

CHAPTER 6

Feed Conditioning — Physical and Chemical

INTRODUCTION

Designers and operators of composting systems have a limited number of areas over which to exercise control of the process. One area of control is the composition of the feed mixture. The proportions of feed components must be adjusted to satisfy the energy balance and avoid rate limitations caused by lack of moisture, lack of free airspace, sterile feed, or low nutrient levels. The quantities of required feed components must be known to size the system and its metering, mixing, and conveying equipment. There are three aspects to feed conditioning: physical or structural conditioning, chemical conditioning, and thermodynamic or energy conditioning. The relationships between free airspace and moisture content are discussed in this Chapter. These are the most important physical factors that must be considered to assure proper structural conditioning of the feed substrates. Chemical conditioning to correct for nutrient and pH imbalances is also discussed. Energy conditioning is discussed in Chapter 8.

THE IMPORTANCE OF MOISTURE AND FREE AIRSPACE

The composting matrix is a network of solid particles that contain voids and interstices of varying size. Voids between particles are filled with air, water, or a mixture of air and water. If the voids become completely filled with water, oxygen transfer is greatly restricted and aerobic composting becomes impractical in the absence of constant agitation. If some water is removed and the voids fill with air, oxygen transfer begins and aerobic composting is possible. If too much water is removed, however, microbial kinetics will be slowed by lack of moisture and the composting activity will decline.

Decomposition of organic matter depends on the presence of moisture to support microbial activity. As Golueke¹ points out, the theoretically ideal moisture content is one that approaches 100% because under such conditions biological decomposition occurs in the absence of any moisture limitation. Autothermal thermophilic aerobic digestion (ATAD) processes are com-

Table 6.1. Maximum Recommended Moisture Contents for Various Composting Materials

Type of Waste	Moisture Content (% of total weight)
Theoretical	100
Straw ^a	75-85
Wood (sawdust, small chips)	75-90
Rice hulls ^a	75-85
Municipal refuse	55-65
Manures	55-65
Digested or raw sludge	55-60
"Wet" wastes (grass clippings, garbage, etc.)	50-55

Source: Golueke.¹

^a Serves as a moisture absorbent and source of carbonaceous material. Requires addition of nitrogenous material to lower C/N ratio to a proper level.

mercially available; they achieve thermophilic temperatures during aerobic decomposition of liquid organic slurries. These processes operate without any moisture rate limitations and have occasionally been referred to as "liquid composting" processes. Such processes cannot produce a dry end product, however, and they are usually limited to situations in which the liquid slurry is land applied.

Composting is usually applied to solid or semisolid materials and the practical moisture content must be considerably <100%. If the substrate is to be placed in windrows, static piles or a reactor system, the question arises as to the maximum moisture content to begin the process. General ranges of moisture contents found suitable for various wastes are listed in Table 6.1. The values shown are related to the structural strength of the composting material. Fibrous or bulky material such as straw or wood chips can absorb relatively large quantities of water and still maintain their structural integrity and porosity. For example, McGauhey and Gotaas² were able to compost mixtures of vegetable trimmings and straw that had initial moisture contents as great as 85%, but 76% moisture was too great when paper was used instead of straw.

Many composting substrates, such as municipal refuse, agricultural residues, and yard wastes, begin the composting process in a relatively dry form. Even animal manures are often field-dried before composting. Many composting systems have been developed to process such dry materials, and provisions are usually made for moisture addition as composting proceeds. Furthermore, the fibrous and bulky nature of such materials allows absorption of relatively large quantities of water. Sludge and other wet organic wastes differ on both accounts. Municipal sludge seldom contains <70% water, and sludge is not a fibrous material capable of supporting such high moisture contents. If sludge cake were composted alone, nearly constant mechanical agitation would be needed to provide aeration because of the lack of free airspace in which to store oxygen.

The importance of proper moisture control was demonstrated by Senn³ during composting of dairy manure. Composting was conducted in 2.4 m deep bins equipped with a forced aeration system mounted in the bin floor. The influence of moisture content on subsequent temperature development is shown in Figure 6.1. At 66% moisture the temperature rose to about 55°C but no higher. The bin was unloaded, dry material added, and the mix reloaded at 61% moisture. Temperature then rose rapidly to above 75°C. In a parallel test using material loaded at 60% moisture, the temperature quickly rose to above 75°C and remained for several days. The higher moisture content impeded the composting process because the excess moisture caused packing and reduced void space which prevented proper air movement throughout the material.

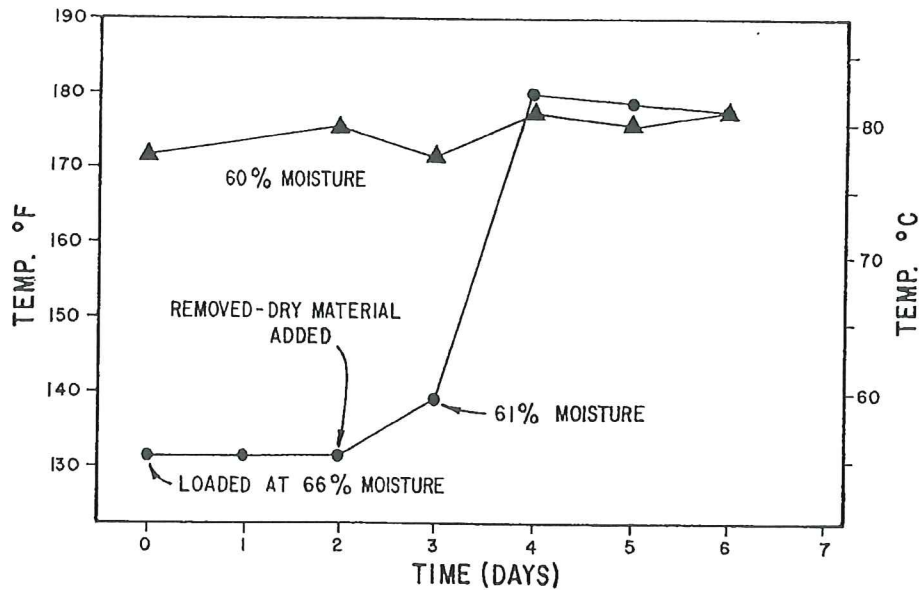


Figure 6.1. Effect of initial moisture content on temperatures developed during composting of dairy manure in deep bins. From Senn.³

