germination and retard seedling growth by limiting gaseous exchange, (c) Seedlings that emerge through hard crust can suffer from drought stress because of low water infiltration into the soil.

Weather

Wetting–drying and freeze-thaw cycles affect aggregation (see Chapter 4). Consequently, these processes also influence formation and strength of crust. Crust strength is more if a heavy rain is followed by dry and hot weather that desiccates the crust.

Soil Properties

Susceptibility to crust formation also depends on numerous soil properties. Important among these are texture, clay mineralogy, soil organic matter content, and degree and strength of aggregates. Resistance of surface aggregates to raindrop impact, shearing force of overland flow, and to the disruptive force of entrapped air upon quick wetting are important soil factors. The mean weight diameter (MWD) and the median aggregate diameter (see Chapter 4) (D_{50}) are strongly correlated with susceptibility to crusting (Bajracharya, 1995).

Field Moisture Content

The antecedent soil moisture content or soil wetness at the beginning of the rainfall influences aggregate strength, slaking or dispersion, infiltration rate, and the rate of overland flow (le Bissonnais, 1990). Under initial dry soil conditions, the dispersion is caused by slaking. Slaking causes rapid aggregate breakdown, quickly filling the intraaggregate pore space with microaggregates or dispersed primary particles. Under initial dry soil conditions, the aggregate breakdown depends more on rainfall rate than on its kinetic energy or momentum. Under wet soil conditions, aggregates are less prone to slaking but more to the raindrop impact. The surface seal formation is caused by the kinetic energy or momentum of the rain and overland flow. Raindrop impact easily disrupts the aggregate when the aggregate strength is low due to wetness (Farres, 1978).

Microrelief

Microrelief is defined by surface cloddiness, clod size, and geometry. The microrelief is prominent soon after plowing (see Fig. 6.13a). Rough seedbed decreases susceptibility to crust formation (Burwell and Larson, 1969). Microrelief also controls the physical processes occurring at the soil surface, e.g., microrills, surface depressions, infiltration rate, etc.

6.1.3 Mechanisms of Crust Formation

Crust formation involves dispersion of aggregates followed by orientation and hardening by desiccation. Thus, properties of the double layer and stability of the colloidal system are important to crusting (van Olphan, 1963; Young and Warkentin, 1966; Sumner, 1992) (see also Chapter 3). Flocculation (which is caused by attractive forces) and slaking (which is caused by repulsive forces) are both present in the electric double layer. In addition, colloid particles are also subject to Brownian movement. Therefore, dispersion depends on the following factors:

Charge Distribution on Soil Colloids. The charge distribution on soil colloids depends on surfaces with permanent charge (e.g., 2:1 clay minerals, 1:1 clay minerals), surfaces with variable charge (e.g., oxides, amorphous minerals, soil organic matter), and other soil conditions. Soils with lowactivity clays are more prone to dispersion than those with high-activity clays. Similarly, soils with low concentration of soil organic matter are more prone to crusting than those with higher concentrations.

Properties of the Electric Double Layer. Effective thickness of the double layer, the surface charge, surface potential, and other properties of the double layer are influenced by relative proportion of the colloidal surfaces with permanent and variable charge, nature of the cations on the exchange complex, and degree of hydration. The thickness of the double layer also depends on the nature of cations on the exchange complex. Predominance of monovalent cations (e.g., Na^+) increases the thickness of the double layer (see Chapter 3).

Surface Charge on Soil Particles. All soils have both permanent and variable charge, and these charges change with soil pH especially in soils with variable charge surfaces. Coulombic interactions are extremely important in dispersion, these interactions depend on variations in surface charges. Under dilute electrolyte conditions, there is a maximum overlap of oppositely charged double layer that results in maximum positive Coulombic interactions and flocculation.

Particle Repulsion. The colloidal stability is determined by the net effect of van der Waals forces of attraction and the electrical double layer repulsion forces. The double layer repulsion is given by Eq. (6.1) (Olphen, 1963; Sumner, 1992).

$$E_r = \left[\frac{64nKT}{k}\right]\left[\frac{\exp(Ze\psi_o/2K_BT)-1}{\exp(Ze\psi_o/2K_BT)+1}\right]^2 e^{-2K_Bd} \quad (6.1)$$

where E_r is the repulsive energy of the double layer, n is the electrolyte concentration in the equilibrium solution, Z is the valency of the counter cations, e is electronic charge K_B is Boltzmann constant, T is temperature. 1/k is an expression of the effective thickness of the double layer, and d *is* the half distance between the plates. The magnitude of repulsive energy between particles suspended in electrolytes of varying counter-ion concentration and valency as computed by Eq. (6.1) is graphically illustrated in Fig. 6.5. The graph shows a rapid increase in repulsive force with reduction in the concentration or valency of the counter ion. For colloidal particles, where the distance between the plates is small compared with the thickness, the attractive energy due to van der Waals forces is given by Eq. (6.2) (Gregory, 1989; Sumner, 1992).

$$E_a = \frac{A}{48\pi d^2} \quad (6.2)$$

where A is the Hamaker constant, and d is the half distance between the plates. The net energy $(E_n=E_r-E_a)$, which determines the dispersion or flocculation, also depends on the electrolyte concentration. In the case of low electrolyte concentration, the repulsive energy (E_r) dominates the attractive energy (E_a) and the clay particles remain dispersed and the colloidal system is very stable. In case of high concentration, the E_a dominates and rapid flocculation takes place. There exists a critical flocculation concentration (CFC) where the energy barrier just disappears (Gregory, 1989). In addition, there are other numerous repulsive forces, such as hydration repulsive forces. Similarly, some other attractive forces include hydrophobic attractive forces. For additional details, readers are referred to a review by Sumner (1992).

Rearrangement of Particles. Once soil particles are dispersed, the next step in the formation of crust is the reorientation and development of a close packing arrangement of particles. The rearrangement may occur due to electrokinetic processes, and movement of dispersed particles with the infiltrating water. Smaller particles get lodged in between the larger particles, clogging the pores and increasing soil bulk density.

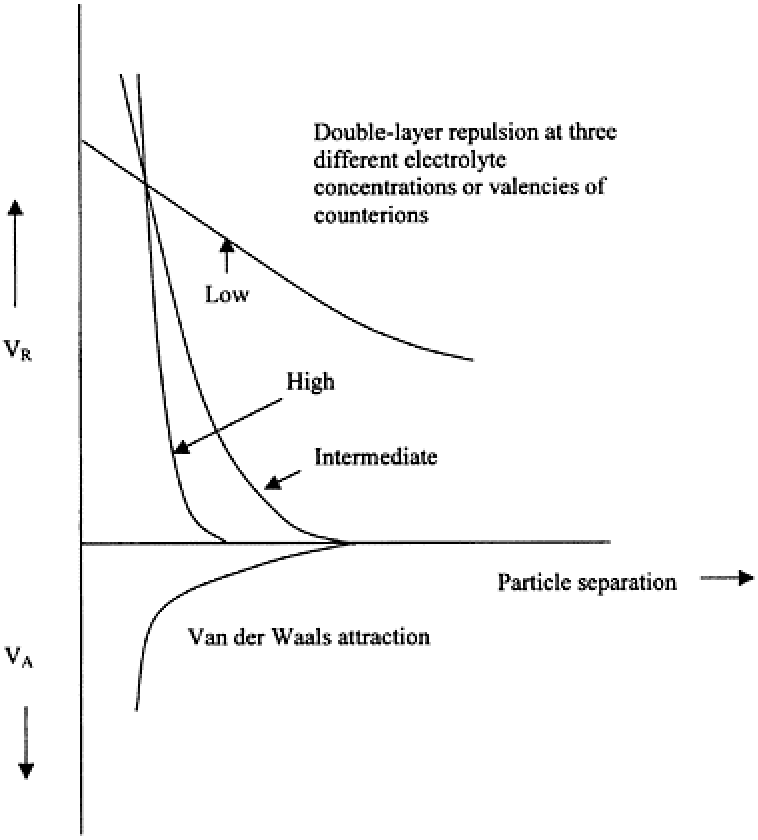

Figure 6.5 Schematic representation of the variation in repulsive and attractive forces between colloidal particles of like charge with distance from the particle surface. (Redrawn from Van Olphen, 1963, and Summer, 1992.)

Desiccation. Rapid drying and desiccation soon after dispersion and reorientation are crucial to crusting and surface seal formation. Crust formation is weak or it completely breaks down if the weather conditions favor freeze-thaw or wet-dry cycles.

6.1.4 Properties of Crust

The crusted layer is more dense but may be of similar textural makeup than the unaffected soil beneath it. The crust is primarily characterized by reduction in total volume, size, shape, and continuity of pores. Thickness of the crust may range from <1 mm to 10 mm (Norton, 1987). Very thin crusts are called “skin seal.” These microlayers are usually <0.1 mm thick, extremely dense with no visible pores (McIntyre, 1958a; b). Skin seals may be formed by reorientation of fine dispersed particles and/or washed-in fine material that plug the larger pores. The magnitude of reduction in porosity of the crust may range from 30 to 90%, with corresponding decrease in pore size. The pore diameter in the crust may be as small as 0.075 mm (Valentin and Figueroa, 1987). There may be no relationship between crust and infiltration rate or hydraulic conductivity due to other interacting factors. The crust may also be in a single or multiple layer (Fig. 6.6, West, et al., 1992). Sedimentary crusts usually comprise multiple layers (Bajracharya and Lal, 1999). The stratification of particles within a crusted layer are indicative of the differences in settling velocity as governed by Stokes law (see Chapter 3). A crust formed upon drying of a ponded area receiving runoff is characterized by clay layer on the top followed by silt and sand. The clay skin cracks on drying and generally curls upward.

6.1.5 General Model for Surface Crust Development

There are several models of crust formation. Important among these is the one proposed by West, et al. (1992). West and colleagues proposed a fourstage model of the formation of crust (Fig. 6.7):

Stage 0. Stage 0 represents the condition of the freshly tilled soil before any rainfall. Prominent microrelief, high surface roughness determined by large clods, and lack of crustation are characteristics of this stage.

