CHAPTER 20

SLUDGE PROCESSING AND LAND APPLICATION

Sludge disposal is one of the major operating expenses of any wastewater treatment process. Recent increasingly restrictive regulations on sludge disposal have contributed to the need for and expense of sludge processing. There are many biological and physical–chemical options to reduce the volume and quantity of sludge. Concentrated sludges are also more easily controlled at their ultimate disposal site. Anaerobic digestion, covered in Chapter 18, is another often used option in addition to those processes covered here.

It is not the intent of this chapter to provide all details on the operation of sludge processing operations. There are many subtleties to fine tuning individual processes and the overall sludge processing train to provide the least cost sludge for disposal. More details are available in Metcalf and Eddy (1991), USEPA (1979, 1987), and from manufacturers of processes. In addition to typical information it is essential to pilot processes with trial and error adjustment.

Sludge handling begins with the processes that generate sludge. Chemical agents and blending in the primary sludge generation processes affect quantities of sludge to be processed and efficiency of sludge concentration processes.

Sludge is a rich source of nutrients and soil conditioning substances; therefore, land application is a natural and desirable disposal option.

20.1 SLUDGE CHARACTERISTICS AND CONDITIONING

The high concentration of solids in sludge slurries affects the density and viscosity of the suspension. Dewatered sludges can have solids concentrations ranging up to 40% on a weight basis.

Sludge Density

The mass of solids in a slurry is normally related to the volatile suspended solids (VSS) and fixed suspended solids (FSS) components in the slurry. The specific gravity (s.g.) of a slurry, S_s, is

$$S_s = \frac{\text{mass of slurry/volume of slurry}}{1.0} = \frac{m_w + m_V + m_F}{V_s} \qquad (20.1)$$

m_w, m_V, m_F MASS of WATER, VSS, FSS

V_s = volume of sludge slurry

Define S_w, S_V, and S_F as the s.g.s of water, VSS, and FSS, respectively. It is assumed that each of these entities is distinct and the volumes contributed by each of them can therefore be added. This is not the case for biological solids, where the inorganic (fixed) solids are intimately associated with the organic (volatile) solids. However, suitable working relations can be developed for particular situations. Expressing the volume relation:

$$V_s = V_w + V_V + V_F$$

where

V_s, V_w, V_V, and V_F are the volumes of sludge, water, VSS, and FSS, respectively

Using the s.g.s,

$$\frac{m_w}{S_w} + \frac{m_V}{S_V} + \frac{m_F}{S_F} = \frac{m_s}{S_s}$$

where

m_s is the total mass in the slurry

Dividing by m_s,

$$\frac{m_w/m_s}{S_w} + \frac{m_V/m_s}{S_V} + \frac{m_F/m_s}{S_F} = \frac{1}{S_s} = \sum_i \frac{f_{mi}}{S_i} \tag{20.2}$$

where

f_{mi} is the mass fraction of the ith component in the slurry. The mass fractions of the solids are on a dry basis.

The water (moisture) or total solids content of a sludge expressed on a percentage basis is often used to express its concentration. The volume of a sludge related to its total solids content is

$$V_s = \frac{M}{(p_M/100)S_s} = \frac{M}{[(100 - p_w)/100]S_s} \tag{20.3}$$

where

M is the mass of dry solids in the slurry; $M = m_V + m_F$

p_M and p_w are the percent solids and water content (both on a mass basis), respectively

The s.g. of organic matter is near the s.g. of water, i.e., near 1.00; the density range of activated sludge solids is 1.01–1.10 g/L (Dammel and Schroeder, 1991). Mineral solids have much higher s.g.s. A value of 2.5 is commonly used for the s.g. of FSS but solids in a chemically conditioned water may have s.g.s ranging from 1.5 to 2.5.

■ Example 20.1 Sludge Volume and Specific Gravity

(a) Calculate the s.g. of a biological sludge that contains 75% VSS and 25% FSS when the sludge has a concentration of 10 000 mg/L (≈1% by weight).

(b) Calculate the volume of 1 kg of this sludge when it is concentrated to 5, 10, and 20% solids concentration by weight.

