.



in which O_2 is reduced to water.

In the absence of O_2 , other substances gains e^- s and are reduced.

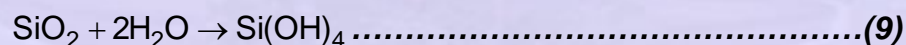


In aerobic conditions oxidation proceeds beyond that shown by equation(5) and ultimately to the formation of CO_2 and H_2O .



With substances other than oxygen as acceptors, oxidation is usually incomplete and various organic compounds are produced including methane, ethylene and acetic acid. All these oxidation reduction reactions are done by soil microorganisms.

(C) Hydration: An example of hydration reaction that is taking place in soils is the hydrolysis of SiO_2 .



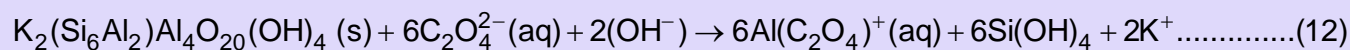
(d) Carbonation: The example for this type of is, that is taking place in sedimentary rocks which contain calcium carbonate.



(e) Complexation:

In many cases chelation contributes substantially to chemical weathering. Aluminium and iron solubility in uncomplexed form in these silicates is small. But their solubility increases substantially due to complex formation.

e.g The reaction of oxalate ion on muscovite as shown below explains this.



Decomposition is also induced by lichens, soil microorganisms and the roots of higher plants. The CO₂ released by respiration into the soil air dissolves in water and lowers the pH, increasing the hydrolysis of minerals. The effect of these biological agents increase the rate of decomposition, especially in soils with strong biological activity.

Soil begin to form as soon as plants establish themselves on a mineral substrate. This might be fragmented rock developed insitu by weathering, debris deposited by ice, wind or rivers, or land reclaimed from the sea. If the conditions for the plant growth are suitable, the content of organic matter can increase quickly. Plant leaves and stem fall on the surface of the soil, and a high density roots develops near the soil surface. Normally therefore, the content of organic matter is highest near the soil surface and decreases with depth.

Mineral components in soil:

As mentioned earlier soil consist of sand, silt and clay particles. The minerals in the soil can be classified as primary minerals and secondary minerals. The minerals in the **sand** and **silt** fractions are the residues from the disintegration of parent material and hence are often known as primary minerals. Generally, the minerals in the sand and silt fractions have little effect on the chemical properties of the soil, although micas and feldspars, when present slowly release plant nutrients such as calcium, magnesium and potassium on weathering.

But the **clay** fraction is different. The minerals in the **sand** and **silt** fractions are the residues from the disintegration of parent material. Those in the **clay** fraction are products of chemical weathering and hence are often known as secondary minerals or clay minerals, and consist of aluminosilicates and hydrated oxides. The minerals in the clay fraction impart chemical and physical properties to soil which strongly influence its behaviour, for example in adsorbing cations, anions and pesticides and acting as a source of plant nutrients. Their properties can be best understood from a knowledge of their structure.

The aluminosilicate in the clay fraction range from crystalline, through poorly crystalline to amorphous, as shown by x-ray diffraction. All consist of repeating units of (i) a silicon atom surrounded by oxygen atoms in the form of a tetrahedron, and (ii) an aluminium, magnesium or iron atom surrounded by oxygen atoms and hydroxyl groups in the form of octahedron. The repeating units are linked to form sheets called tetrahedral and octahedral sheets, which are chemically combined.

In poorly crystalline and amorphous aluminosilicates, these units are combined with little discernible order but have an extensive surface, characteristically of hydroxyl groups.

The three types each layer consist of the following:

1:1 clay minerals, 1 tetrahedral : 1 Octahedral sheet, as in kaolinite and halloysite;

2:1 clay minerals, 2 tetrahedral: 1 Octahedral sheet as in pyrophyllite, illite, vermiculite, and smectites, eg. montmorillonite;

2:2: clay minerals, 2 tetrahedral: 1 Octahedral sheet plus an octahedral interlayer of magnesium hydroxide or aluminium hydroxide, as in chlorite.

The simplest of the clay structure is shown by kaolinite (fig.1) ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$), with one octahedral (Al) sheet and one tetrahedral (Si) sheet forming a 1:1 clay mineral. Successive 1:1 layers are stacked above each other and held together by hydrogen bonds between the oxygens in one layer and the hydroxyl groups in the next layer. The hydrogen bonds prevent the other groups from entering between the individual layers and keep the structure relatively rigid.