Stage 1. Stage 1 or the initial stage of crust development involves breakdown of aggregates and particle rearrangement due to raindrop impact and slaking. The aggregate disruptions result in formation of a disruptional layer.

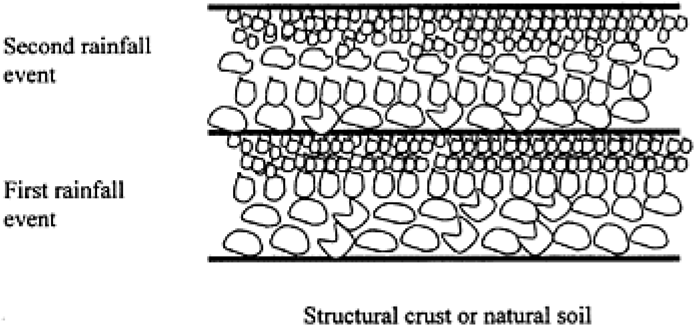

Figure 6.6 Multiple layer crust formed due to successive rainfall events. (Redrawn from West et al., 1992.)

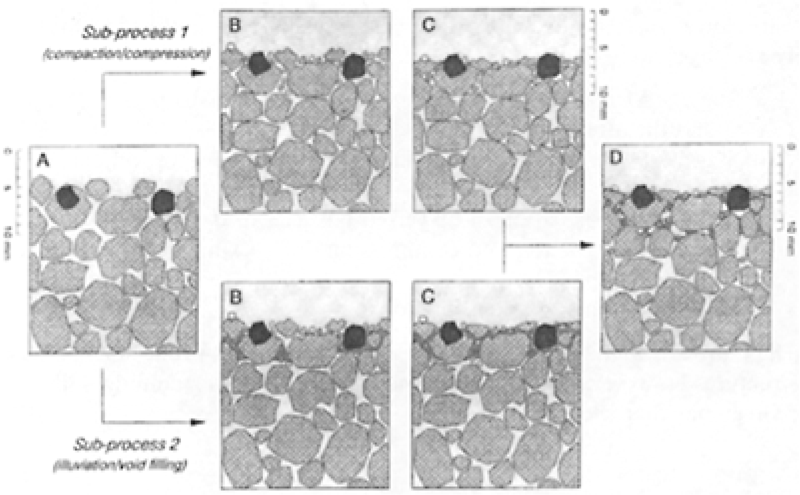

FIGURE 6.7 Conceptual model of crust formation processes and resulting crust. Black polygons represent stones, gray polygons—aggregates, small circles—sand grains, and dark gray shading—oriented fine particles (clay). (From Bajracharya, 1995.)

Stage 2. Stage 2 may involve two pathways. For a soil of high aggregates stability and low susceptibility to dispersion, this stage represents continued development of the disruptional layer. In addition, aggregate coalescence may occur beneath the zone of aggregate disruption and thicken the disruptional layer. For a soil with weak aggregation and high potential for dispersion, the particle disfunction is more extensive, and the released micromass may move downward to form a washed-in layer. The surface layer may become smooth due to removal of the microrelief.

Stage 3. Stage 3 represents the maximum development of the crust, leading to maximal runoff and erosion of the washed-out layer. There may be further thickening of the disruptional layer and formation of a secondary washed-out layer. However, the released micromass may be washed out in the runoff. The microrelief may flatten during this stage, and soil surface may be covered by a sedimentary crust.

Bajracharya and Lal (1999) proposed another model. They observed that there are two parallel subprocesses leading to formation of crust on an Alfisol in central India. These are: (i) physical compaction and compression due to the force of raindrop impact, and (ii) close packing of particles by filling in of pores by aggregate breakdown products. Formation of a "structural crust" of this nature occurs in five stages as outlined in Fig. 6.7. These stages are:

Stage 1: Mechanical breakdown of aggregates due to raindrop impact and the attendant slaking

Stage 2: Differential swelling, slaking and dispersion of soil due to soil wetting

Stage 3: Translocation of dispersed particles into the pores

Stage 4: Compaction and compression due to kinetic and mechanical forces

Stage 5: Drying and densification

These processes are generic and may apply to all crust-prone soils of weak structure. However, specific steps and stages may differ among soils and ecoregional characteristics.

6.1.6 Characterization of Crust

There are several methods to characterize properties of crust (Fig. 6.8). Properties of the crust may be characterized by evaluation of: (i) thickness, (ii) micromorphology by thin section (Norton, 1987), (iii) hydraulic properties by measuring crust conductance (McIntyre, 1958a; Falayi and Bouma, 1975), (iv) strength by penetrometer measurement, and (v) potential adverse effect on seedling emergence by measuring crust strength through the buried nail or buried balloon technique (Arndt, 1965a; b). Crust strength can also be measured by modulus of rupture (see chapter on strength properties). Simple techniques of characterizing soil crust have been developed for use in the field and laboratory conditions (Brossman et al., 1982; Franzmeier et al., 1977; Parker and Taylor, 1965; Taylor, 1962, etc.). A simple device used in the laboratory, described by Sutch, et al. (1983), is shown in Fig. 6.9.

6.1.7 Crust Management

Crusting has adverse impacts on seedling emergence and growth (Arndt, 1965a; b; Parker and Taylor, 1965). Thus, crust management is important to obtaining high yields. There are several technological options for crust management (Fig. 6.10), and the choice of technology also depends on the causes of crust formation. In addition to the impact of raindrops on an unprotected soil, crust may also be caused by the trampling action of livestock or humans, or vehicular traffic of farm operations. Preventative measures are based on strategies of enhancing aggregation,

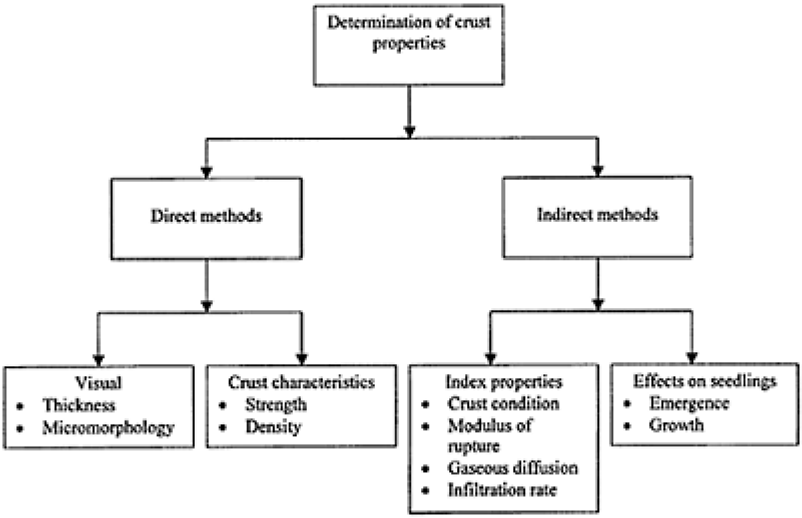

FIGURE 6.8 Methods of determining properties of crust.

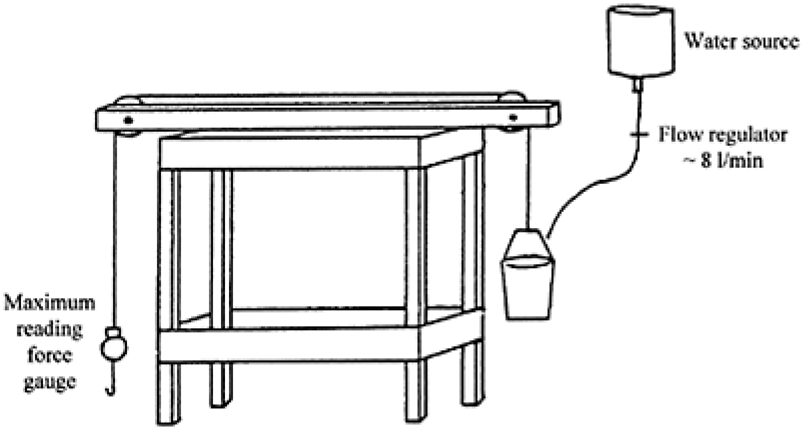

FIGURE 6.9 An apparatus used to measure crust strength. (Sutch et al., 1983.)

improving soil structure, and minimizing the disruptive effects of raindrop impact. The curative measures involve strategies of managing crust once it has been formed. Use of inorganic (gypsum) and organic amendments (compost, farmyard manure) helps to maintain clay in an aggregated or flocculated state. Use of conservation tillage and residue

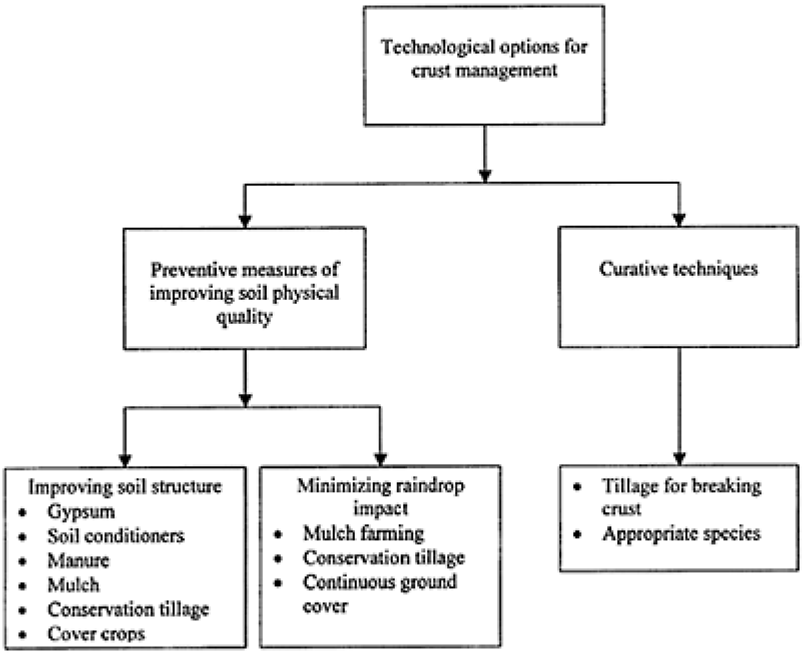

FIGURE 6.10 Soil and crop management options for reducing crust formation and minimizing adverse effects on crops.

mulch minimizes crust formation because of the protection against raindrop impact. Cover on the soil surface, canopy cover or crop residue mulch, is an effective measure to reduce the raindrop impact. On the other hand, tertiary tillage (harrowing or rotary hoe) can be used to disrupt depositional crust and produce rough soil surface. Better spacing of plants in the row (Metzer, 2002) can also improve stand establishment in crustprone soils. Choice of appropriate planters and sowing depth are also critical to reducing adverse impact of crust on stand establishment (Nabi et al., 2001; Hemmat and Khashoei, 2003). Management and enhancement of soil organic matter content is a useful strategy to increase aggregate strength and stability and minimizes risks of structural crust formation. Soil conditioners and polymers have also been found useful to improve aggregation and minimize crusting (Shainberg et al., 1989). Application of soil conditioners, manure, or mulch on the seed row can reduce the risks of crusting.