(a) At 10 000 mg/L, 1 L of the sludge contains 10 g of solids that consist of 7.5 g VSS and 2.5 g FSS. The first inclination might be to assume that a liter of sludge had a mass of 1 010 g. But because the s.g.s of VSS and FSS are ≥1.00, the water content of 1 L of sludge will be very near 990 g. Assuming the s.g.s of VSS and FSS are 1.00 and 2.50, respectively, from Eq. (20.2):

$$\frac{1}{S_s} = \frac{990/1\,000}{1.0} + \frac{7.5/1\,000}{1.0} + \frac{2.5/1\,000}{2.5} = 0.998\,5 \qquad S_s = \frac{1}{0.998\,5} = 1.001\,5$$

It is seen that the assumption about the water content is correct. Further iterations are needless to refine the estimate of the mass of water in the sludge.

(b) At a solids content of 5% by weight, the mass of solids in 1 kg of sludge is 50 g. Using 50 g, the s.g. of the sludge (by trial and error solution of Eq. 20.2) is

$$\frac{1}{S_s} = \frac{958/1\,008}{1.0} + \frac{37.5/1\,008}{1.0} + \frac{12.5/1\,008}{2.5} = 0.992\,6 \qquad S_s = \frac{1}{0.992\,6} = 1.008$$

From this result, the solids content is 50 g/1 008 g = 0.049 6 or 4.96%. The actual solids content of 1 L should be increased by a factor of approximately 5.00/4.96 = 1.008 and Eq. (20.2) should be solved again using 37.8 g and 25.2 g for VSS and FSS, respectively. The error is negligible in this case but at higher solids concentrations it would be necessary to perform the correction.

Applying Eq. (20.3),

$$V_s = \frac{50\text{ g}}{(5/100)\left(1.008\,\dfrac{\text{g}}{\text{cm}^3}\right)\left(\dfrac{1\,000\text{ cm}^3}{\text{L}}\right)} = 0.992\text{ L}$$

By similar calculations, the s.g.s of sludges at 10 and 20% solids content are 1.014 and 1.031, respectively. The volumes of 1 kg of sludge are 0.985 and 0.970 L, respectively.

As Example 20.1 shows, the volume of sludge to be removed is essentially indirectly proportional to the solids content of the sludge. Figures 20.1a and 20.1b show the variation in the volume of sludge as a function of FSS : VSS ratio, mass percentage of