Achieving a balance of moisture and free airspace in the starting mixture does not guarantee that the balance is maintained once composting starts. If proper aeration rates are supplied, the thermophilic temperatures of composting will cause significant moisture removal. It is not unusual for the composting mixture to dehydrate to the point that reaction rates are seriously impacted. Water must then be added back into the process to correct the moisture imbalance.

The free airspace of a composting mixture is important in determining the quantity and movement of air through the mixture. It is generally believed that the optimum moisture content for a particular material is related to maintenance of a certain minimum free airspace. In general, more fibrous and friable materials can maintain higher moisture contents while still retaining adequate free airspace. Thus, different materials can hold different moisture levels while still maintaining the same free airspace. The term "optimum moisture" represents a tradeoff between the moisture requirements of the microbes and their simultaneous need for an adequate oxygen supply.

Maintaining proper moisture and free airspace levels is a matter of balancing numerous competing forces. Moisture levels must be high enough to assure adequate rates of biological stabilization, yet not so high that free airspace is eliminated, thus reducing the rate of oxygen transfer and in turn the rate of biological activity. In addition, it is advantageous to produce a reasonably dry compost product, one that can be stockpiled and transported economically for subsequent reuse. It may not be possible to optimize all of these factors at the same time. Tradeoffs will usually be necessary. Relationships between these competing factors are developed in the discussion of process dynamics in Chapters 11 through 14. The discussion here will focus on methods available to control moisture and free airspace in the starting mixture.

WEIGHT AND VOLUME RELATIONSHIPS

A schematic representation of the composting matrix considered as a three phase system of solids, water, and gas is shown in Figure 6.2. The figure must be understood as a schematic representation because the void and solid volumes cannot be segregated as shown. Neverthe-

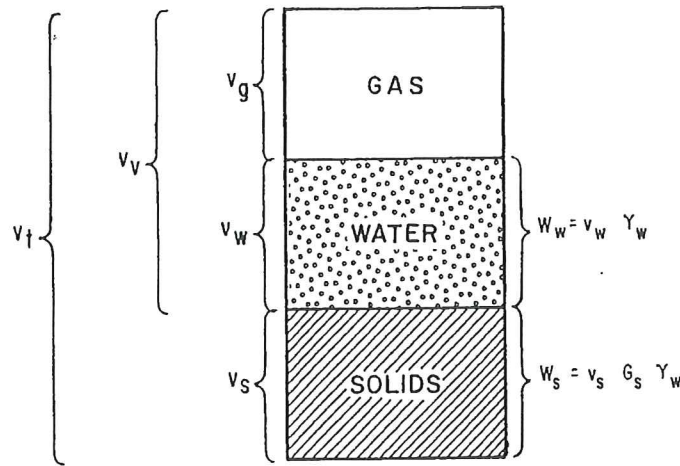


Figure 6.2. Diagram of the compost matrix as a three phase system of solids, water, and gas.

less, the sketch facilitates understanding of the relationships between terms given in this chapter. As shown in Figure 6.2, total volume, v_t , consists of two parts, the volume of solid matter, v_s , and the volume of voids, v_v . The volume of voids is further distinguished into water volume, v_w , and gas volume, v_g .

The specific gravity of a solid is a function of the specific gravities of component parts making up the solid. If specific gravities of organic (volatile) and ash (fixed) components are known, the specific gravity of the solids as a whole can be calculated as

$$\frac{1}{G_s} = \frac{V_s}{G_v} + \frac{(1-V_s)}{G_f} \tag{6.1}$$

where

V_s = volatile fraction of the substrate solids

G_s = specific gravity of the substrate solids

G_v = specific gravity of the organic or volatile fraction of the substrate solids

G_f = specific gravity of the ash or fixed fraction of the substrate solids

$$\frac{1}{G_s} = \frac{V_s}{1} + \frac{(1-V_s)}{2.5} = \frac{2.5 \cdot V_s + (1-V_s)}{2.5}$$

$$G_s = \frac{2.5}{2.5V_s + (1-V_s)}$$

The specific gravity of the volatile solids (VS) normally is about 1.0 and that of fixed solids about 2.5.

The total volume of a composting mixture equals the sum of the volumes of water, solids, and gas contained in the mixture. The maximum bulk weight can be estimated by assuming the gas volume to be zero. Municipal and industrial sludge cakes often approach this condition. Assuming zero gas volume, total volume becomes

$$V_t = \frac{W_s}{G_s \delta_w} + \frac{W_w}{\delta_w} = \frac{W_s}{G_s \delta_w} + \frac{W_s(1-S_s)}{S_s \delta_w} \tag{6.2}$$

$$V_t = (W_s / \delta_w) [1/G_s + (1-S_s)/S_s] \quad (V_g = 0)$$

USA -
SI - metric

where

- W_s = weight of dry solids
 W_w = weight of water
 δ_w = unit weight of water
 S_s = fractional solids content of the substrate

