HEAT TRANSFER IN SOIL

3-1 Definition of soil

Soil is a mixture of organic matter, minerals, gases, liquids, and organisms that together support life. The Earth's body of soil is the pedosphere, which has four important functions: it is a medium for plant growth; it is a mean of water storage, supply and purification; it is a modifier of Earth's atmosphere; it is a habitat for organisms; all of which, in turn, modify the soil. Soil interfaces with the lithosphere, the hydrosphere, the atmosphere, and the biosphere. The term pedolith, used commonly to refer to the soil, literally translates ground stone. Soil consists of a solid phase of minerals and organic matter (the soil matrix), as well as a porous phase that holds gases (the soil atmosphere) and water (the soil solution). Accordingly, soils are often treated as a three-state system of solids, liquids, and gases. Soil is a product of the influence of climate, relief (elevation, orientation, and slope of terrain), organisms, and its parent materials (original minerals) interacting over time. It continually undergoes development by way of numerous physical, chemical and biological processes, which include weathering with associated erosion. Given its complexity and strong internal connectedness, it is considered an ecosystem by soil ecologists. Most soils have a dry bulk density (density of soil taking into account voids when dry) between 1.1 and 1.6 g/cm^3, while the soil particle density is much higher, in the range of 2.6 to 2.7 g/cm^3. Little of the soil of planet Earth is older than the Pleistocene and none is older than the Cenozoic, although fossilized soils are preserved from as far back as the Archean. Soil science has two basic branches of study: edaphology and pedology. Edaphology is concerned with the influence of soils on living things. Pedology is focused on the formation, description (morphology), and classification of soils in their natural environment. In engineering terms, soil is included in the broader concept of regolith, which also includes other loose material that lies above the bedrock. Soil is commonly referred to as earth or dirt; technically, the term dirt should be restricted to displaced soil.

3-1-1 Functions of soils

Soil is a major component of the Earth's ecosystem. The world's ecosystems are impacted in far-reaching ways by the processes carried out in the soil, from ozone depletion and global warming, to rainforest destruction and water pollution. With respect to Earth's carbon cycle, soil is an important carbon reservoir, and it is potentially one of the most reactive to human disturbance and climate change. As the planet warms, it has been predicted that soils will add carbon dioxide to the atmosphere due to increased biological activity at higher temperatures, a positive feedback (amplification). This prediction has, however, been questioned on consideration of more recent knowledge on soil carbon turnover. Soil acts as an engineering medium, a habitat for soil organisms, a recycling system for nutrients and organic wastes, a regulator of water quality, a modifier of atmospheric composition, and a medium for plant growth, making it a critically important provider of ecosystem services. Since soil has a tremendous range of available niches and habitats, it contains most of the Earth's genetic diversity. A gram of soil can contain billions of organisms, belonging to thousands of species, mostly microbial and in the main still unexplored. Soil has a mean prokaryotic density of roughly 108 organisms per gram, whereas the ocean has no more than 107 procaryotic organisms per milliliter (gram) of seawater. Organic carbon held in soil is eventually returned to the atmosphere through the process of respiration carried out by heterotrophic organisms, but a substantial part is retained in the soil in the form of soil organic matter; tillage usually increases the rate of soil respiration, leading to the depletion of soil organic matter. Since plant roots need oxygen, ventilation is an important characteristic of soil. This ventilation can be accomplished via networks of interconnected soil pores, which also absorb and hold rainwater making it readily available for plant uptake. Since plants require a nearly continuous supply of water, but most regions receive sporadic rainfall, the water-holding capacity of soils is vital for plant survival. Soils can effectively remove impurities, kill disease agents, and degrade contaminants, this latter property being called natural attenuation. Typically, soils maintain a net absorption of oxygen and methane, and undergo a net release of carbon dioxide and nitrous oxide. Soils offer plants physical support, air, water, temperature moderation, nutrients, and protection from toxins. Soils provide readily available nutrients to plants and animals by converting dead organic matter into various nutrient forms.

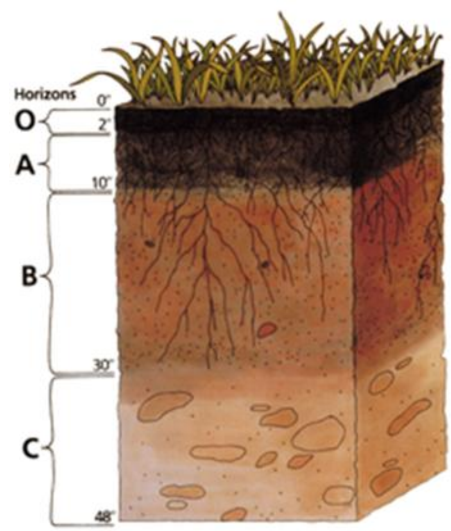

Fig.1. Soil Profile: Darkened topsoil and reddish subsoil layers are typical in some regions.