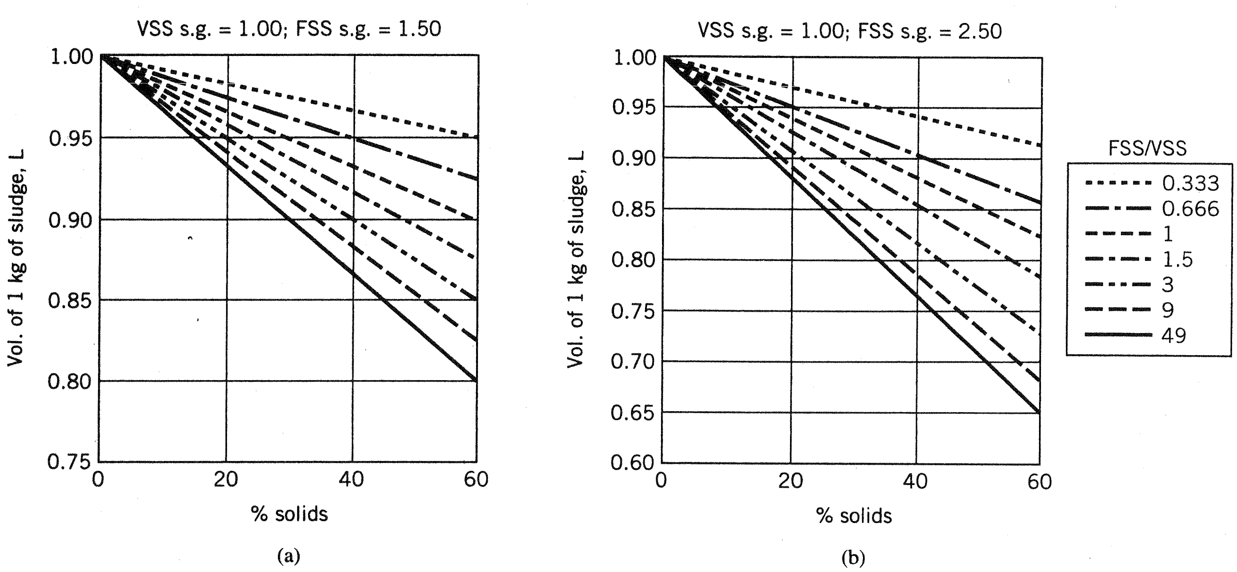


Figure 20.1 (a) Volume variation of sludge. (b) Volume variation of sludge.

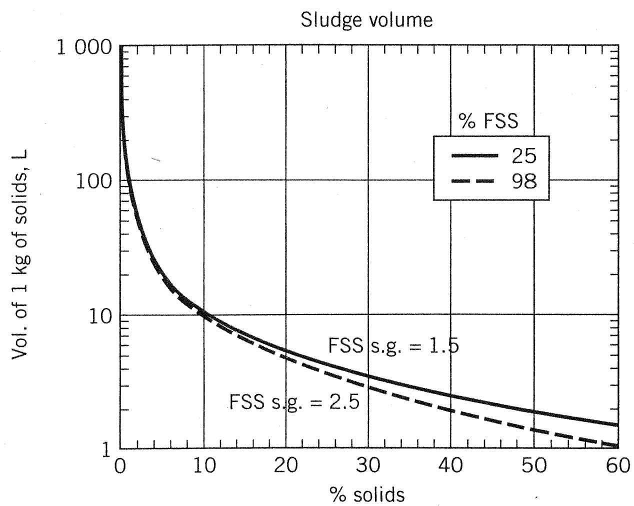


Figure 20.2 Volume occupied by 1 kg of solids.

solids in the sludge, and s.g. of FSS. These graphs were prepared by solving Eq. (20.2) and then applying Eq. (20.3). Biological sludges have FSS : VSS ratios near 1 : 3, which results in the lowest overall solids density in sludges. Mineral sludges from water treatment plants do not contain significant amounts of VSS.

Figure 20.2 shows the extremes in volume variation that can occur for sludges found in water and wastewater treatment plants as a function of mass concentration. Solids content has to be above 10% to significantly change the volume of 1 kg of sludge from 1 liter. Sludge concentration processes can have a dramatic effect on the volume of sludge produced. Influent water to a water treatment plant will contain 1 kg of solids in 10^4–10^5 L (1 lb per 10^3–10^4 gal) of water. Municipal raw wastewaters will contain 1 kg of solids in 10^3–10^4 L (1 lb per 10^2–10^3 gal) of water.

Sludge Viscosity

Vesilind (1979) notes that pumping sludge is more of an art than a science. The capricious nature of sludge viscosity is one of the reasons for this statement. Sludge varies from a Newtonian fluid, where shear is proportional to the velocity gradient, to a plastic fluid, where a threshold shear must be reached before the sludge will move. Most wastewater sludges are pseudoplastic; this behavior can be described by the following viscosity law (Vesilind, 1979):

$$\tau = \eta \left(\frac{dv}{dy}\right)^n \tag{20.4}$$

where

τ is the shear stress
η is the plastic viscosity
n is a constant
dv/dy is the velocity gradient

Vesilind (1979) notes that it is impractical to apply Eq. (20.4) because there are no typical sludges and the rheological characteristics of a given sludge vary with concentration of solids and other factors. Practical approaches to estimating headloss for sludge pumping use empirical correlations of a friction factor as a function of a Reynold's number and apply the Darcy–Weisbach equation. Otherwise empirical plots of headloss as a function of velocity are utilized. Solids concentration is a parameter on the plots.