Let δ_s = unit bulk weight of the substrate solids = total wet weight per unit volume, and let δ_s (dry) = unit dry weight = dry weight per unit volume. Based on Equation 6.2, unit bulk and dry weights for the substrate can be calculated as

$$\delta_s = \frac{W_s}{S_s V_t} = \frac{W_s}{S_s (W_s / \delta_w) [1 / G_s + (1 - S_s) / S_s]} \quad (6.3)$$

$$\delta_s = \frac{\delta_w}{[(S_s / G_s) + 1 - S_s]} \quad (V_g = 0)$$

$$\delta_s \text{ (dry)} = S_s \delta_s \quad (6.4)$$

Equation 6.3 is valid as long as pore spaces within the material are completely filled with water. Wet substrates such as sludge cake usually contain little or no gas volume and generally meet the conditions of Equation 6.3. As moisture is removed, however, the gas volume begins to increase and bulk weights become less than the maximum. This is illustrated by the data of Figure 6.3 which was developed for digested sludge cake. The maximum bulk weight was calculated from Equation 6.3 using the procedures of Example 6.1. Although there is some data scatter, unit bulk weight does decrease with increasing solids content, with measured values beginning to deviate from the maximum at solids contents above ~35%. Thus, FAS becomes measurable above about 35% TS for the sludge tested for Figure 6.3. Many sludge composting systems operate with initial mixtures near 40% TS for this reason. If amendments with low bulk weights, such as sawdust, are blended with the sludge cake, FAS may be present at higher moisture contents.

Corresponding values of unit dry weight are shown in Figure 6.4. Unit dry weight is reasonably constant above solids contents of 35 to 40%. Within this range, it is likely that moisture evaporates from the solids causing little net change in the total volume. If the unit dry weight is assumed constant, Equation 6.4 becomes

$$\delta_s \text{ (dry)} = \text{constant}, C = S_s \delta_s$$

$$\delta_s = C / S_s \quad (6.5)$$

The form of Equation 6.5 provides the basis for algorithms used to predict unit bulk weights in the simulation models of Chapters 11 through 14.

Data scatter in Figures 6.3 and 6.4 is probably caused in part by different levels of compaction and consolidation, which are functions of the methods used in handling the material. Compaction was minimized during collection of data shown in Figures 6.3 and 6.4.

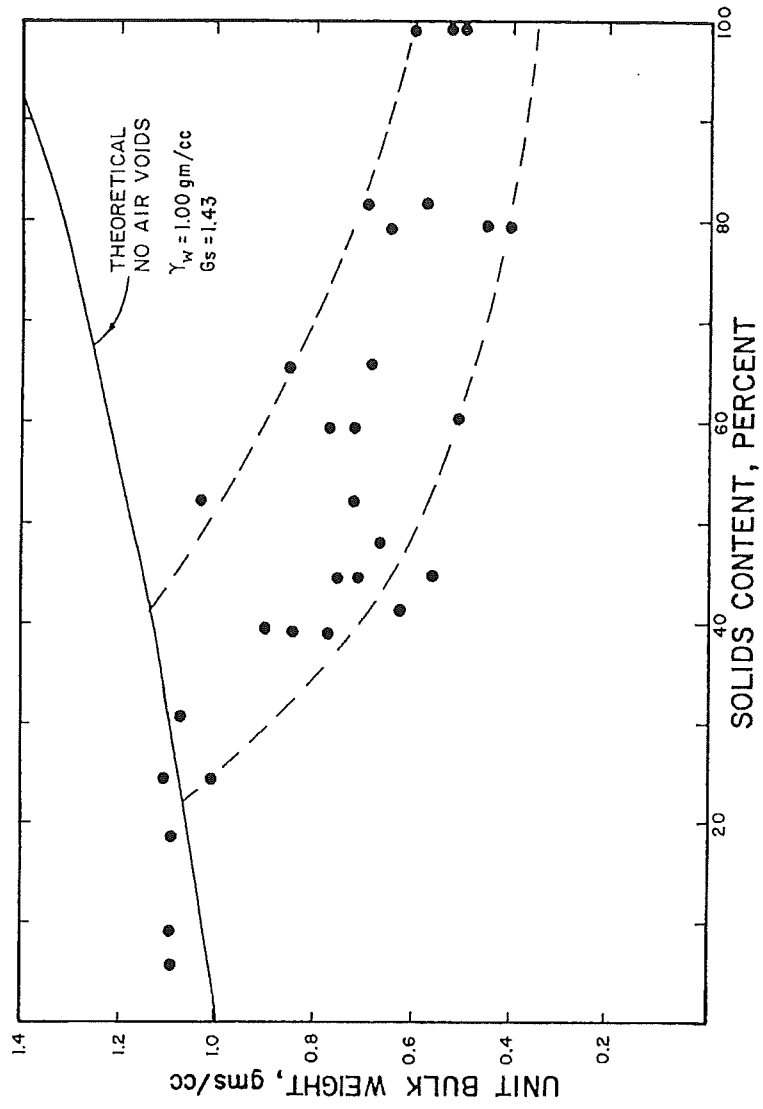


Figure 6.3. Unit bulk weight of sludge and compost as a function of solids content. Data are for sludge-only systems and do not include effects of amendment or bulking agent additions. From Haug.⁴

