8.3.4 Performance of the high rate anaerobic digester

The removal efficiency of the volatile solids concentration in an anaerobic digester depends basically on three factors: the digestion temperature, the retention time in the digester and the nature of the excess sludge to be digested. In Fig. 8.15 it can be noted that anaerobic digestion is more complete as the digestion temperature approaches the optimal range for mesophilic bacteria of 35 to 37°C. However, even at the optimal temperature, anaerobic digestion will be incomplete: the maximum solids removal efficiency does not exceed 55 to 60 percent in the case of primary sludge and is even lower for secondary sludge.

Araújo and Van Haandel (1998) operated anaerobic digesters with secondary sludges of different compositions. The active sludge concentration was varied between 17 and 83 percent of the volatile sludge concentration. It was observed that in completely mixed anaerobic digesters, operated in steady state at 20 days retention time and a temperature of 25°C, the removal efficiency of the volatile solids depended on the active sludge fraction. The removal efficiency of the active sludge fraction was found to be equal to the efficiency found by O'Rourke (1969) for primary sludge. However, the reduction of the inactive sludge was much smaller, only 15% at 25°C. Based on these experimental results, the following empiric relationship is suggested to estimate the maximum removal efficiency of volatile solids as a function of temperature and sludge composition:

(a) For primary sludge and the active fraction in secondary sludge:

$$R_{dp} = 0.67 \cdot T + 36 \qquad (8.60a)$$

(b) For inactive secondary sludge:

$$R_{dn} = 0.19 \cdot T + 10 \qquad (8.60b)$$

Where:

R_{dp} = fraction of the primary or active sludge mass that can be digested (%)
R_{dn} = fraction of the inactive sludge mass that can be digested (%)
T = temperature in °C (<37°C)

The biogas production is directly related to the removal of volatile solids. Knowing that the COD/VSS ratio of average excess sludge (f_{cv}) equals 1.5 kg COD.kg^{-1} VSS and that the COD content of methane is 4 kg COD.kg^{-1} CH_4, the production of methane is determined as 1.5/4 = 0.375 kg CH_4.kg^{-1} VSS. Hence for a primary sludge production of mE_{v1} kg VSS.kg^{-1} COD and a secondary sludge production of mE_{v2} with an inactive fraction of $(1 - f_{av}) \cdot mE_{v2}$ and an active fraction of $f_{av} \cdot mE_{v2}$, the digested influent COD fraction can be expressed as:

$$mS_d = 1.5 \cdot [R_{dp} \cdot (mE_{v1} + f_{av} \cdot mE_{v2}) + R_{dn} \cdot (1 - f_{av} \cdot mE_{v2})] \qquad (8.61)$$

$$mM_e = MS_d/4 = 0.375 \cdot [R_{dp} \cdot (mE_{v1} + f_{av} \cdot mE_{v2}) + R_{dn} \cdot (1 - f_{av} \cdot mE_{v2})] \qquad (8.62)$$

Where:

mS_d = influent COD fraction that is digested
mM_e = mass of methane produced per unit mass applied COD

As the volume of 1 mole of methane is around 25 litres under normal operational conditions in the digester (at 25°C and atmospheric pressure), the volume of methane per kg digested sludge (1.5 kg COD) is $0.375 \cdot 25/16 = 0.6\ m^3\ CH_4.kg^{-1}$ VSS. The volume of methane per unit of influent COD mass can now be calculated as:

$$mV_{me} = 0.6 \cdot [R_{dp} \cdot (mE_{v1} + f_{av} \cdot mE_{v2}) + R_{dn} \cdot (1 - f_{av}) \cdot mE_{v2}] \qquad (8.62)$$

For a biogas containing 55 to 70 percent of methane, the volume of produced biogas will be:

$$\begin{aligned} mV_{biogas} &= mV_{me}/(0.55 \text{ to } 0.7) \\ &= (0.85 \text{ to } 1.1) \cdot [R_{dp} \cdot (mE_{v1} + f_{av} \cdot mE_{v2}) + R_{dn} \cdot (1 - f_{av}) \cdot mE_{v2}] \qquad (8.63) \end{aligned}$$

Where:

mV_{me} = volume of methane per unit mass of applied COD
mV_{biogas} = volume of biogas per unit mass of applied COD

The production of stabilised sludge can be calculated easily as the difference between the total mass of excess sludge and the digested sludge mass:

$$\begin{aligned} mE_{ev} &= mE_{v1} + mE_{v2} - mE_d \\ &= mE_{v1} + mE_{v2} - R_{dp} \cdot (mE_{v1} + f_{av} \cdot mE_{v2}) + R_{dn} \cdot (1 - f_{av}) \cdot mE_{v2} \\ &= (1 - R_{dp}) \cdot (mE_{v1} + f_{av} \cdot mE_{v2}) + (1 - R_{dn}) \cdot (1 - f_{av}) \cdot mE_{v2} \qquad (8.64) \end{aligned}$$

$$\begin{aligned} mE_{et} &= mE_{t1} + mE_{t2} - mE_d \\ &= (1 - R_{dp}) \cdot (mE_{v1} + f_{av} \cdot mE_{v2})/f_v + (1 - R_{dn}) \cdot (1 - f_{av}) \cdot mE_{v2}/f_v \qquad (8.65) \end{aligned}$$

Where:

mE_e = stabilised sludge mass per unit mass of applied COD
mE_d = digested sludge mass per unit mass of applied COD
Indexes v, t and d refer to the volatile, total and digested sludge fractions