3-1-2 Description

Components of a loam soil by percent volume:

Water (25%), Gases (25%), Sand (18%), Silt (18%), Clay (9%), Organic matter (5%).

A typical soil is about 50% solids 45% mineral and 5% organic matter, and 50% voids of which half is occupied by water and half by gas. The percent soil mineral and organic content can be treated as a constant (in the short term), while the percent soil water and gas content is considered highly variable whereby a rise in one is simultaneously balanced by a reduction in the other. The pore space allows for the infiltration and movement of air and water, both of which are critical for life in soil. Compaction, a common problem with soils, reduces this space, preventing air and water from reaching plant roots and soil organisms. Given sufficient time, an undifferentiated soil will evolve a soil profile which consists of two or more layers, referred to as soil horizons that differ in one or more properties such as in their texture, structure, density, porosity, consistency, temperature, color, and reactivity. The horizons differ greatly in thickness and generally lack sharp boundaries; their development is dependent on the type of parent material, the processes that modify those parent materials, and the soil-forming factors that influence those processes. The biological influences on soil properties are strongest near the surface, while the geochemical influences on soil properties increase with depth. Mature soil profiles typically include three basic master horizons: A, B and C. The solum normally includes the A and B horizons. The living component of the soil is largely confined to the solum, and is generally more prominent in the A horizon. The soil texture is determined by the relative proportions of the individual particles of sand, silt, and clay that make up the soil. The interaction of the individual mineral particles with organic matter, water, gases via biotic and abiotic processes causes those particles to flocculate (stick together) to form aggregates or peds. Where these aggregates can be identified, a soil can be said to be developed, and can be described further in terms of color, porosity, consistency, reaction (acidity), etc. Water is a critical agent in soil development due to its involvement in the dissolution, precipitation, erosion, transport, and deposition of the materials of which a soil is composed. The mixture of water and dissolved or suspended materials that occupy the soil pore space is called the soil solution. Since soil water is never pure water, but contains hundreds of dissolved organic and mineral substances, it may be more accurately called the soil solution. Water is central to the dissolution, precipitation and leaching of minerals from the soil profile. Finally, water affects the type of vegetation that grows in a soil, which in turn affects the development of the soil, a complex feedback which is exemplified in the dynamics of banded vegetation patterns in semi-arid regions. Soils supply plants with nutrients, most of which are held in place by particles of clay and organic matter (colloids)The nutrients may be adsorbed on clay mineral surfaces, bound within clay minerals (absorbed), or bound within organic compounds as part of the living organisms or dead soil organic matter. These bound nutrients interact with soil water to buffer the soil solution composition (attenuate changes in the soil solution) as soils wet up or dry out, as plants take up nutrients, as salts are leached, or as acids or alkalis are added. Plant nutrient availability is affected by soil pH, which is a measure of the hydrogen ion activity in the soil solution. Soil pH is a function of many soil forming factors, and is generally lower (more acid) where weathering is more advanced. Most plant nutrients, with the exception of nitrogen, originate from the minerals that make up the soil parent material. Some nitrogen originates from rain as dilute nitric acid and ammonia, but most of the nitrogen is available in soils as a result of nitrogen fixation by bacteria. Once in the soil-plant system, most nutrients are recycled through living organisms, plant and microbial residues (soil organic matter), mineral-bound forms, and the soil solution. Both living microorganisms and soil organic matter are of critical importance to this recycling, and thereby to soil formation and soil fertility. Microbial activity in soils may release nutrients from minerals or organic matter for use by plants and other microorganisms, sequester (incorporate) them into living cells, or cause their loss from the soil by volatilization (loss to the atmosphere as gases) or leaching.