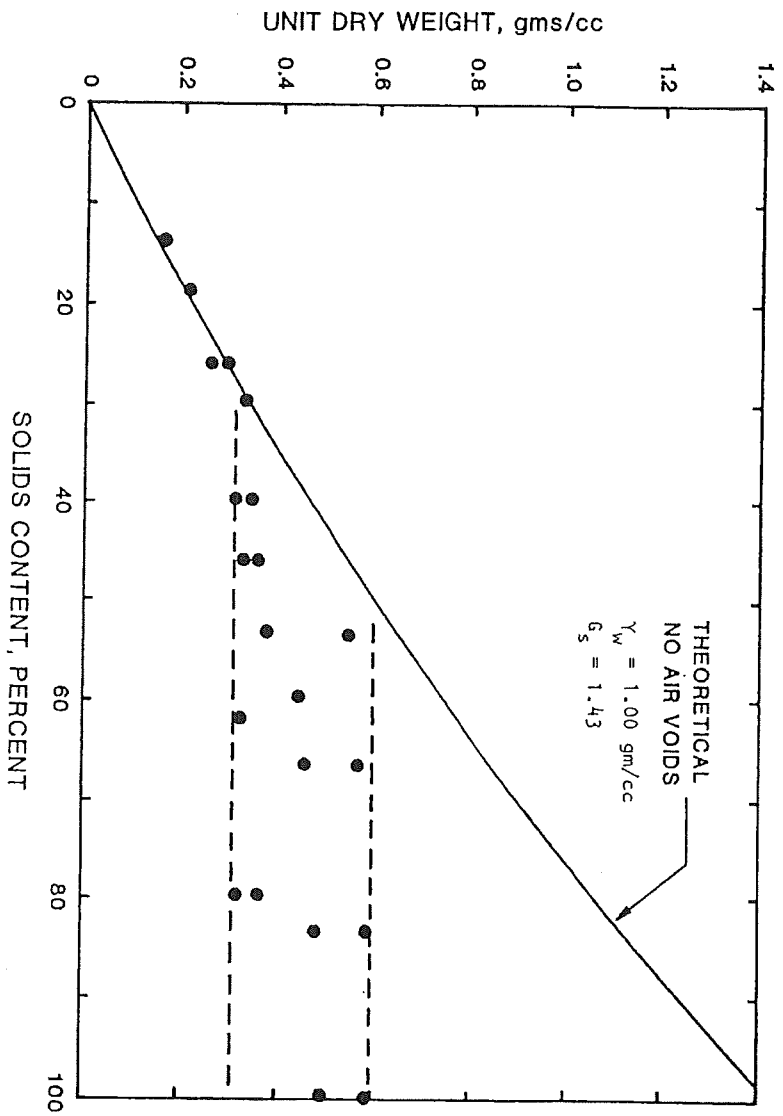


Figure 6.4. Unit dry weight of sludge and compost as a function of solids content. Data are for sludge-only systems and do not include effects of amendment or bulking agent additions. From Haug.⁴

It should be noted that relatively high unit weights are possible if FAS is removed by compaction. Volume reductions are often observed during composting caused in part by consolidation of material. One of the functions of compost agitation or turning is to decrease the unit bulk weight and minimize effects of compaction.

It is generally advisable to measure bulk weights for the actual substrates in question. Substrates such as sawdust, wood chips, and yard wastes can vary significantly in bulk weight. For example, some dry sawdusts can have bulk weights as low as 0.15 g/cm^3 (9.4 lb/ft^3). Also, the bulk weight of mixtures of substrates is not equal to the average of the individual bulk weights. Consider the case where a small amount of sawdust is added to a very wet sludge cake. The sawdust may be completely absorbed and the bulk weight of the mixture may only be slightly reduced from that of the sludge cake. Bulk weight is also affected by the method of handling. Dry leaves generally have a very low bulk weight, which increases if they are shredded.

Example 6.1

A wet substrate with a volatile solids fraction of 0.50 is dewatered to 30% solids. Estimate the unit bulk and dry weights of the substrate assuming no measurable gas volume in the cake. Assume the specific gravities of volatile and ash fractions to be 1.0 and 2.5, respectively.

Solution

1. The specific gravity of the substrate is given by Equation 6.1:

$$\frac{1}{G_s} = \frac{0.5}{1.0} + \frac{(1-0.5)}{2.5}$$

$$G_s = 1.43$$

2. Unit bulk weight is then determined from Equation 6.3, assuming the unit weight of water as 1.00 g/cm^3 :

$$\delta_s = \frac{1.00}{[(0.3/1.43) + 1 - 0.3]} = 1.099 \text{ g/cm}^3 \quad (68.6 \text{ lb/ft}^3)$$

3. Using Equation 6.4, the unit dry weight is

$$\delta_s(\text{dry}) = (0.30)(1.099) = 0.33 \text{ g dry solids (ds)/cm}^3 \text{ or } 20.6 \text{ lb ds/ft}^3$$

4. A number of factors can cause substrates to have bulk weights below the maximum values calculated above. For example, digested sludge often contains considerable gas volume from the biogas that continues to be produced. Sludge dewatered in belt or filter presses can contain air pockets between the "pancakes" of material. Experience has shown that the bulk weights of sludge cake can be as low as 0.80 g/cm^3 (50 lb/ft^3) because of these effects.

POROSITY AND FREE AIRSPACE

One might argue that the volume of voids shown in Figure 6.2 should not include the water volume, v_w . After all, if the substrate is saturated with water it seems somewhat incorrect to

say that it still has void volume. The problem is that the concept of void volume, and related ideas such as porosity, void ratio and degree of saturation, have their origin in the science of soil mechanics. Both the concepts and nomenclature have been borrowed and applied to composting systems. To change nomenclature at this point would be difficult and of dubious value to the student who must still contend with the terms as they are used in the composting literature. Instead, let us define terms as clearly as possible and overlook minor problems of nomenclature.