In Eq. (8.65) it is tacitly assumed that there is no net solubilisation in the digester. In reality, some solubilisation will occur as the COD of the digester effluent is higher than that of the liquid phase of the raw sludge. However, under normal conditions most of the liquefied material is digested. The most important characteristic of the digester effluent is the high nitrogen concentration, predominantly in the form of ammonia. If it is assumed that the release of ammonia from digested secondary sludge is f_n per digested unit mass of excess sludge, and that no nitrogen is released during the digestion of primary sludge, the effluent ammonium concentration can be estimated as:

$$mN_{ld} = f_n \cdot (R_{dp} \cdot f_{av} \cdot mE_{v2} + R_{dn} \cdot (1 - f_{av}) \cdot mE_{v2}) \qquad (8.66)$$

mN_{ld} = nitrogen production in the digester per unit mass of applied COD

In general, the settleability of anaerobic digested sludge is much better compared to that of fresh (undigested) sludge. The values of the settling constants k and v_0 of digested sludge are in the order of 0.20 to 0.25 $l.g^{-1}$ and 200 to 300 $m.d^{-1}$ respectively. A problem is that during digestion a large number of microscopic sludge flocs are formed which practically do not settle. Therefore, the COD value of the liquid effluent is relatively high (COD_t between 500 and 1500 $mg.l^{-1}$) of which a large fraction is not biodegradable.

The fraction of anaerobic degraded organic material increases as the sludge age decreases, because the excess sludge will have a higher active fraction. In Fig. 8.18 the COD fractions in the effluent and in the stabilised, oxidised and digested sludge are shown plotted as functions of the sludge age for temperatures of 20°C (left) and 30°C (right), maintaining the same assumptions as in the preceding example. Fig. 8.18 shows that when primary settling is applied and the process is operated at a short sludge age, the influent COD fraction digested in the process may exceed the oxidised fraction, so that the process as a whole actually becomes predominantly anaerobic.

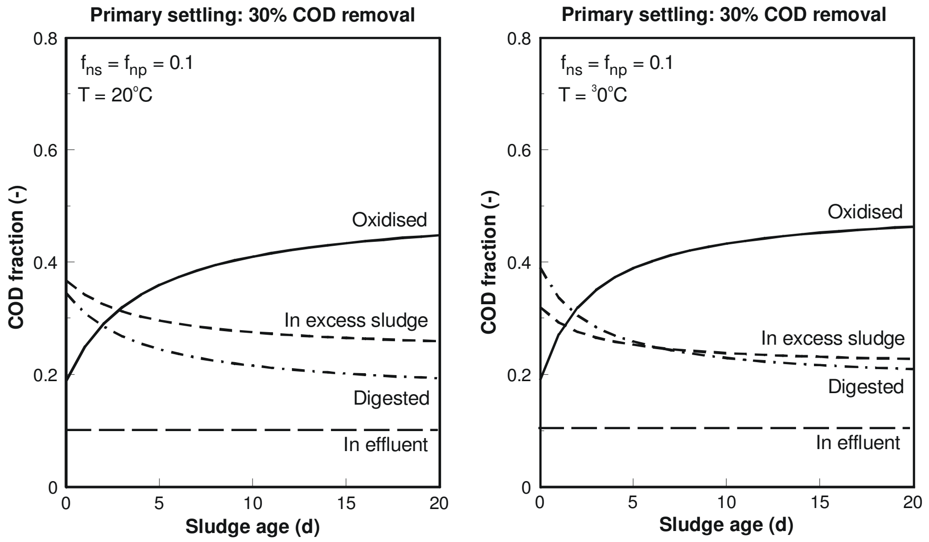

Figure 8.18a Division of the influent COD over fractions mS_e, mS_o, mS_{xv} and mS_d as a function of the sludge age with primary settling, at different temperatures

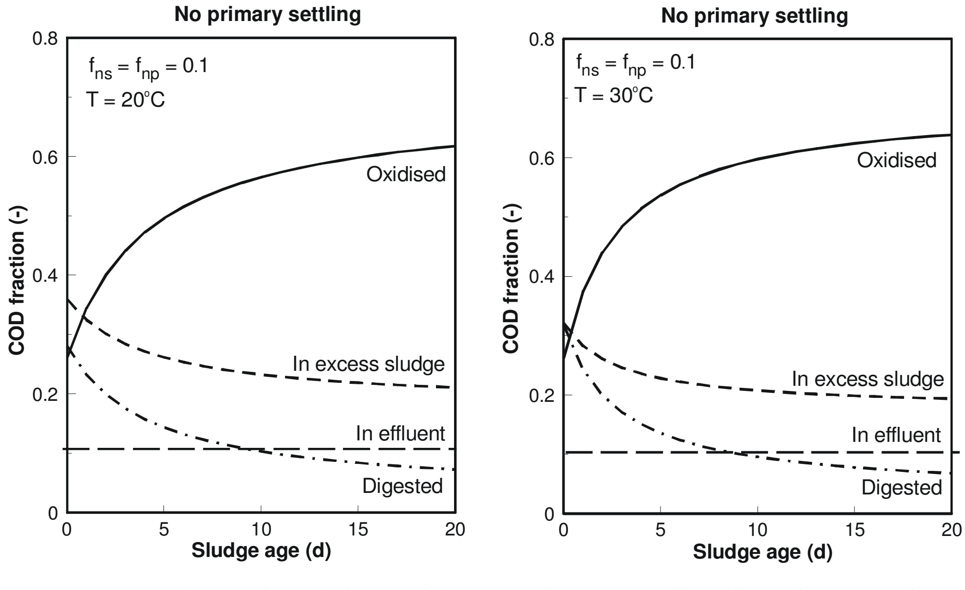

Figure 8.18b Division of the influent COD over fractions mS_e, mS_o, mS_{xv} and mS_d as a function of the sludge age without primary settling, at different temperatures