FIGURE 6.11 Puddling is a deliberate attempt to break aggregates and destroy structure by plowing when the soil is wet. The objective is to decrease infiltration rate and increase water retention in the puddled layer.

6.2 PUDDLING

Puddling refers to physical manipulation of a wet soil to slake and disrupt structural aggregates and decrease total and macroporosity (Fig. 6.11; see also Chapter 5). Puddling implies reduction in apparent specific volume ρ_b^{-1} or inverse of bulk density) and void ratio (e) of a soil by mechanical work done on it (Rodman and Rubin, 1948; Ghildyal and Tripathi, 1987). The stress applied when soil is wet (Θ=s), leads to reorientation of clay and reduction in air porosity (f_a). The term puddlability (P) expresses the susceptibility of soil to puddling, and is numerically equal to the change in apparent specific volume of a soil (dv) per unit of work (dw) expended in causing such a change.

$$P=dv/dw \tag{6.3}$$

The change in volume per unit of work is related to the air-filled pore space on drying. Cohesion of a puddled soil increases with progressive decrease in soil moisture content until it reaches the maximum value when soil is dry. Increase in cohesion on drying is due to an increase in interparticle contacts and forces of surface tension as the water film drains into small pores. Puddling of a soil leads to: (i) reduction of macroaggregates, (ii) decrease in total and air-filled porosity, (iii) reduction in hydraulic conductivity,

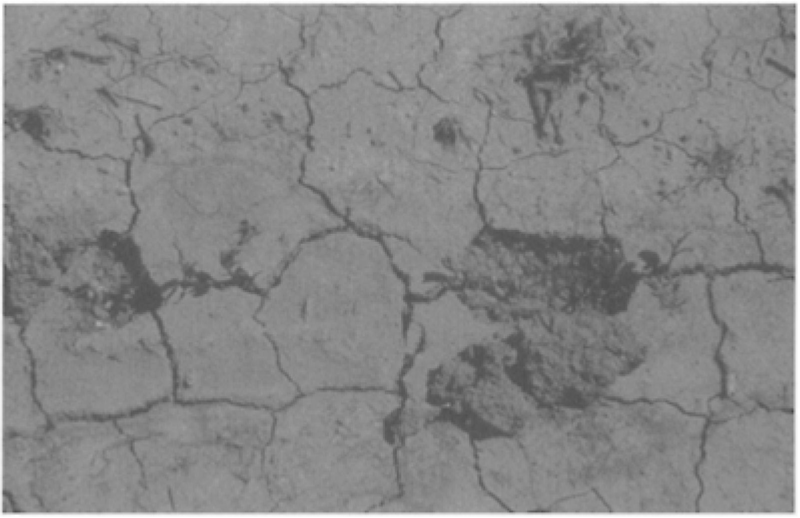

FIGURE 6.12 Drying of the puddle soil leads to formation of cracks, which may have an adverse impact on root growth of rice seedlings.

and (iv) increase in retention pores. Puddling leads to change in soil from a 3-phase (solid, liquid, and gases) to a 2-phase (solid and liquid) system (Fig. 6.11). Drying of a puddled soil, transformation from a 2-phase to 3-phase system, lead to formation of wide cracks (Fig. 6.12).

Mechanical puddling is done for rice cultivation. Being a semiaquatic plant, rice is grown under saturated soil conditions with surface ponding. Therefore, maintaining a ponded water condition is important to rice growth. Such ponding conditions increases losses of water by deep percolation and seepage (see Chapter 9). These losses must be reduced for improving water use efficiency. In order to reduce percolation and seepage losses, soil aggregates are destroyed to reduce transmission pores and increase retention pores. Aggregates are weakest when saturated with water, and the electric double layer of the clay particles is fully expanded. Easy to puddle soils are those that contain high clay content, 2:1 expanding lattice clay minerals, high proportion of Na^+ on the exchange complex, and low concentration of sesquioxides (see Chapter 3). It is difficult to puddle coarse-textured soils with low clay and high organic matter contents.

The process of puddling occurs in two stages. The first stage involves increasing soil water content, the second is the mechanical work done to disrupt the aggregates and reduce soil volume. Increase in soil moisture content decreases cohesion and soil strength. The work done during puddling involves two kinds of deformation stresses: (i) normal stress causing compression, and (ii) tangential stress causing shear (see Chapter 7). The work done during puddling may be computed from these two stresses. The porosity, and therefore the hydraulic conductivity, of a puddled soil decreases rapidly with increase in the degree of puddling.

6.3 HARDSETTING

“Hardsetting” refers to a process in which soils set hard into a structureless mass following drying and ultradesiccation (Mullins et al., 1990). When dry and set hard, these soils have a high bulk density, high penetration resistance, high strength, and are difficult to plow or dig. Hard setting soils have a narrow range of workable soil moisture content. Extreme types of such soils are often called “lunch-time soils.” These soils may be too wet to plow before lunch and too hard after lunch. Hardsetting soils have a weekly developed structure characterized by: (i) low aggregation, (ii) aggregates prone to slaking and dispersion, (iii) low infiltration rate, and (iv) high runoff and erosion (Fig. 6.13). (Ley et al., 1989; 1993). The hardsetting process begins with slaking followed by slumping or consolidation, and desiccation. The major difference between hardsetting and compaction is that the densification in hardsetting occurs without the application of an external load (e.g., machinery traffic, trampling by animals or humans) (for definition of compaction, see Chapter 7). The forces leading to hardsetting are generated within the soil itself. Hardsetting is also different than surface seal formation or crusting. Some soils that exhibit crusting may not be hardsetting. A hardsetting soil differs from the one that crusts by the fact that the A horizon is extremely unstable that mere wetting causes the slaking, dispersion, and mobilization of the fine material. The kinetic energy of raindrop or running water and low electrolyte concentration in soil solution, essential to crusting, are not necessary to hardsetting.

There are some soil attributes that make it susceptible to hardsetting. Hardsetting soils have textural properties ranging from loamy sand to sandy clay, low swell-shrink capacity, low soil organic matter content, and predominantly low activity clays. Risks of hardsetting are accentuated by factors and processes that increase susceptibility to slaking, dispersion, and slumping including: (i) cultivation under wet conditions, (ii) mechanical soil disturbance, (iii) low application of compost and organic amendments, and (iv) clean cultivation.

Hardsetting behavior has numerous limitations with regards to timings of cultivation, restricted root growth, high-energy requirement for soil management, low crop stand, and poor yield (Ley et al., 1989; 1993). Management of hardsetting soils involve techniques that improve aggregation and aggregate strength. These techniques include use of residue mulch, no-till or conservation tillage, cover crops, etc.

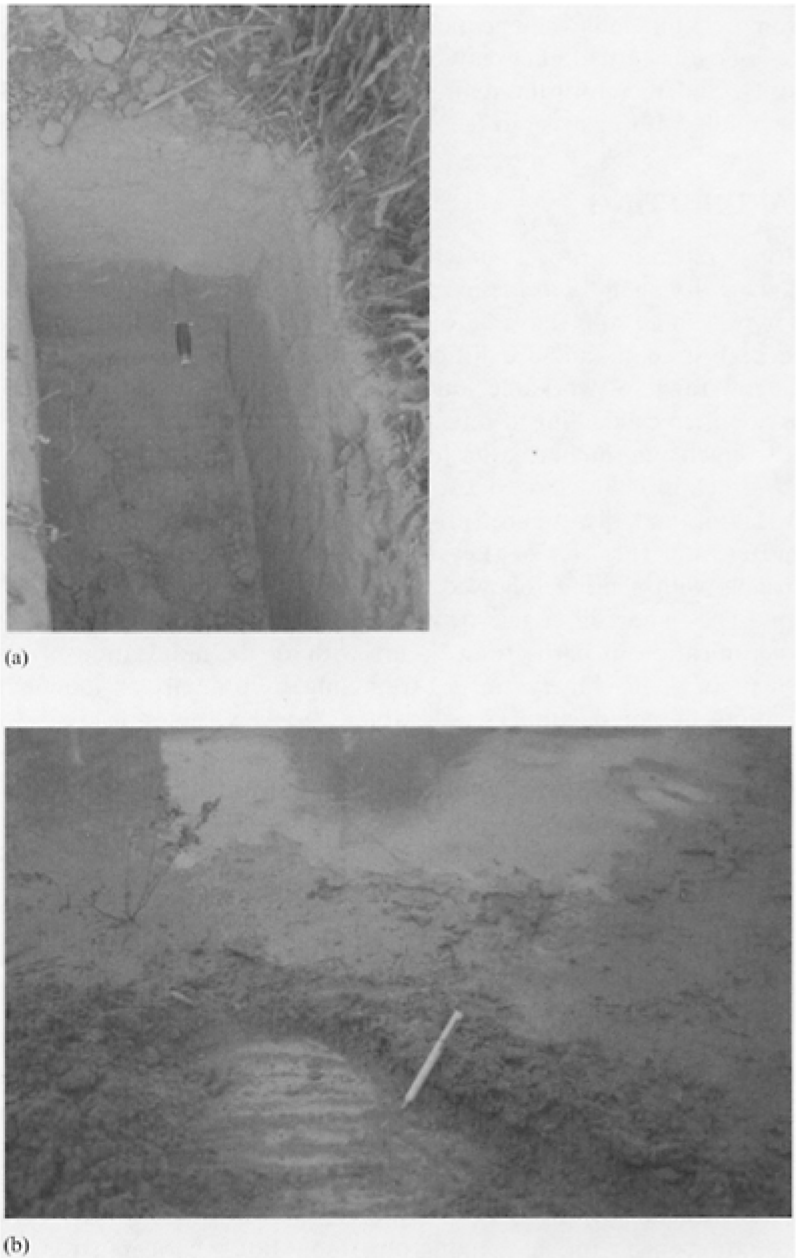

FIGURE 6.13 (a) Hardsetting soils are characterized by predominantly low activity clays, low organic matter content and structurally inert

characteristics. Consequently, they set hard on drying, (b) Hardsetting soils may also have low infiltration rates, especially when combined with a hydrophobic surface crust.