Members of the other major group (i.e 2:1 clay minerals) the smectites, each consist of one octahedral sheet sandwiched between two tetrahedral sheets. Montmorillonite ($\text{Al}_2(\text{Si}_4\text{O}_{10})_2(\text{OH})_4$) and illite ($\text{K}_{0.5}\text{Al}_3(\text{Si}_5\text{Al})\text{O}_{20}(\text{OH})_4$) and illite ($\text{K}_{0.5}\text{Al}_3(\text{Si}_5\text{Al})\text{O}_{20}(\text{OH})_4$).

are the two most common members of 2:1 clays. In each the oxygens of one 2:1 layer always face oxygen of the next layer, therefore no hydrogen bonding can take place.

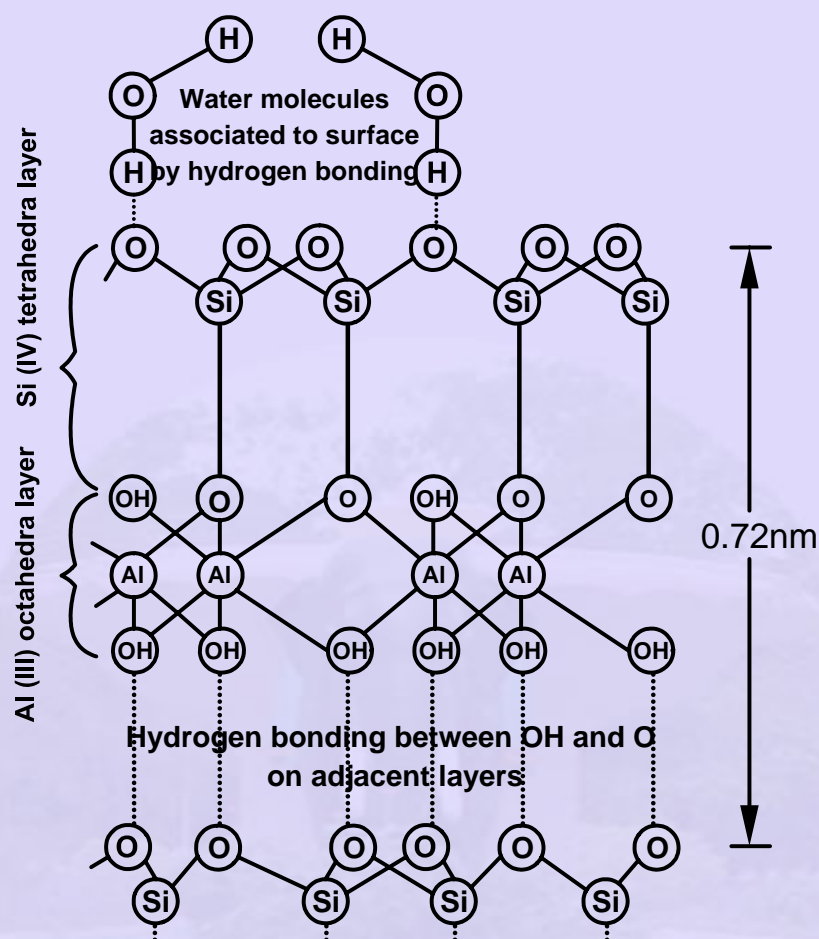


Fig 1 Representation of structure of clay (Kaolinite)

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In the tetrahedral sheet silicon may be replaced by aluminium and in the octahedral sheet aluminium may be replaced by magnesium and iron. The smectite structure (montmorillonite) is electrically neutral, but substitutions make the structure electrically negative, because the substituting ion has a lower positive charge. Substitution of tetrahedral Si^{4+} by Al^{3+} or octahedral Al^{3+} by Mg^{2+} , gives a single negative charge which is balanced by a cation held between silicate layers. The substitution is described as isomorphous because the substituting ion must be of similar size.

Isomorphous substitution is not significant in 1:1 minerals and only in partial in 2:1 and 2:2 clay minerals. The negative charge that results from substitution is 'permanent' in that it is independent

One other property of 2:1 clay minerals needs to be mentioned here. The extent of isomorphous substitution is illite>vermiculite>smectite. Illite has a high charge and the alumina/silica layers are held tightly together by potassium ions. With smectites, the layers are more weakly held, water molecules can enter the interlayer space and cause the mineral to swell. This has implications for the cation exchange property of the mineral.

Also constituents of the clay fraction are the hydrated oxides of Fe, Al and Mn which are often important in highly weathered soils. Commonly occurring minerals include goethite, $\text{Fe O}(\text{OH})$; haematite, Fe_2O_3 ; gibbsite $\text{Al}(\text{OH})_3$; and birnssite, a magnesium oxide of variable composition. Generally they occur in poor crystalline form. Depending on the pH they can be either positively or negatively charged.