20.2 SLUDGE GENERATION AND TREATMENT PROCESSES

Solids generated in water treatment operations consist of essentially all suspended solids in the influent plus all chemical agents added that produce precipitates or conditioning agents that are incorporated into the sludge in sludge processing operations. Lime and alum recovery are sometimes used but all other solids, regardless of recycling within the water treatment plant, ultimately are present in the sludge streams.

Solids generation in physical–chemical wastewater treatment plants is similar to water treatment plants. Solids generation in biological wastewater treatment plants is more difficult to estimate. All suspended solids in the influent do not appear in the sludge. Some are biologically metabolized to soluble or gaseous end products in the biological treatment process or sludge digestion process. Some soluble wastewater components will be transformed into biological solids that can be reduced in digestion. Solids generation in a biological process is a function of the type of process and the operation of the process. Final effluent from a wastewater treatment plant may contain a solids concentration that has a significant effect on the solids remaining for sludge processing.

Solids formed from addition of precipitation agents can be estimated from the stoichiometry of the reaction (for example, the reactions in Table 13.2); however, the stoichiometry of precipitate formation can vary from the chemical equations because of side reactions. Solids generation (or destruction) from biological treatment is discussed in Chapters 17 and 18, which should be reviewed.

Water treatment plants may dispose of their sludge streams in sewers for processing at the wastewater treatment plant. This economizes sludge handling at one central location. Chemical agents added at water treatment plants normally are not harmful to biological treatment processes and they often contribute to enhanced solids separation at wastewater treatment plants. Return of sludge generated in water treatment to surface waters is discouraged or prohibited.

Onsite sludge treatment refers in general to processes used to concentrate sludge. The exceptions in water treatment are processes to recover lime and metal coagulants (alum and iron salts) from $CaCO_3$ and metal coagulant sludges (Sections 13.1 and 15.2), respectively. In wastewater treatment anaerobic and aerobic sludge digestion reduce quantities and therefore volumes of sludge. Sludge quantities may be reduced by thermal processes (e.g., incineration, pyrolysis, or wet-air oxidation) before ultimate disposal. Landfill and land application are the most commonly used means of ultimate disposal. Some wastewater sludges may be composted for land application. Ocean dumping of sludge is discouraged or prohibited.

Except for land application of sludge this chapter focuses on sludge concentration processes. There are a variety of standard and proprietary devices for processing sludge. Some are described in more detail in following sections. Performance of processes varies widely and recommendations for different processes from various sources are even contradictory. Careful study of the options and pilot-scale testing is recommended to make the best choice.

TABLE 20.1 Water Treatment Sludge Concentrations

Sludge type	Solids concentration %
Sedimentation basin underflow	0.5–2
Slurry from upflow clarifier	2–5
Filter backwash water	50–1 000[a]
Settled solids from lime–soda softening	2–15
Alum–lime coagulation softening settled sludge	Up to 10
Iron–lime coagulation softening settled sludge	10–25
Gravity thickener	
Coagulation settlings and backwash water	2–20 (2–4 is more typical)
Filter backwash water	Up to 4
Lime sludge	15–30
Vacuum filter	
Coagulant sludge	10–20
Lime softening (>85% $CaCO_3$ content)	50–70
Lime softening [high $Mg(OH)_2$ content]	20–25
Centrifuge	
Coagulant sludge	10–20
Lime and alum sludge	15–40
Lime sludge	30–70
Pressure filter	
Coagulant sludge	30–45
Lime sludge	55–70
Belt filter	
Coagulant sludge	10–15
Sand drying bed	
Coagulant sludge	20–25
Lime sludge	50
Storage lagoon	
Coagulant sludge	7–15
Lime sludge	50–60

[a]Given in mg/L.

Options for sludge concentration or treatment for water treatment and wastewater sludges are given in Figs. 20.3a and 20.3b in the general sequence in which they occur. All of the processing phases are not necessarily used. Chemical conditioning agents may be added before each of the processes. Chemicals must be added before some of the processes.

Performance ranges for water treatment plant sludge processes are given in Table 20.1. Such tables can only be used as guides. The sources of sludge are the sedimentation basins and backwash water from the filters. Backwash water is commonly returned ahead of the coagulation basin or it may be separately thickened and combined with other sludges for dewatering. Softening sludges with a high $CaCO_3$ content are able to achieve the highest concentrations.