Volume ratios commonly used in composting are the porosity and free airspace (FAS). Porosity, n , of a composting mass is defined as the ratio of void volume to total volume:

$$n = v_v / v_t = \text{porosity} \quad (6.6)$$

$$n = (v_t - v_s) / v_t = 1 - v_s / v_t \quad (6.7)$$

Considering a unit total volume,

$$n = 1 - \frac{\delta_m S_m}{G_m \delta_w} \quad (6.8)$$

where

δ_m = unit bulk weight of the mixed material to be composted, wet weight per unit volume

S_m = fractional solids content of the mixture

G = specific gravity of the mixture solids

FAS, f , is defined as the ratio of gas volume to total volume:

$$f = v_g / v_t \quad (6.9)$$

$$f = (v_t - v_s - v_w) / v_t \quad (6.10)$$

Again consider a unit total volume:

$$f = 1 - \frac{\delta_m S_m}{G_m \delta_w} - \frac{\delta_m (1 - S_m)}{\delta_w} \quad (6.11)$$

Recall from the previous discussion that the term "optimum moisture" represents a tradeoff between the moisture requirements of the microbes and their simultaneous need for an adequate oxygen supply. The effect of moisture content on FAS is shown in Figure 6.5 for various composting substrates. Reported optimum moisture contents tend to fall in the range of FAS between 30 and 35%. Jeris and Regan⁵ further examined the effect of FAS on oxygen consumption rates of mixed refuse samples. Approximately 67% moisture and 30% FAS were found to be optimum conditions as shown in Figure 6.6. About 95% of the maximum oxygen consumption rate was maintained when FAS was between about 20 and 35%. Working with garbage and sludge mixtures, Schulze⁶ concluded that a minimum of ~30% FAS should be maintained.

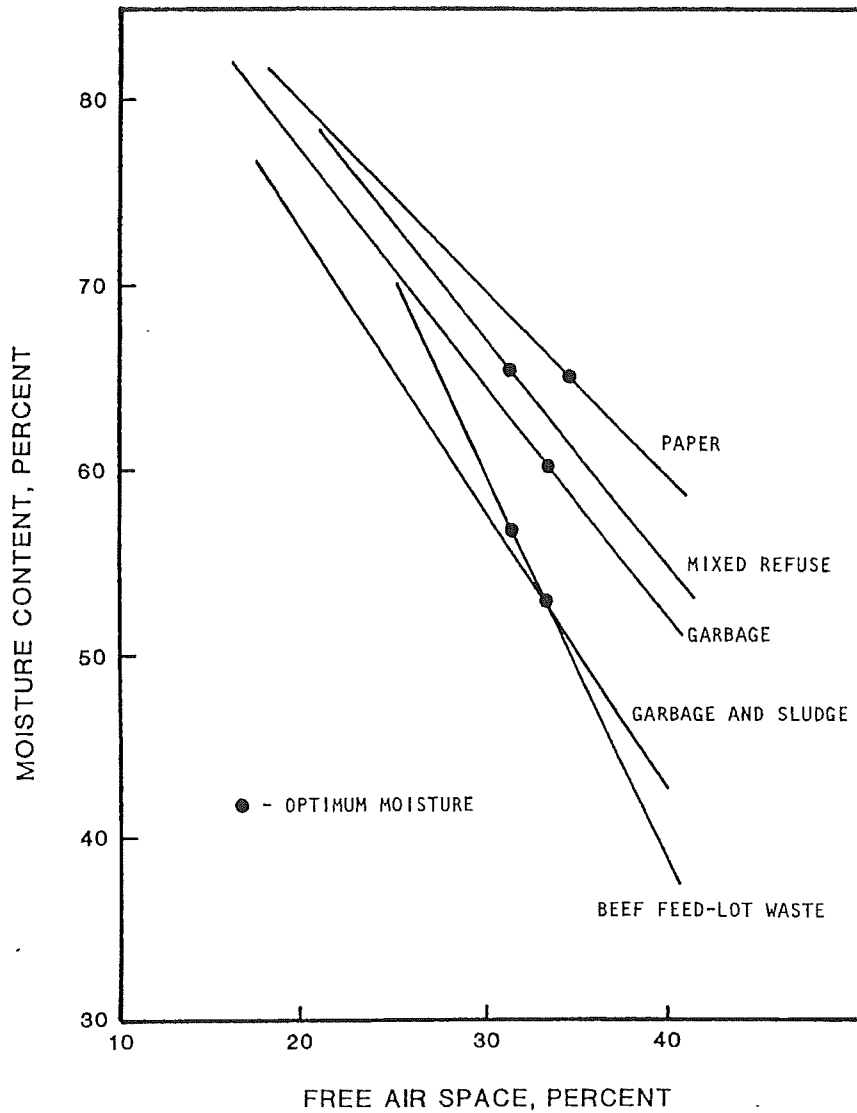


Figure 6.5. FAS as a function of moisture content for various feed materials. Reported optimum moisture contents tend to fall within a reasonably narrow range of FAS. From Jeris and Regan.⁵

The minimum FAS is probably influenced to some extent by method of aeration. With constant tumbling or turning, a lower FAS should be acceptable because of repeated exposure of new surfaces to the oxygen. However, constant agitation is not characteristic of most compost systems. Windrow, static pile, and most reactor systems will require FAS more in keeping with previously quoted results. Therefore, a FAS of ~30% is recommended for most substrates and composting systems.

Example 6.2

An organic slurry is dewatered to 30% TS and blended with recycled compost to give a mixture solids of 45%. Assuming a mixture volatility of 0.50 and a unit bulk weight of 0.85 g/cm^3 , calculate the porosity and FAS of the mixed material.