Application of gypsum and other soil amendments is crucial. Maintenance of soil temperature and moisture regimes in optimal range by avoiding too dry and too hot conditions minimizes risks of hardsetting.

6.4 CRACKING

Heavy textured soils containing high amounts of expanding lattice clays have a high coefficient of expansion and contraction and develop large and deep shrinkage cracks on drying (Fig. 6.14). This process is also discussed in Chapter 20. It is the three-dimensional shrinkage which is accompanied by cracking. A crack is initiated where soil cohesion (strength) is the lowest and the soil moisture content is the highest (Mitchell and Van Genuchten, 1992). Crack initiation occurs where soil is the wettest, i.e., in the middle of two rows in the inter-row zone or in between two plants. The phenomenon of between-row cracking has long been observed by farmers and soil scientists/ agronomists. Johnson and Hill (1944) reported extensive between-row cracking in Houston black clay and Austin clay under corn. In New South Wales, Australia, Fox (1964) proposed a theory of root-anchoring that increases soil strength and reduces cracking. Plant roots provide a skeleton to which soil adheres as it shrinks causing formation of large cracks along the outer boundaries of the rooted volume. Because of additional surface

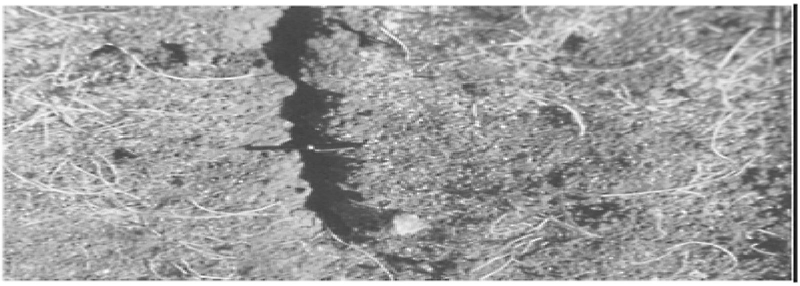

FIGURE 6.14 Veritsols and other soils containing predominantly high activity clays develop wide and deep cracks on drying.

area exposed to evaporation, cracks accelerate soil drying. If the soil is not disturbed and rows are planted at the same location, as with a no-till system of seedbed preparation, the crack will appear on the same place upon redrying after wetting or in the next season. Cracking intensity and number of cracks per unit area depend on clay mineralogy and structural attributes such as particle arrangement. A large number of cracks are formed in a soil with flocculated clay. In contrast, a few cracks are formed in soils with high cohesive strength. Soils with well-developed crumb structure and selfmulching characteristics usually do not exhibit intensive cracking.

Formation of cracks or soil failure involves energy. Cracking occurs when the release of energy per unit area by the crack is more than the increase of surface energy due to creation of additional surface area (Ghildyal and Tripathi, 1987).

Soil cracking is a special case of soil failure. It occurs when the release of energy per unit area by the crack is greater than the increase of surface energy. There are two separate energy terms involved. First, energy is due to the forces of surface tension (γ_s) which is proportional to the new surface created by cracking [Eq. (6.4)].

$$dU/dA = 2\gamma_s \tag{6.4}$$

where *U* is the energy of soil surfaces, *A* is the area of the exposed new crack, and γ_s is the surface tension at the soil-air interface. The second energy involved in cracking is due to the tensile strength of the soil which is released per unit free surface energy due to the new area exposed by cracking [Eq. 6.5)].

$$dU/dA = \frac{\pi\sigma^2 D}{E} \tag{6.5}$$

where σ is tensile stress normal to the plane of the crack, *D* is major diameter of the crack which is assumed to be elliptical, and *E* is Young's modulus of soil (see Chapter 7).

Combining Eq. (6.4) and (6.5) lead to the Griffith formula related to the development of crack [Eq. (6.6)].

$$\sigma_s = \left(\frac{2E\gamma_s}{\pi S}\right)^{1/2} \tag{6.6}$$

where σ_s is the limiting stress in dynes/cm^2. Both σ_s and *E* depend on soil moisture content and ρ_b.

PROBLEMS

Write a brief note to answer the following questions.

1. Why is crusting a more serious problem in soils of loamy rather than sandy or clayey texture?

2. Why does a "clay skin" formed on a dry soil after ponding curl upward?

3. Why is “dense planting” or high seed rate recommended for crust-prone soils?

4. Why does manuring and application of biosolids decrease risks of crusting?

5. List factors affecting thickness of soil crust.

6. In what soil and environmental conditions does plowing increase and decrease the risks of crusting?

7. Complete a matrix listing processes involved in crusting, hardsetting, and cracking.

Number	Crusting	Hardsetting	Cracking
1			
2			
3			

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7

Soil Strength and Compaction

Soil strength is an important soil physical property, with numerous applications to agronomy and engineering. Important agronomic applications are those related to impacts of crusting and compaction on plant growth and agronomic yield. Relevant engineering applications are related to trafficability, draft power required to till the soil for alleviating soil compaction, and soil as a foundation for hydraulic and civil structures (e.g., dams, roads, buildings). For detailed discussions on soil strength, readers are referred to textbooks on soil mechanics (Wu, 1982; Whitlow, 1995; Aysen, 2002; Brown, 2001; NAS, 2002).

7.1 BASIC RHEOLOGICAL MODELS

Rheology deals with the study of flow, and the degree and principles of deformation (see Chapter 8). There are several rhelogical models relevant to understanding the soil responses called strain *(ε)* (or deformation) and stress *(σ)* (or pressure). Some basic models used to explain stress-strain behavior ae discussed by Yong and Warkentin (1966) and Hillel (1980). Available models can be grouped under three categories: elementary, complex, and compound.

7.1.1 Elementary Models

The stress-strain behavior is explained by three simple models:

Hookean Model. This linear spring model states that strain *(ε)* is proportional to stress *(σ),* and that strain occurs instantaneously when stress is applied and it disappears when the stress is removed.

$$\sigma=K\varepsilon \tag{7.1}$$

where σ is expressed in units of pressure or force per unit area (PSI, bars, Pa), K is constant of proportionality (units of pressure), and ε is a dimensionless ratio (L/L). This model applies to perfectly elastic bodies. *Newtonian Model.* The stress-strain relationship is characterized by a constant rate of strain *(εs)* under an applied stress (a).

$$\sigma = K'\dot{\varepsilon} \tag{7.2}$$

where $\dot{\varepsilon} = \mathrm{d}\varepsilon/\mathrm{dt}$ and K' is constant of proportionality and has units of stress (bars) *x* time. When ε=0 at t=0, Eq. (7.3) can be rewritten as follows:

$$\sigma K' = \dot{\varepsilon} \tag{7.3}$$

Yield Stress Model. There is a threshold stress needed to initiate a strain. Such a type of stress-strain behavior follows a yield-stress model.

$\sigma > \alpha_o$ for ε=0 where σ_o=frictional resistance

$\sigma > \alpha_o$ for finite ε (7.4)

7.1.2 Complex Models

Soil is a complex mixture of four components and three phases (see Chapter 2). Thus, stress-strain behavior of soils does not follow any of the elementary models. Such models are not sufficient to accurately represent stress-strain-time behavior of soils. Thus, a combination of two or three models is often used to assess the stress-strain behavior of soils. Elementary models, however, comprise essential components of complex models.

St. Vincent Model. This model involves a combination of the Hookean and Yield Stress models in a series. The stress-strain behavior is explained by the condition of an elastic strain up to the yield point.

Kelvin Model. The Kelvin model is a combination of the Hookean and Newtonian models. It involves the parallel coupling of two models. The strain is characterized by elastic deformation delayed by time effects. This behavior is also sometimes called the Voigt model.

$$\sigma = \sigma_{\mathrm{Hookean}} + \sigma_{\mathrm{Newtonian}} \tag{7.5}$$

$$\sigma = K\varepsilon + K'\dot{\varepsilon}$$

$$\frac{\sigma}{K'} = \frac{K}{K'}\varepsilon + \frac{d\varepsilon}{dt}$$

Maxwell Model. This complex model is used to explain the stress– strain behavior using the series coupling of the Hookean and Newtonian models. Thus,

$$\varepsilon_{\mathrm{total}} = \varepsilon_{\mathrm{Hookean}} + \varepsilon_{\mathrm{Newtonian}} \tag{7.6}$$

$$\varepsilon_{\mathrm{total}} = \frac{\sigma}{K} + \frac{\sigma}{K'} \tag{7.7}$$

7.1.3 Compound Models

These models involve a combination of complex and simple models to achieve a higher order of combination for explaining the stress-strain behavior of soils.

Linear Model. A combination of Hookean model and Maxwell model in parallel is called the Linear model. This model is used to explain the stress-strain relationship of a material with skeletal structure.

$$\sigma=\sigma_H+\sigma_M \tag{7.8}$$

Burger Model. This model combines in series the Maxwell and Kelvin models.

Bingham Model. This model combines Newtonian model in a series with the St. Venant model.

Of the three compound models, the Burger model is applicable to simulating the soil behavior.