Primary sedimentation solids and biological solids generated in wastewater treatment processes are different in nature and offer more choices for blending and processing before dewatering. Waste solids from the secondary clarifier may be recycled to the primary clarifier if there is a net gain in underflow solids concentration. Table 20.2 gives characteristics of primary solids and solids generated in different biological treatment processes. Solids removed in primary clarifiers concentrate to a higher

(a)

Thickening	Solids Reduction	Dewatering
Dissolved air flotation	$CaCO_3$ recovery	Centrifugation
Gravity	Alum recovery	Drying bed
		Horizontal belt filter
		Lagoon
		Pressure filter
		Vacuum filter

(b)

Thickening	Solids Reduction	Physical–Chemical Stabilization	Dewatering
Centrifugation			Centrifugation
Dissolved air flotation			Drying bed
Gravity belt	Aerobic sludge digestion	Heat Treatment	Horizontal belt filter
Gravity	Anaerobic sludge digestion	Lime stabilization	Lagoon
Rotary drum			Pressure filter
			Vacuum filter

Figure 20.3 (a) Water treatment sludge operations. (b) Wastewater sludge processing operations.

degree than biological solids and if recycle of the biological solids to the primary clarifier is not practiced, biological solids may be separately thickened before blending with primary clarifier solids. A greater variety of processes are used to thicken sludge for digestion or dewatering. Typical performance ranges of thickening processes are given in Table 20.3. Performance of dewatering processes are given in Table 20.4. Variation in performance data is evident from the tables and the values should only be taken as guides.

TABLE 20.2 Wastewater Treatment Sludge Concentrations[a]

Sludge type	Sludge concentration %
Primary sludge	5–8
Waste activated sludge	0.5–2.0
Fixed film waste sludge	3–10
Primary and waste activated sludge	2.5–4
Primary and fixed film sludge	3–5
Aerobically digested sludge (thickened)	1–2
Anaerobically digested sludge (thickened)	6–12

[a]Adapted from Metcalf and Eddy (1991) and USEPA (1979, 1987).

TABLE 20.3 Thickeners Performance for Wastewater Sludges[a]

Sludge type	Dissolved air flotation	Gravity thickener	Belt thickener (with polymer)	Centrifuge
	Solids concentration, %			
Primary clarifier		8–10	9–12	9–12
Waste activated sludge	3–5	2–2.5	4–6	4–6
Fixed film waste sludge	3–5	2.5–3	5–7	5–7
Primary + waste activated sludge	4–6	4–5	5–7	5–7
Primary + fixed film sludge	4–6	5–6	5–10	6–10
	Solids capture, %			
Without chemicals	80–95	80–92	na[b]	80–90
With chemicals	90–98	na[b]	—	90–98

[a]Adapted from Metcalf and Eddy (1991) and USEPA (1987).
[b]na-not applicable.