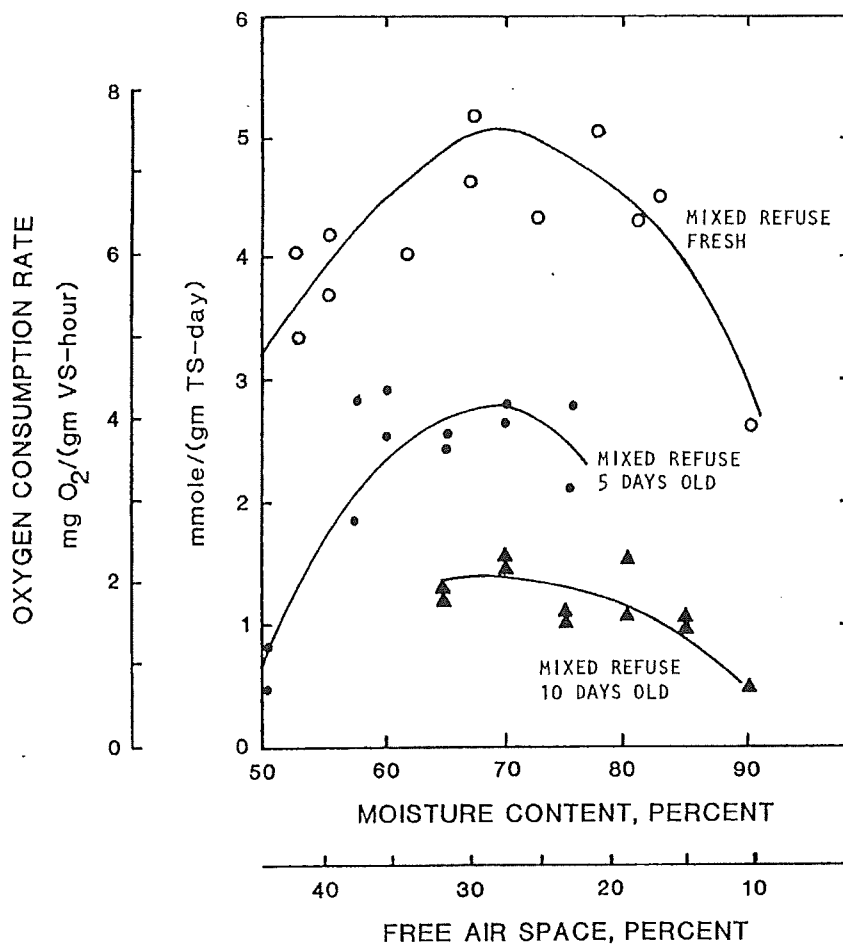


Figure 6.6. Effects of moisture and FAS on oxygen consumption rates of mixed refuse samples. Data were developed from Warburg respirometer runs. Incubation temperatures were not specified. From Jeris and Regan.⁵

Solution

1. From Example 6.1, specific gravity of the solids, G_s , is 1.43.
2. From Equation 6.8, the porosity is calculated as

$$n = 1 - [(0.85 \times 0.45) / (1.43 \times 1.00)]$$

$$n = 0.73$$

3. Using Equation 6.11, FAS is calculated as

$$f = 1 - \frac{0.85(0.45)}{1.43(1.00)} - \frac{0.85(1 - 0.45)}{1.00}$$

$$f = 0.27$$

4. Volume and weight fractions for the substrate mixture are determined as

$$\text{Gas } v_g = 0.27$$

$$\text{Water } W_w = 0.85(1 - 0.45) = 0.46 \text{ g/cm}^3$$

$$v_w = 0.46 / (1.00) = 0.46$$

$$\text{Solids } W_s = 0.85(0.45) = 0.38 \text{ g/cm}^3$$

$$v_s = 0.38 / [1.43(1.00)] = 0.27$$

$$\text{Total } v_g + v_w + v_s = v_t$$

$$0.27 + 0.46 + 0.27 = 1.00$$

Note that water occupies the greatest part of the mixture volume. This emphasizes the problem of maintaining proper free airspace with wet substrates.

GENERALIZED PROCESS SCHEMATIC

A process diagram for a generalized composting system is presented in Figure 6.7. The diagram is a generalized model for performing mass balances and is applicable to all composting systems. Pre- and postprocessing stages are not shown for convenience. Inputs of substrate, amendment, and bulking agent are included in Figure 6.7. This is not meant to imply that all additives would be used at the same time. Whether one or all are used depends on the composting system under study.

The following nomenclature, first proposed by the author in 1977,⁸ is used in Figure 6.7 and subsequent discussions:

X_s	= wet weight of the main substrate produced per day
X_p	= wet weight of compost product produced per day
X_r	= wet weight of material recycle per day
X_a	= wet weight of amendment added to the mixture per day
X_b	= wet weight of bulking agent added to mixture per day
X_w	= weight of water added to the mixture per day
X_m	= wet weight of mixed feed materials entering the compost process per day
S_s	= fractional solids content of the substrate
S_p	= fractional solids content of compost product
S_r	= fractional solids content of recycle material
S_a	= fractional solids content of amendment
S_b	= fractional solids content of bulking agent
S_m	= fractional solids content of the feed mixture
V_s	= volatile solids content of the substrate, fraction of dry solids
V_p	= volatile solids content of compost product, fraction of dry solids
V_r	= volatile solids content of recycle material, fraction of dry solids
V_a	= volatile solids content of amendment, fraction of dry solids
V_b	= volatile solids content of bulking agent, fraction of dry solids
V_m	= volatile solids content of mixture, fraction of dry solids
k_s	= fraction of substrate volatile solids degradable under composting