7.2 STRESS-STRAIN RELATIONSHIP

Soil rheology also involves the study of soil strength or soil's ability to bear or withstand stress without collapsing or deforming excessively. Soil strength is attributed to forces of cohesion and adhesion and varies with soil moisture content. When subjected to external force or stress, soil undergoes different types of deformation or strain. There are different types of stress that result in different types of strain.

7.2.1 Stress (Tension or Compression)

Stress refers to the force per unit area. For a given plane at a point, the resultant stress vector may be divided into two components: normal and tangential stress.

Normal Stress (a). Normal stress is caused by a force vector perpendicular to the area of action [Eq. (7.9)]

$$\sigma=F_n/A \tag{7.9}$$

where F_n is the force acting normal to the area A. The transmitted normal stress generally decreases with distance from the applied load and with distance from its line of action.

Tangential Stress (τ) or Shearing Stress. This stress is caused by a force vector parallel to the area of action [Eq. (7.10)].

$$\tau=F_t/A \tag{7.10}$$

where F_t is the tangential force acting on area A.

7.2.2 Strain

Strain refers to soil's reaction to stress in the form of deformation that the stress has created. There are two principal types of strain: longitudinal strain and shear strain.

Longitudinal Strain (ε). Longitudinal strain refers to the relative change in length [Eq. (7.11)].

$$\varepsilon=\Delta L/L \tag{7.11}$$

where ΔL is the change in soil length and L is the original length. The soil may be compressed or expanded (swelling).

Shear Strain (γ) *or Tangential Strain.* This strain refers to the angular deformation [Eq. (7.12)].

$$\gamma=u/h \tag{7.12}$$

where is lateral or tangential displacement, h is the height of the soil, and the ratio u/h is the tangent of the deformation angle (Fig. 7.1). The strain defined by Eqs. (7.11) and (7.12) refers to a small degree of deformation, usually less than 0.1%.

7.2.3 Time-Dependent Stress and Strain

Time-dependent longitudinal strain (ε') refers to the rate of change in longitudinal strain over time (t). Differentiating Eq. (7.11) with respect to time (t):

$$\varepsilon'=\frac{d\varepsilon}{dt}=\frac{1}{L}\frac{d(\Delta L)}{dt} \tag{7.13}$$

where ε' is the time rate of elongation or contraction, L is length and t is time.

Similarly, time-dependent stress application can be expressed as per Eq. (7.14), which is obtained by differentiating Eq. (7.12) with respect to time (t):

$$\gamma\prime=\frac{d\gamma}{dt}=\frac{1}{h}\frac{du}{dt}=v/h \tag{7.14}$$

where γ' is the velocity (v) gradient (du/dt) in the direction perpendicular to that of the shearing displacement. The time dependent stress-strain relationship of soil (body) govern several rheological properties such as elasticity and plasticity. Plastic properties are important to soil tilth.

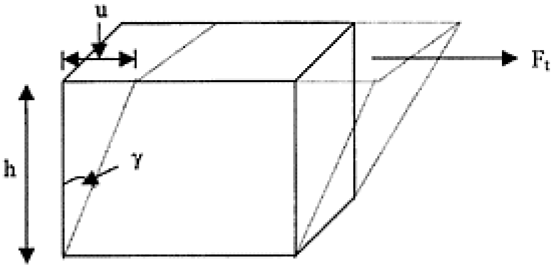


FIGURE 7.1 Shear strain exemplified by angular deformation.

7.3 ELASTICITY

An elastic material deforms under stress instantaneously and retains its new form as long as the stress is maintained. However, it returns to its original form when the stress is released. Soil, similar to other solids, is not a perfectly elastic material. Most natural bodies do not return to their original form, and exhibit some residual deformation after release of stress. The rate and total magnitude of deformation is called "creep," which depends on the "relaxation" characteristic of the material. Relaxation refers to the tendency of a material to relieve stresses gradually through internal structural adjustments. Perfectly elastic bodies exhibit the following characteristics that can be expressed through well-defined laws called "elastic constants":

1. *Young's Modulus:* Based on the college physics experiment relating weights hung from a spring and-the length to which it is stretched, Hooke's law states that strain *(ε)* is proportional to stress *(σ)*. Further, strain *(ε)* occurs instantly when the stress *(σ)* is applied and it disappears when the stress is removed. This relationship between normal stress and the attendant strain it produces is expressed in terms of Young's modulus [Eq. (7.15)].

$$\varepsilon = \frac{\sigma}{Y_m} \tag{7.15}$$

where Y_m is Young's modulus.

2. *Poisson's Ratio (v):* Normal *(σ)* or tangential stress *(γ)* may result in change in length *(L)* as well as thickness of a material *(d)*. Poisson's ratio (P_R) is defined as the "ratio of elongation along one axis to the corresponding contraction of another axis." It is dimensionless and its value ranges from 0 for rigid bodies to 0.49 for rubber. The value of P_R for soils depends on total porosity (f_t) and macroporosity (f_a).

$$P_R = -\frac{\Delta d/d_o}{\Delta L/L_o} = -\frac{\Delta d/\Delta L}{d_o/L_o} \tag{7.16}$$

Poisson's ratio is small (approaches zero) for porous materials (cork) and about 0.5 for elastic material (rubber). Highly porous soils may have a low Poisson's ratio and extremely clayey soils with high swell/shrink properties may have a high Poisson's ratio.

3. *Modulus of Shearing:* Similar to the Hooke's law and Young's modulus in case of the normal stress, the elastic relation for shearing stress is expressed by the modulus of shearing or rigidity [Eq. (7.9)]:

$$\gamma=\tau/M_R \tag{7.17}$$

where M_R is the modulus of rigidity or shearing.

4. *Bulk Modulus:* Rather than decrease in length (in case of normal stress) or thickness (in case of tangential stress), isotropic stress (e.g., immersion of a body in a liquid) can change the total volume. The magnitude of change in volume (ΔV) is proportional to the pressure (P) as per Eq. (7.18).

$$\Delta V \propto P, \quad \Delta V=\frac{P}{B_M} \tag{7.18}$$

The proportionality constant B_M is called the *bulk modulus* and refers to the volume compression or expansion relative to the original volume. Depending on soil structure and layering, it may be isotropic or anisotropic. Isotropism in soil may also depend on soil properties. Soil may be anisotropic in relation to hydraulic conductivity (refer to Chapter 11) but isotropic in relation to texture. These four elastic constants are interrelated [Eqs. (7.19) to (7.22)], and can be verified through solving the algebraic equations:

$$Y_m=9B_M\cdot M_R/(3B_M+M_R) \tag{7.19}$$

$$P_R=(3B_M-2M_R)/(6B_M+2M_R) \tag{7.20}$$

$$M_R=Y_m/2(1+P_R) \tag{7.21}$$

$$B_M=Y_m/3(1-2P_R) \tag{7.22}$$

7.4 PLASTICITY

Plasticity refers to the property of a body to deform progressively under stress and to retain its deformed shape when the stress is removed. Some materials are ideally plastic. In such materials, the behavior is elastic up to a certain magnitude of stress (σ_o) beyond which the deformation exhibits plastic behavior. This threshold or critical stress (σ_o) is called the yield point. Transition from elastic to plastic behavior may be gradual rather than abrupt and is determined by a property of the material called "strain hardening." Strain hardening in metals under stress is caused by deformation, internal structural changes, and recrystallization. A soil under compactive stress may also undergo structural changes and exhibit "strain hardening." A third category of materials is ideally brittle material, which exhibits elastic properties under stress up to the peak stress and all strength is lost upon failure.

For details on the stress-strain relationship of materials, readers are referred to reviews on soil mechanics (Barber, 1965; Hillel, 1980; Ghildyal and Tripathi, 1987).

7.5 STRESS-STRAIN RELATIONSHIP IN SOIL

In soils, strain is often large as is evident from an increase in soil bulk density from 0.8 Mg/m^3 under forest to 1.6 Mg/m^3 with cultivation (Lal and Cummings, 1979; Lal, 1985; 1996). Further, change in bulk density or strain (εs) may not be uniform. Therefore, stress-strain relationship in soils is difficult to predict, is soil-specific and must be determined experimentally. Soil is neither a perfectly elastic nor an ideally plastic material. Being highly heterogenous, soil deformation in response to stress is a complex process.

Assume a soil is subjected to a known stress. When the stress is small, the soil may deform slightly (low strain) and may recover its original shape when the stress is released (elastic deformation). If the stress is large, it may produce larger strain resulting in permanent deformation from which soil may not recover even when the stress is released (plastic deformation). The strain increases linearly up to the critical or threshold stress (σ_0). This region of linear response represents the "elastic region" and response follows the theory of elasticity. Permanent deformation occurs as the stress is increased beyond the threshold, critical stress or yield. This is also known as the failure stress or the highest stress that the soil can safely withstand. In case of brittle or sensitive soil, it completely loses its strength. Tensile failure of soil is a measure of the cohesive component of the shear strength. In contrast, failure of soil by shear is definable when it is in rigid or brittle state and exhibits a distinct failure plane. This type of failure is observed in relatively dry and cohesive soils (see Sec. 7.1 on basic rheological models). In contrast to elastic, plastic or viscous material, soil may exhibit a combination of these responses as follows:

1. Elastoplastic soils are those that exhibit partial recovery when stress is removed.
2. Viscoelastic soils are those that exhibit time-dependent soil deformation [Eq. (7.5)], as is the case in the creep phenomena.
3. There are numerous ramifications of the stress-strain behavior of the soil including soil compaction and soil strength.

7.6 SOIL STRENGTH

Soil strength is the resistance that has to be overcome to obtain a known soil deformation. It refers to the capacity of a soil to resist, withstand, or endure an applied stress (σ) without experiencing failure (e.g., rupture, fragmentation, or flow). It is soil's resistance that must be overcome to cause physical deformation (ε) of a soil mass. It implies the maximal stress which may be induced in soil without causing it to fail. As stated in the introductory paragraph of this chapter, the concept of soil strength has numerous applications in agriculture and engineering. In agriculture, soil strength has applications to root growth, seedling emergence, aggregate stability, erodibility and erosion, compaction and compactability, and draft requirements for plowing. In engineering, soil strength has applications to soil and slope stability, foundation engineering, and bearing capacity with regard to agricultural application, high soil strength may have both positive and negative effects. Positive effects are those related to soil trafficability and bearing capacity, and resistance to compactive and erosive forces. Negative effects are those due to high draft power requirement, poor root growth, low seedling emergence, and poor crop stand.