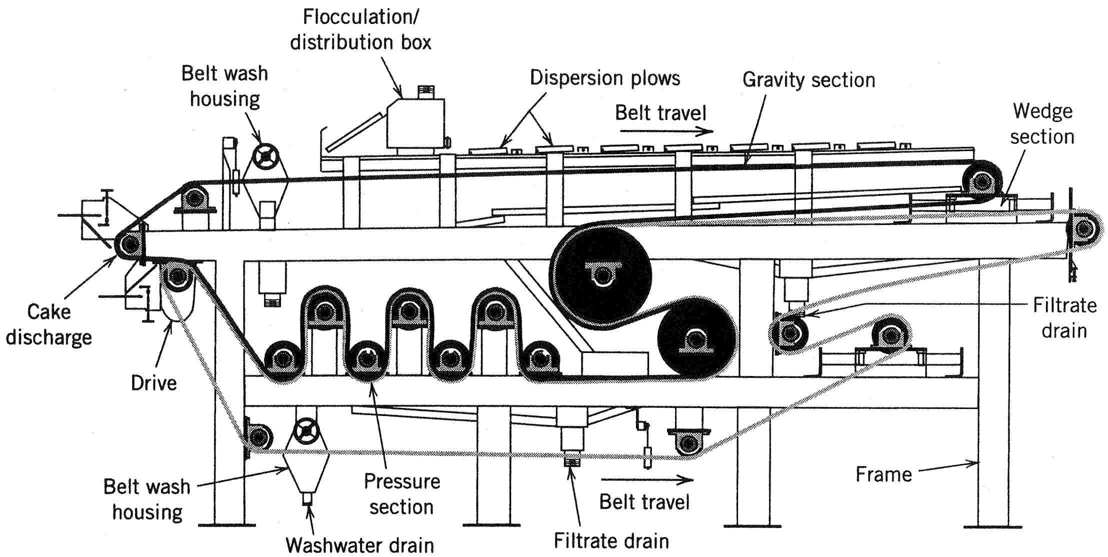
Higher solids concentration in the influent to a sludge concentration process yield higher concentrations of solids in the product. Sludge processing is both energy and labor intensive. Gravity sludge thickeners are the most common primary sludge concentration processes in both water and wastewater treatment because the process requires minimal energy input. Sludge thickeners should not be used for storage of sludge or their performance deteriorates. General considerations for selection of sludge volume reduction processes are as follows:

1. Sludge characteristics.
2. Volume reduction attainable.
3. Energy inputs and other operation and maintenance costs. Skills required to operate the process must also be considered.
4. Chemical inputs.
5. Other operations in the sludge processing train.
6. Ultimate disposal. It may be desirable to have sludge in a liquid form for spreading on land but a sludge with minimal moisture content is desirable for landfill. Sludge may be pumped to a disposal location or hauled by truck or railway which have opposing moisture requirements.

TABLE 20.4 Performance of Dewatering Units for Wastewater Sludges

Process	Sludge concentration, % Without chemicals	Sludge concentration, % With chemicals	Solids capture, % Without chemicals	Solids capture, % With chemicals
Centrifuge	10–30	10–35	55–90	85–98
Drying beds	30–60	na[a]		
Horizontal belt press	na	15–30	na	85–98
Lagoon	15–40	na		
Pressure filter	na	20–50	na	90–98
Vacuum filter	na	15–30		90–98

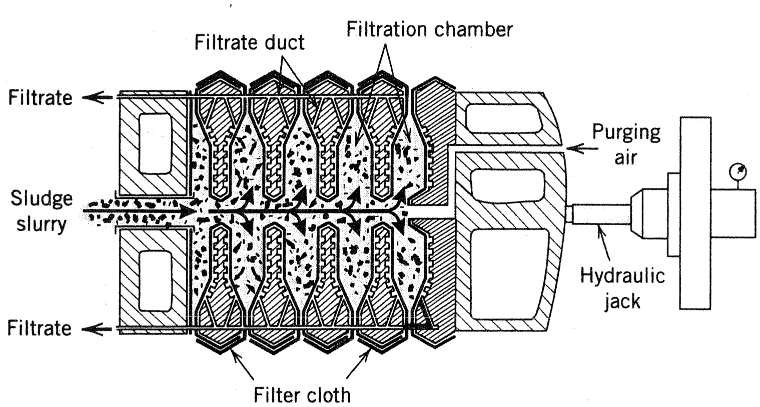
[a]na, not applicable.



Horizontal belt press. Courtesy of Envirex.

7. Concentration of solids in the reject liquid.
8. Space requirements. Mechanical processes require much smaller areas than land dewatering.

More details on the design and operation of the most common concentration operations are given in later sections.



Filter press. Courtesy of Degrémont Infilco.

20.3 SLUDGE CONDITIONING

Sludges are conditioned to improve their dewatering and cake forming properties in processes described in the above section and below. The tables in Section 20.2 show that both product cake concentrations and percentage solids capture generally improve with chemical addition. Common coagulating agents such as ferric chloride and lime in addition to a variety of synthetic chemicals are good conditioning agents. Inorganic chemical conditioning is associated principally with vacuum and pressure filtration processes with lime and ferric chloride being the most often used agents (USEPA,