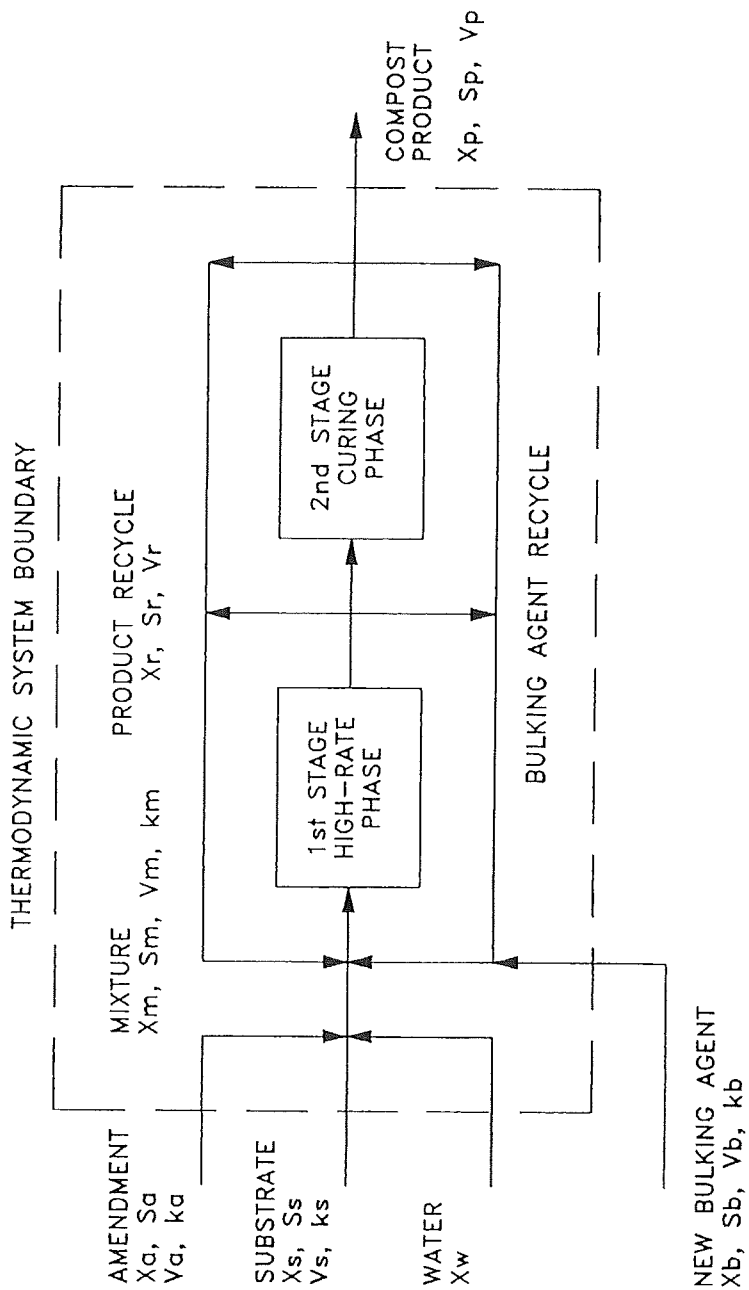


Figure 6.7. Generalized mass balance diagram for composting showing inputs of substrate, amendment, and bulking agent. Adapted from Haug.⁷

- conditions
- k_a = fraction of amendment volatile solids degradable under composting conditions
- k_b = fraction of bulking agent volatile solids degradable under composting conditions
- k_m = fraction of the mixture volatile solids degradable under composting conditions

A point should be made about the above nomenclature. All materials added to the composting process should be considered as substrates. Amendments and bulking agents are substrates because they add new materials to the process. Using separate terms for these substrates is convenient and consistent with the nomenclature used in the industry. For example, a sludge composting facility may use sawdust for feed conditioning. Sludge is considered the substrate and sawdust the amendment. There is no particular problem in this as long as one recognizes that the sawdust is also a substrate.

If multiple substrates are input to the process, the combined feed characteristics from these substrates can be determined as,

$$X_s = \sum_{j=1}^n X(j) \quad (6.12)$$

$$S_s = \left[\sum_{j=1}^n S(j)X(j) \right] / X_s \quad (6.13)$$

$$V_s = \left[\sum_{j=1}^n V(j)S(j)X(j) \right] / S_s X_s \quad (6.14)$$

$$k_s = \left[\sum_{j=1}^n k(j)V(j)S(j)X(j) \right] / V_s S_s X_s \quad (6.15)$$

where

- $X(j)$ = daily wet weight of substrate j
- $S(j)$ = fractional solids content of substrate j
- $V(j)$ = fractional VS content of substrate j
- $k(j)$ = fractional degradability of substrate j
- n = the number of substrates

The following discussion assumes that, where multiple substrates are involved, Equations 6.12 through 6.15 have been used to convert them into an equivalent single substrate with characteristics X_s , S_s , V_s , and k_s .

CONDITIONING OF WET SUBSTRATES

A number of approaches are available to overcome the problem of high moisture content in the feed substrate. First, dry compost product can be recycled to condition the starting

mixture. Second, dry amendments, such as sawdust or yard wastes, can be added to the wet substrate either with or without compost product recycle. Third, bulking agents, such as wood chips, can be added to maintain structural integrity. Fourth, the wet substrate can be air or heat dried to decrease the moisture content before composting. Fifth, constant agitation can be provided by mechanical means. Shell and Boyd⁹ successfully used the latter approach on a bench scale, but even then found that compost recycle was advantageous. The use of constant agitation has never been practical on a full scale. Therefore, the following discussion addresses the use of recycled compost, amendments, bulking agents, and drying for feed conditioning.