Soil strength may be of two types: (i) resistant to volumetric compression, and (ii) resistant to linear deformation or shear strength. The resistance to volumetric compression can be measured by evaluating stress density relationship at different soil moisture content. This may involve measurement of penetration resistance of a soil at different density and different soil moisture content (potential). For a given bulk density, soil strength decreases with increasing soil moisture content. For a given soil moisture content, soil strength increases with increase in soil bulk density. In general, fine-textured soils at low moisture content exhibit high strength. Shear strength of a soil is the resistance to deformation by continuous shear displacement of soil particles due to tangential (shear) stress. Soil's shear strength is due to three separate but interactive forces: (i) the structural resistance to displacement of soil particles, (ii) the frictional resistance to translocation between the individual soil particles due to interparticle contacts, and (iii) forces of cohesion and adhesion.

7.6.1 Mohr Theory of Soil Strength

This theory is based on the functional relationship between normal stress (σ) and tangential or shearing stress (τ). The envelope of the family of circles is used as a criterion of shearing strength of soil. When a series of stress states just sufficient to cause failure is imposed on the same soil material, these states can be plotted as a set or family of Mohr circles. The line tangent of these circles, called the envelope of the family of circles, is used as a criterion of shear strength. When this envelope is a straight line, it can be described mathematically by Eq. (7.23) (Fig. 7.2).

$$\tau=\tau_o+b\sigma \tag{7.23}$$

where the constant τ_0 is the intercept of the envelope line on the τ axis, and constant *b* is the tangent of angle ϕ which the envelope line makes with the horizontal line. This linear relationship between τ and *a* is analogous to the Coulomb's law that states that "the frictional resistance toward a tangential stress tending to slide one planar body over another is proportional to the normal force pressing the bodies together." In view of this analogy for sliding friction between bodies, the angle ϕ is called the angle of internal friction. The intercept (τ_o) is the shear stress needed to cause failure when normal stress (σ) is zero, and is called soil cohesion *(C)* or cohesiveness. Substituting these terms in Eq. (7.23) yields Eq. (7.24) used to express soil shear strength.

$$\tau=C+\sigma\tan\phi \tag{7.24}$$

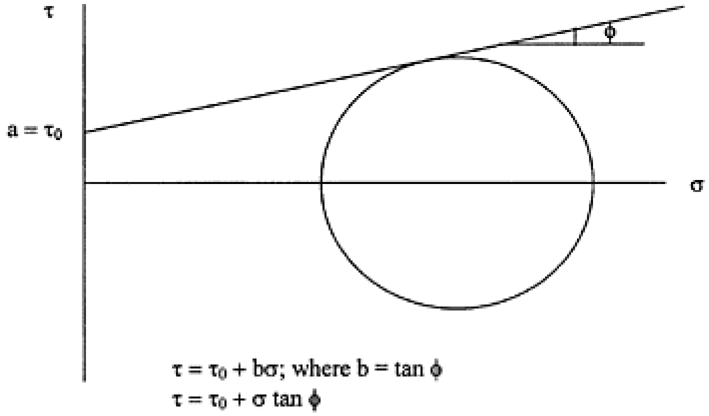


FIGURE 7.2 The functional relationship between shearing stress (τ) and normal stress *(σ)* is given by Mohr's circle *(a* or τ_0 is the intercept and constant *b* is the tangent of angle ϕ

7.6.2 Factors Affecting Soil Strength

Soil deformation under stress happens when solid constituents (both primary and secondary particles) are able to separate and move with respect to each other. Particle movement under stress is restricted by particleto-particle friction and interparticle bonds. Frictional forces increase with: (i) increase in soil bulk density, (ii) decrease in soil moisture content, and (iii) increase in over burden pressure. Forces due to interparticle bonds include: (i) cohesion due to surface tension at the air-water interface and soil matric potential or pore water pressure, (ii) link bonds or particle-to-particle contents, e.g., mineral-mineral, mineral-organic-mineral, etc. There are numerous types of cementing agents that bind the particles together (refer to Chapter 4).

Soil properties affecting soil strength are discussed by Guerif (1994) and include the following:

Soil Structure. Aggregate size is an important determinant of soil strength. Stress at fracture decreases exponentially with increase in aggregate (clod) diameter.

Soil Bulk Density. It determines the magnitude of particle-to-particle contacts. Effects of soil bulk density on soil strength are confounded with those of soil moisture content. Because soil bulk density is related to total volume (V_t) and total porosity (f_t), soil strength may be expressed on the basis of strength-volume or strength-porosity relationships. Soil strength decreases with increase in total soil volume [Eq. (7.25); Braunack, et al., 1979].

$$\ln S = -F \ln V + A \tag{7.25}$$

where S is soil strength, V is soil volume, A is an adjustment factor, and F is soil constant which is a measure of the ease of breakdown of large clods into smaller aggregates. The factor F, called soil friability (Utomo and Dexter, 1981), is defined as "the tendency of a mass of unconfined soil to break down and crumble under applied stress into a particular size range of smaller fragments." The topic of soil friability is discussed in Chapter 8.

Properties of Soil Solids. Soil constitution (i.e., particle size distribution, clay mineralogy, and soil organic matter concentration) affects soil strength through changes in aggregation, soil bulk density and specific volume, moisture content, and types of pores. Relative proportion of textural versus structural pores can affect soil strength. Soil organic matter influences soil strength through its effects on aggregation and porosity.

Clayey soils have more strength and cohesiveness *(C)* than sandy soils. Dry sand, being non-cohesive, may actually expand during shear, a phenomenon known as dilatancy. Moist sand is apparently cohesive and can withstand traffic (is trafficable) but dry sand cannot. Guerif (1990) observed that tensile strength increases linearly with clay content [Eq. (7.26)].

$$S_T=m(\text{clay})+b \tag{7.26}$$

where S_T is the mean tensile strength of dry spherical aggregates of 2–3 mm diameter, clay content is expressed as a fraction (g/g), and b is an empirical constant. The intercept m is considered as the mean tensile strength of an ideal clay representative of different soils involved in the regression analysis. Textural tensile strength is an intrinsic property of the soil. The textural strength, defined at the scale of the smallest significant elementary volume of cohesive material, is considered as the upper limit of the strength that a given soil may exhibit following a severe compaction (Guerif, 1994).

Soil Moisture Content. Soil strength increases with decrease in soil moisture content or moisture potential. Soil drying increases strength by increasing capillary cohesion as it increases the effective stress, and compactness by shrinkage.

7.6.3 Measurement of Soil Strength

Tensile strength is a sensitive indicator of the condition of a soil and is a useful measure of strength of individual soil aggregates. Two principal theories describing the strength of porous materials like soils are: (i) Mohr– Coulomb maximum shear strength and (ii) Griffiths's tensile failure theory. The Mohr–Coulomb theory states that shear failure occurs when the maximum resolved shear stress on fracture plane is attained. According to Griffin theory, fracture occurs when the highest local tensile stress in the longest cracks reaches the critical tensile strength of the material (Hadas and Lennard, 1988).

The tensile strength of a spherical particle can be determined by a simple crushing test. A force of magnitude F applied across the poles of a particle causes elastic deformation of the particle (Fig. 7.3). This produces a proportional tensile stress in the center of particle perpendicular to the direction of applied force. If the force F is increased gradually, the internal tensile stress reaches the tensile strength *(Y)* of the particle, and a slight increase thereafter results in cracking of particle on a plane through the polar diameter.

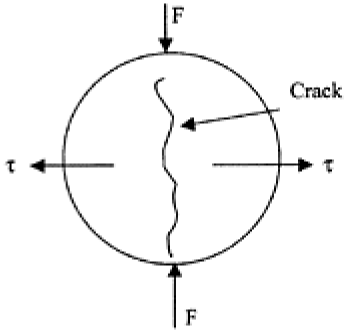


FIGURE 7.3 Schematic of loading *(F)* of an aggregate at poles and the resultant tensile stress *(τ)* at right angles to *F* and development of a crack as τ approaches tensile strength (S_T) of soil.

Measurement of soil strength involves characterization of two parameters of Eq. (7.24): (i) cohesiveness C, and (ii) angle of internal friction ϕ. The cohesiveness factor *C* represents the adherence or bonding of soil particles which must be broken if the soil is to be sheared. The angle of internal friction ϕ represents the frictional resistance encountered when soil is forced to slide over soil.

There are direct and indirect methods of measuring *C* and ϕ, the strength properties of soil. These methods are described in details by Sallberg (1965), Wu (1982), Snyder and Miller (1985), Ghildyal and Tripathi (1987), Guerif (1994), and others.

Direct Methods

The direct methods involve a direct application of stress to a soil sample.

Laboratory Techniques. In the direct shear test, the shear strength (or the shearing resistance) and the normal stress are both measured directly at a predetermined plane of a soil. The primary objective of strength measurement is to determine the failure envelope, or the relationship between τ and σ The values are plotted on τ- σ coordinate system, and the line connecting the points is an envelope from which *C* and ϕ are computed (Fig. 7.2).

The direct shear test has several limitations: (i) the shearing plane does not remain constant during the test, (ii) stresses vary even though normal and tangential forces remain constant, and (iii) test results are influenced by the size and shape of the container.

The triaxial shearing test is designed to overcome these limitations. In this test, the failure surface is not predetermined, and longitudinal and lateral stresses are applied to a sample of the soil and these stresses determine the plane of failure. The strength envelope is obtained by using different combinations of the applied stresses.