3-2 Transfer of heat within soil

Transport of heat within soils can occur by conduction and convection, with or without latent heat transport. Heat conduction is governed by the thermal soil properties, volumic heat capacity, and heat conductivity. The thermal exchange processes at the soil surface are dominated by the meteorological conditions and occur by radiation, conduction, and convection, with or without phase changes. The thermal soil properties are strongly dependent on water content. Many processes occurring in soils are strongly influenced by temperature. This is true especially for biological processes such as germination of seeds, plant growth, root development and activity, and microbial activity. Physical and chemical processes influenced by temperature are frost heaving, weathering, and decomposition of organic matter. Soil temperatures are determined by the transport processes of heat within the soil and exchange of heat between the soil and the atmosphere. There are three basically different processes whereby heat can be transported—conduction, convection, and radiation. Conduction of heat occurs by transmission of thermal energy of motion from one microscopic particle to another. The transportation of heat by a fluid in motion is called convection. Heat convection with accompanying phase changes can increase heat transfer tremendously. This is especially true for water, which has very high values of latent heat of condensation/evaporation and freezing/melting. Radiation is the transfer of thermal energy from a body to its surroundings by electromagnetic waves. Thus, in contrast to conduction and convection, radiation can occur through a vacuum. The thermal state may have a major influence on the moisture condition of a pavement or foundation. Thermal gradients due to temperature changes on the surface will induce not only heat flow in the pavement but also moisture flow. Freezing and thawing are definitely the most important aspects linking temperature to water flow. Furthermore, a freezing temperature significantly reduces the permeability of soils but also increases the moisture flow caused by hydraulic gradients due to ice lens formation in the frozen soil. Moreover, the water viscosity depends on the temperature; at higher temperature, some water will flow in the vapour phase, and this depends on the temperature gradient. Heat flow and moisture flow are, therefore, linked processes with complex interaction between them. This chapter will describe the basis of heat transfer laws and models.

3-2-1 Basic Principles of Heat Transfer

The basic principles to model the complete time-dependent heat transfer in soils are described in this section. More details of these and the associated effects can be found in some of the better or more specialist geotechnical textbooks, for example Mitchell and Soga (2005) or Fredlund and Rahardjo (1993). The water content in various road structures and the underlying soil are subject to climatic (temperature) effects. An example of the thermal variation in a road structure is given in Fig. 2. It can be clearly seen that the thermal state is definitely changing, which means that it is characterized by the heat transfer properties of the material. Temperatures may be positive or negative (inducing freezing). Heat transfer in soils is due to conduction, radiation, convection and vapor diffusion. A general overview of thermal transfer may be found in many textbooks, e.g. Selvadurai (2000) or Lewis and Schrefler (1998). As pavement surface temperature depends greatly on the weather, typically changing hourly and daily, the physical process never reaches a steady state (i.e. there would be only a long-term equilibrium). Geostructures, like road pavements and embankments, are made up of porous materials with solid and fluid phases. At micro-scale, i.e. the grains and pores scale, the heat transfer is highly complex, involving convection and radiation in the pores.

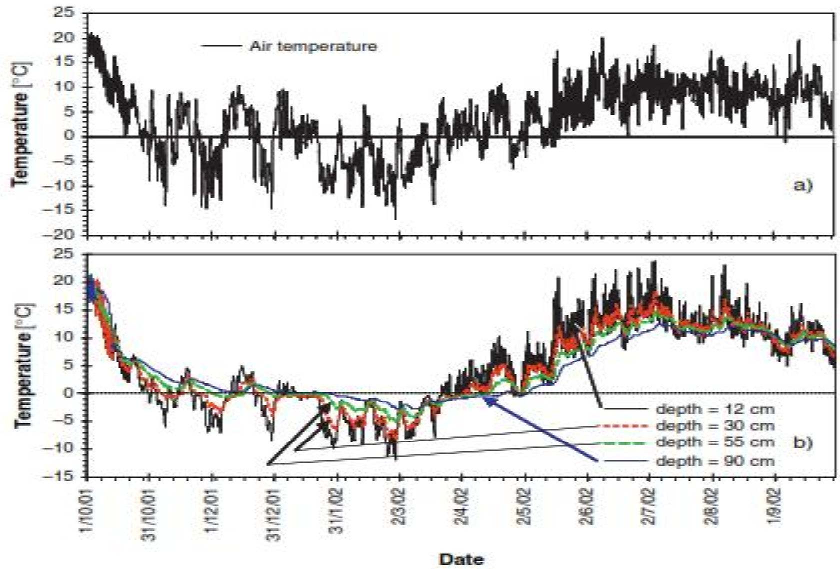

Fig. 2. Hourly measurement during one year in SW Iceland (a) of air temperature and (b) at four depths in a pavement structure

3-3 Nature of soil

- **Formation of Soil**

Weathering gradually breaks rock into smaller and smaller fragments.
1. Does not become high quality soil until plants and animals live on them.
2. Plants and animals add organic matter to the rock fragment.
Remains of plants and animals including leaves, twigs, roots and dead worms and insects.
3. Soil is a mixture of weathered rock, decayed organic matter, mineral fragments, water, and air.