On the basis of the concentration and the tendency of particles to interact, four types of gravitational settling can occur: (1) discrete particle, (2) flocculent, (3) hindered (also called *zone*), and (4) compression. Because of the fundamental importance of the separation processes in the treatment of wastewater, the analysis of each type of separation process is discussed separately. In addition, tube settlers, used to enhance the performance of sedimentation facilities, are also described. Other gravitational separation processes include high-rate clarification, accelerated gravity settling, and flotation and are discussed in subsequent sections.

Particle Settling Theory

The settling of discrete, nonflocculating particles can be analyzed by means of the classic laws of sedimentation formed by Newton and Stokes. Newton's law yields the terminal particle velocity by equating the gravitational force of the particle to the frictional resistance, or drag. The gravitational force is given by

$$F_G = (\rho_p - \rho_w) g V_p \tag{5-16}$$

where F_G = gravitational force, MLT^{-2} ($kg \cdot m/s^2$)
ρ_p = density of particle, ML^{-3} (kg/m^3)
ρ_w = density of water, ML^{-3} (kg/m^3)
g = acceleration due to gravity, LT^{-2} ($9.81\ m/s^2$)
V_p = volume of particle, L^3 (m^3)

The frictional drag force depends on the particle velocity, fluid density, fluid viscosity, particle diameter, and the drag coefficient C_d (dimensionless), and is given by Eq. (5-17).

$$F_d = \frac{C_d A_p \rho_w v_p^2}{2} \tag{5-17}$$

where F_d = frictional drag force, MLT^{-2} ($kg \cdot m/s^2$)
C_d = drag coefficient (unitless)
A_p = cross-sectional or projected area of particles in direction of flow, L^2 (m^2)
v_p = particle settling velocity, LT^{-1} (m/s)

Equating the gravitational force to the frictional drag force for spherical particles yields Newton's law:

$$v_{p(t)} = \sqrt{\frac{4g}{3C_d}\left(\frac{\rho_p - \rho_w}{\rho_w}\right) d_p} \approx \sqrt{\frac{4g}{3C_d}(sg_p - 1) d_p} \tag{5-18}$$

where $v_{p(t)}$ = terminal velocity of particle, LT^{-1} (m/s)
d_p = diameter of particle, L (m)
sg_p = specific gravity of the particle

The coefficient of drag C_d takes on different values depending on whether the flow regime surrounding the particle is laminar or turbulent. The drag coefficient for various particles is shown on Fig. 5-20 as a function of the Reynolds number. As shown on Fig. 5-20, there are three more or less distinct regions, depending on the Reynolds number: laminar ($N_R < 1$), transitional ($N_R = 1$ to 2000), and turbulent ($N_R > 2000$). Although