The internal or total stress *(σ)* acting on any plane inside a soil body consists of two components: (i) the effective stress due to interparticle pressure, and (ii) the pore-water pressure or soil matric potential (see Chapter 10). These relationships are described by Terzaghi's effective stress equation [Eq. (7.27), Terazghi, 1953].

$$\bar{\sigma} = -\Psi + \sigma \tag{7.27}$$

where $\bar{\sigma}$ is the effective stress, σ is the internal or total stress, and ψ is the hydrostatic pressure. In unsaturated soil, ψ is negative and increases effective stress. The term effective stress is also called the inter-granular stress, and ψ the neutral stress, because in saturated soil the hydrostatic pressure acts equally in all directions.

A special case of the cylindrical shearing test is called the "unconfined compression test" in which no lateral pressure is applied. There are other laboratory techniques of measuring tensile strength (Gill, 1961; Vomocil et al., 1961).

Cohesive strength of soil is also measured under laboratory conditions by measuring the modules of rupture (Richards, 1953; Reeve, 1965). Modulus of rupture is defined as the maximum force per unit area that a material can withstand without breaking. It is a measure of the breaking strength of the soil, and is used to assess the physical status of seedbed, especially the crust strength (see Chapter 6). This method involves making a small briquette of the soil of known width *(b)* and thickness *(d)*. The briquette is prepared to simulate seedbed preparation involving wetting and drying of soil and eventually crust formation. The briquette is loaded on both ends until it fails. The modulus of rupture *(σ_b)* is computed from Eq. (7.28).

$$\sigma_b=3Fl/2bd^2 \tag{7.28}$$

where F is the force applied to cause failure, l is the length of the briquette, b is the breadth, and d is depth or thickness. For a cylindrical briquette, σ_b is computed by Eq. (7.29).

$$\sigma_b=Fl/r^3 \tag{7.29}$$

Modulus of rupture is also related to soil crusting (Richard, 1953), and is an indirect method of measuring soil strength. Changes in the dimension of the briquette upon drying are used to compute linear shrinkage [Eq. (7.30)].

$$\%\ \text{Linear shrinkage} = \frac{\text{decrease in length}\ (\Delta L)}{\text{original length of the model}\ (L)} \times 100 \tag{7.30}$$

Field Techniques. Kirkham, et al. (1959) used the cylindrical speci-men to determine the strength required to split a specimen laterally into two longitudinal halves. The modulus of rupture for lateral failure is given by Eq. (7.31).

$$\sigma_b=F/\pi lr \tag{7.31}$$

In situ determination of soil strength under field conditions is done by two methods. A first and simple one is the Vane shear test (ASTM, 1956). A vane is driven into the soil to a known depth and then rotated to measure the torque *(T).* The torque is related to soil cohesiveness as per Eq. (7.32).

$$T=C\pi(1/2\, d^2 l+1/3\, d^3) \tag{7.32}$$

where C is soil cohesiveness, d is diameter of the vane, and l is length of the vane. If the length-to-radius ratio is 4:1, soil cohesiveness can be computed from Eq. (7.33).

$$C=6T/7\pi d^3 \tag{7.33}$$

The second field method is based on the measurement of tensile strength, which is the normal force per unit area required to detach or pull apart one section of soil from another (Sourisseau, 1935).

Indirect Methods

The indirect methods involve indirect failure induced by applying external compressive forces or bending moments that generate tensile or shear stresses within the sample.

Strength of Soil Aggregates. Soil aggregates are highly irregular, they are placed in the most stable position, and force is applied across the minor principal diameter. For a particle of incompressible material with Poisson's ratio (ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force) of 0.5 and diameter d, the tensile strength for a polar force F at failure is given by Eq. (7.34):

$$Y=R\frac{F}{d^2} \tag{7.34}$$

where R is the proportionality constant and usually equal to 0.576, although it may be correlated to bulk density and/or pore size distribution. Tensile deformation is considered positive and compressive deformation is considered negative. The definition of Poisson's ratio [Eq. (7.16)] contains a minus sign so that normal materials have a positive ratio. Aggregate diameter needs to be determined before tensile strength can be calculated from above equation. Since aggregates are irregularly shaped, exact determination of an effective spherical diameter is not possible. One method employs sieving of soil aggregates through two sieves of opening sizes as s_1 and s_2 $(s_1>s_2)$. The mean diameter of the aggregates passing through s_1 but retained on s_2 can be calculated as Eq. (7.35).

$$d=\frac{s_1-s_2}{2} \tag{7.35}$$

the ratio $(s_1-s_2)/s_2$ is to be kept small. The other method involves measurement of the diameter of each individual aggregate (with calipers) and then calculating the effective mean diameter as the arithmetic or geometric mean or as a weighted mean mass or weighted mean density basis (Dexter and Kroesbergen, 1985).

There are numerous factors that affect tensile strength of aggregates. Analysis of the fracture of air-dry soil aggregates is important for the management of soil structural stability, root growth and tillage operations (Hadas and Lennard, 1988; Causarano H., 1993). The effect of aggregate size on root growth and nutrient uptake is due to the increase in mechanical stress adjacent to the soil-root interface with increasing aggregate size (Mishra et al., 1986). The knowledge of magnitude and distribution of aggregate strengths is key to understanding the amount of aggregate break up during tillage or movement of farm machineries. Factors influencing the tensile strength of soil aggregates are: moisture content, clay content, organic matter content, and size of aggregate. The tensile strength of soil aggregates generally decreases with increasing moisture content and/or aggregate size (Causarano, 1993).

7.7 SOIL COMPACTION

Soil compaction can be conceptually viewed in a dynamic or a static situation, and in practical applications. In a dynamic situation, it is a physical deformation or a volumetric strain. In a static situation, it is the characteristic related to soil resistance to increase its bulk density. In practice, soil compaction is a process leading to compression of a mass of soil into a smaller volume and deformation resulting in decrease in total and macroporosity and reduction in water transmission and gaseous exchange. The degree or severity of soil compaction is expressed in terms of soil bulk density (ρ_b), total porosity (f_t), aeration porosity (f_a), and void ratio (e). The volume decrease is primarily at the cost of soil air, which may be expelled or compressed. The compression of soil solids (i.e., change in ρ_s) and water (i.e., change in ρ_w) is evidently not possible. However, soil solids may be rearranged or deformed as a result of compactive pressure.

Compression of a moist soil due to external load may displace the liquid and increase the contact area between two particles (Fig. 7.4). The magnitude of increase in contact area depends on the degree of rearrangement or deformation of the particles. The menisci formed by the liquid may also change due to differences in the contact area. The shape of the meniscus depends on surface tension forces, which are usually small compared with the external load. The deformation may be elastic and soil particles may regain their original shape when the applied load is released.

The degree of deformation and rearrangement depends on soil structure and aggregation, and on the extent to which soil particles can change position by rolling or sliding. For partly saturated clayey soils, the volume change depends on reorientation of the particles and displacement of water between particles. The particle rearrangement may lead to closed packing (Chapter 3) with attendant decrease in void ratio [Eq. (7.36)].

$$e=e_o-c\log P/P_o \tag{7.36}$$

where e_o is the void ratio at the initial pressure P_o, c is the slope of the curve on semilogrithmic plot, and P is the applied pressure that changed the final void ratio to e. Degree of soil compaction may also be expressed in terms of total porosity in relation to the external load (Soehne, 1958) [Eq. (7.37)].

$$f_t = -A \ln P + f_{10} \tag{7.37}$$

where f_t is total porosity, f_{10} is the porosity obtained by compacting loose soil at a pressure of 10 PSI, A is the slope of the curve, and P is the applied pressure.

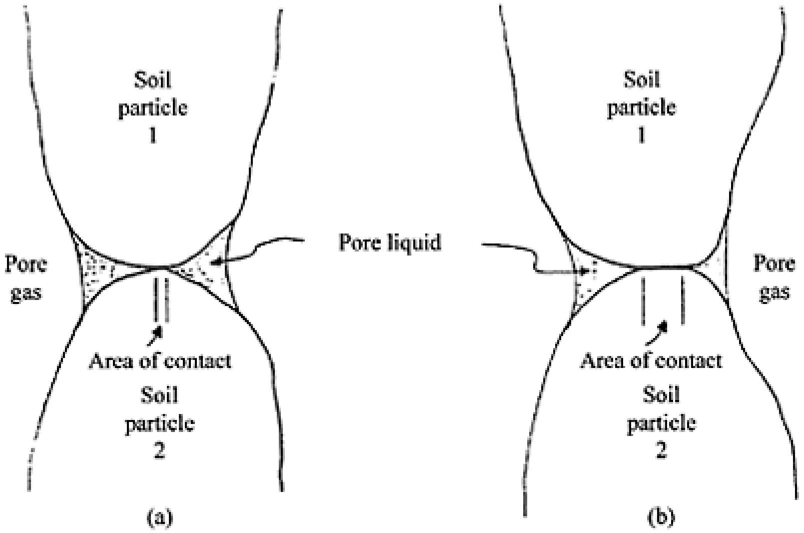


FIGURE 7.4 Two soil particles in contact in a partly saturated condition: (a) no external load; (b) with an external load applied.

Soil compaction is extremely relevant to agriculture because of its usually adverse impact on root development and crop yields (Table 7.1); civil engineering because of its relation to settlement, stability, and groundwater flow; and to environments because of its effects on erosion, anaerobiosis, transport of pollutants in surface and sub-surface flow, and nature and rate of gaseous flow from soil to the atmosphere. From an agricultural perspective especially in relation to plant root growth, there is an optimal range of soil bulk density, which for most soils is <1.4 Mg/m^3. However, the optimum range of soil bulk density may differ among soils and crops (Kyombo and Lal, 1994). For some soils (e.g., Andisols or soils of volcanic origin) the optimal density may be as low as 1.0. A similar case may be in soils containing a high level of soil organic matter content. It is precisely because of these differences in response to bulk density that effects of compaction on crop yield are highly soil-dependent. An example of variable response is shown by the data in Table 7.1, which indicate severe adverse effects on yield of corn on a clayey soil but slight or more on a loamy soil. Soils of the tropics are easily compacted, and can cause severe reductions in crop yields (Tables 7.2 and 7.3). Thus, the objective of soil management is to maintain soil bulk density within the optimal range that favors root growth, water retention and transmission, and gaseous exchange. In contrast, engineers consider soil bulk density in terms of the strength and stability of the foundation. The desirable goal, therefore, is to

TABLE 7.1 Effects of Axle Load on Corn Grain Yield on Coarse- and FineTextured Soils

Compaction level/axle load	Grain yield (Mg/ha)			
	Wooster silt loam soil-corn grain yield			
	1988		1997	1998
Control	5.8		6.1	8.6
7.5 Mg (controlled traffic)	5.0		5.4	8.2
7.5 Mg (entire plot)	5.0		5.4	7.3
LSD (0.05)	0.8		NS	0.9
	Hoytville clay soil-soybean grain yield (1996)			
	No till		Chisel plow	Moldboard plow
Control	2.6		2.6	2.3
10 Mg	2.4		2.2	2.2
20 Mg	2.4		2.1	2.0
LSD (0.05)				
(i) compaction		0.2		
(ii) tillage		0.2		
	Hoytville clay soil-corn grain yield (1990)			
	No till		Chisel plow	Moldboard plow
Control	9.3		7.7	6.5
10 Mg	5.2		3.9	3.6
20 Mg	2.7		3.5	4.1
LSD (0.05)				
(i) compaction (C)		0.6		
(ii) tillage (T)		1.6		
C×T		0.9		

Source: Adapted from Lal and Ahmadi, 2000.

form the densest and tightest possible soil condition. While achieving the highest soil compaction is the goal for civil engineers, it is a major concern for soil scientists and agricultural engineers.

7.7.1 Soil Compactibility

Soil compaction or densification happens due to external load or force applied to the soil. The force applied per unit area is defined as stress, which

TABLE 7.2 Effects of Progressive Decline in Structure of a Tropical Alfisol with Continuous Cultivation on Corn Grain Yield in Southwestern Nigeria

Tillage method	First season corn grain yield (Mg/ha)								
1980	1981	1982	1983	1984	1985	1986	1987	Mean	
Plow till	2.7	3.1	3.8	3.7	4.8	2.2	2.0	1.7	3.0
No till without mulch	2.1	2.8	4.2	3.6	4.2	3.6	2.3	1.7	3.1
No till with mulch	2.5	3.6	4.6	4.4	5.1	3.5	2.8	1.6	3.5
LSD (0.05)	NS	NS	NS	NS	0.9[a]	0.8[a]	0.5[a]	NS	

Source: Lal, 1997.

[a] Treatments differ at 5% level of probability.

TABLE 7.3 Decline in Corn Grain Yield on a Tropical Alfisol Due to Soil Compaction Caused by Vehicular Traffic Under Mechanized Farming

	Maize grain yield (Mg/ha)					
Tillage method	1975	1976	1977	1978	1979	1980
No till	2.8	4.5	4.8	5.0	3.8	3.0
Plow till	2.7	4.0	3.9	4.0	2.9	1.0

Source: Lal, 1984.

may be normal stress when it is perpendicular to the soil or shear stress when it has a tangential component. Compression is the process of increase in soil mass per unit volume due to external load. The load may be static or dynamic. The latter is applied in the form of vibration, rolling, or trampling (Fig. 7.5). While compression in unsaturated soils is called “compaction,” that in saturated soils is termed “consolidation.” Soil compressibility is the “resistance of a soil against volume decrease by external load.” In comparison, soil compactability is the difference between the initial bulk density and the maximum bulk density to which a soil can be compacted by a given amount of energy at a defined moisture content. Factors affecting soil compactability include the following:

Soil Wetness

Soil's response to external load depends on soil moisture content *(w)*. There is an optimum range of w at which the soil is most compactable. In general, ρ_b changes nonlinearly in relation to change in w (Fig. 7.6). Beginning with a low moisture content, increase in w serves to render the soil more plastic and workable and facilitate the compaction process (Hogentogler, 1936;

FIGURE 7.5 (a) A single-axle grain cart with capacity of 10 or 20 Mg can cause severe compaction during harvest in the fall, (b) A kneading roller is used to create a compact road bed. Spikes cause more compaction than a smooth roller.

Olson, 1962). The dry bulk density increases with an increase in *w*, and the maximum ρ_b is obtained at an optimum w, beyond which ρ_b drops with further increase in w. The magnitude of the peak ρ_b at a given w depends on soil texture and the load applied. The laboratory evaluation of soil's compactability in relation to *w* and the load is done according to the Proctor compaction test (Proctor, 1933; Lambe, 1951). The zero-air-void curve

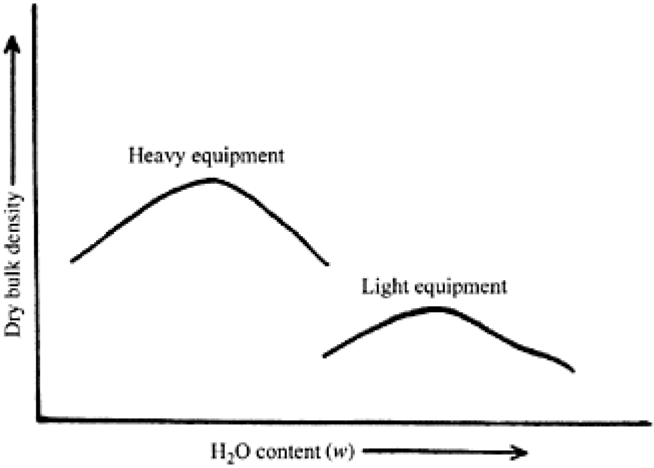


FIGURE 7.6 Relationship between moisture content and soil compaction.

obtained when the Proctor test is done at different moisture content is the w vs. ρ_b curve for a saturated soil. Compaction curves of all soils approach this curve at high *w*. Well-graded soils can be compacted to higher ρ_b than poorly graded soils, and the effect of w on ρ_b is more pronounced in heavytextured than coarse-textured or cohesionless soils. Compactability is significantly influenced by soil organic matter content and slip-induced shear. In addition to determining compactability, it is also useful to compute the relative density [Eq. (7.38)].

$$R_d = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \tag{7.38}$$

where R_d is the relative density, *e* is the void ratio of the soil in situ, $e_{\max}$ is the void ratio of the soil in the loose state that can be attained in the laboratory, and $e_{\min}$ is the void ratio of the soil in the densest state. Rather than a simple proctor density, vibratory maximum density test is done for cohesionless or sandy soils (ASTM, 1965).

Soil Compaction and Wheel Traffic

Heavy traffic of agricultural machinery is a major cause of compaction on arable lands (Gill and Vanden Berg, 1967; Harris, 1971; Chancellor, 1976; Soane and Van

Ouwerkerk, 1994). The pressure exerted by pneumatic tires of a single-axle load is proportional to the total weight [Eq. (7.39)].

$$W_v = \sum_{i=1}^{n} (P_w \times A_w) \tag{7.39}$$

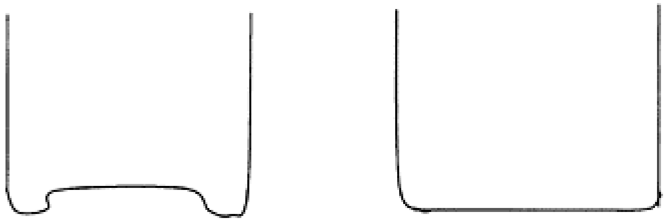
where W_v is total weight of the vehicle at rest, P_w is the pressure exerted by the wheel (inflation pressure in the pneumatic tire), and A_w is the area of contact of wheel with the soil. Therefore, an increase in load increases the pneumatic pressure and/or the contact area. For a rigid surface, increase in pneumatic pressure results in an increase in the contact area. For porous media, however, increase in pressure is also accompanied by soil deformation that causes compaction and formation of a wheel rut. Because of the wall rigidity, the shape of the wheel rut is of W shape, because pressure at the edges is more than that at the center (Gill and van den Berg, 1967; Figs. 7.7 and 7.8). Wheel rut depth or shrinkage of the soil under a load is related to the pressure, as per Eq. (7.40) (Bekker, 1961).

$$Z = M_d P^n \tag{7.40}$$

where P is pressure, Z is depth of wheel rut, M_d is modulus of deformation, and n is constant. For most mineral soils, M_d is about 4 and n is about 2. The pneumatic tire behaves like a rigid wheel in case of extremely high pressure and very soft (extremely wet) soil (Chancellor, 1976). Soil compaction by vehicles with crawler tracks is complicated by other additional factors: (i) backward tilt of the vehicle increasing pressure on the rear side two to three times that of the average pressure, (ii) shearing

FIGURE 7.7 The cold method is a useful technique to determine soil bulk density under field conditions. The

cold dipped in saran or any other resin can be used to determine total volume by the water displacement method.



A. Rigid well type

B. Non-rigid walls

FIGURE 7.8 A wheel tire with rigid walls creates a W shaped rut because of high pressure on the edges. A.Rigid well type; B.Nonrigid walls.

force due to tilting and shift of pressure, and (iii) particle displacement due to slippage. Similar compactive effects are observed under moving wheels.

The pressure distribution under wheel can be computed by using the Boussinesq equation, details of which are given by Soehne (1958) and others [Eq. (7.41)].

$$\sigma_z = \frac{3FZ^3}{2\pi(r^2 + Z^2)^{5/2}} \tag{7.41}$$

where σ_z is the stress at a depth Z, F is the total force applied, and r is the radial distance away from the center. When r is 0, directly beneath the wheel, $\sigma_z=3F/2\pi Z^2$. Soehne (1958) applied the Boussinesq theory to compute the pressure distribution under the tire. A schematic of the pressure distribution under the tire is shown in Fig. 7.9.

7.7.2 Measurement of Soil Compaction

Soil compaction may be measured by assessing bulk density and porosity, and pore size distribution (see Chapter 5). Thus, there are direct and indirect methods of measuring soil compaction (Fig. 7.10).

Soil Bulk Density

There are several methods of measuring soil bulk density. Basic principles, practical applications, and limitations of different methods are described in details by Gardner (1986), Campbell and Henshall (2001), and Campbell (1994). Most methods fall under two categories: (i) measurement of mass and volume, and (ii) assessment of other properties. Because dry bulk density is computed by dividing dry soil mass by its total