Conditioning with Compost Recycle

Compost product can be recycled and used to condition the feed substrate. The quantity of recycled material required to adjust the mixture moisture content can be determined from the process diagram of Figure 6.7. Total dry solids produced per day is $S_s X_s$. Similarly, dry solids in recycled compost product is $S_r X_r$. Assuming no amendment or bulking agent addition, a mass balance on total wet weight gives

$$X_s + X_r = X_m \quad (6.16)$$

Similarly, a mass balance on dry solids gives

$$S_s X_s + S_r X_r = S_m X_m \quad (6.17)$$

Substituting Equation 6.17 into 6.16:

$$\begin{aligned} S_s X_s + S_r X_r &= S_m (X_s + X_r) \\ X_r &= X_s \frac{(S_m - S_s)}{(S_r - S_m)} \end{aligned} \quad (6.18)$$

Let R_w be defined as the wet weight recycle ratio defined as

$$R_w = X_r / X_s \quad (6.19)$$

Substituting into Equation 6.18 gives

$$R_w = \frac{(S_m - S_s)}{(S_r - S_m)} \quad (6.20)$$

Let R_d be defined as the dry weight recycle ratio defined as

$$R_d = S_r X_r / S_s X_s \quad (6.21)$$

Substituting the expression for R_d into Equation 6.17 and rearranging gives

$$R_d = \frac{[(S_m / S_s) - 1]}{[1 - (S_m / S_r)]} \quad (6.22)$$

Equations 6.20 and 6.22 can be used to calculate the required recycle ratios given the substrate solids, S_s , compost recycle solids, S_r , and desired solids content in the mixture, S_m .

Example 6.3

10 dry metric tpd (dmtpd) of substrate at 20% TS is to be reactor composted using recycled compost for feed conditioning. The desired mixture solids is 40% and recycled compost is 60% TS. Calculate the required recycle ratios and the total weight of mixture processed daily.

Solution

1. From Equation 6.20, the wet weight recycle ratio, R_w is

$$R_w = (0.40 - 0.20) / (0.60 - 0.40) = 1.00$$

2. The dry weight recycle ratio, R_d is determined from Equation 6.22:

$$R_d = \frac{[(0.40 / 0.20) - 1]}{[1 - (0.40 / 0.60)]} = 3.0$$

3. The daily weight to be processed can be determined from either R_d or R_w as follows:

total weight = substrate weight + recycle weight

$$\text{Based on } R_d: \quad \text{total wt} = 10 / 0.20 + 10(3.00) / 0.60 = 100 \text{ wmtpd}$$

$$\text{Based on } R_w: \quad \text{total wt} = 10 / 0.20 + 10(1.0) / 0.20 = 100 \text{ wmtpd}$$

4. Using procedures from Example 6.2, the mixture FAS should be ~20%, sufficient to avoid significant rate limitations.

A bar diagram of the substrate, recycle, and mixed materials from Example 6.3 is shown in Figure 6.8 based on a unit dry weight of substrate. Some new terms are introduced in this diagram. WAT is the water component, BVS the biodegradable volatile solids component, NBVS the nonbiodegradable volatile solids component, and ASH the ash or inert component. Equations used to calculate these component fractions of the substrate are as follows:

$$\text{BVS} = K_s V_s S_s X_s \quad (6.23)$$

$$\text{NBVS} = (1 - K_s) V_s S_s X_s \quad (6.24)$$

$$\text{ASH} = (1 - V_s) S_s X_s \quad (6.25)$$

$$\text{WAT} = X_s - S_s X_s \quad (6.26)$$

Similar equations can be developed for amendment, bulking agent, and recycle components. Further development and use of these Equations is presented in Chapter 11.

Example 6.4

Based on the results of Example 6.3, develop the bar diagram shown in Figure 6.8. Assume 1 kg of substrate solids. The substrate has an organic content of 75% ($V_s = 0.75$) and degradability of 50% ($k_s = 0.50$).

Solution

1. The wet weight of substrate is determined as

$$X_s = 1 / 0.20 = 5 \text{ kg}$$

2. The 5 kg of substrate contains the following components based on Equations 6.23 to 6.26:

$$\text{BVS} = 0.5(0.75)(0.20)(5) = 0.375 \text{ kg}$$

$$\text{NBVS} = (1 - 0.50)(0.75)(0.20)(5) = 0.375 \text{ kg}$$

$$\text{ASH} = (1 - 0.75)(0.20)(5) = 0.250 \text{ kg}$$

$$\text{WAT} = 5 - (0.20)(5) = 4.000 \text{ kg}$$

The left bar in Figure 6.8 represents the substrate with the above component fractions.

3. From Example 6.3, $R_w = 1.0$; therefore, $X_r = X_s R_w = 5(1) = 5 \text{ kg}$. All BVS are assumed to be degraded during composting so that none appear in the compost recycle, i.e., $k_r = 0$. The NBVS and ASH components are assumed to act conservatively in the process; therefore, their distribution in the recycle reflects their distribution in the feed substrate.

$$\text{BVS} = 0.00$$

$$\text{NBVS} = [0.375 / (0.375 + 0.250)](0.60)(5) = 1.80$$

$$\text{ASH} = [0.250 / (0.375 + 0.250)](0.60)(5) = 1.20$$

$$\text{WAT} = 5 - (0.60)(5) = 2.00$$

The middle bar in Figure 6.8 represents the compost recycle with the above component fractions.

4. The right bar in Figure 6.8 represents the combined mixture of substrate and recycle. Each fraction in the mixture bar is the sum of substrate and recycle contributions. Note that the mixture solids content is 40%, which is the desired condition from Example 6.3.

Based on Examples 6.3 and 6.4, it would appear that the mixture is properly conditioned. Indeed, from the structural standpoint of moisture and free airspace the mixture is acceptable. However, mixture conditions must also be checked from the standpoint of the energy balance. The latter is considered in Chapter 8.

Equations 6.20 and 6.22 were solved for various substrate and compost product solids contents, assuming a desired mixture solids of 40% ($S_m = 0.40$). Resultant total and dry weight recycle ratios are presented in Figures 6.9 and 6.10, respectively. Referring to Figure 6.9, R_w

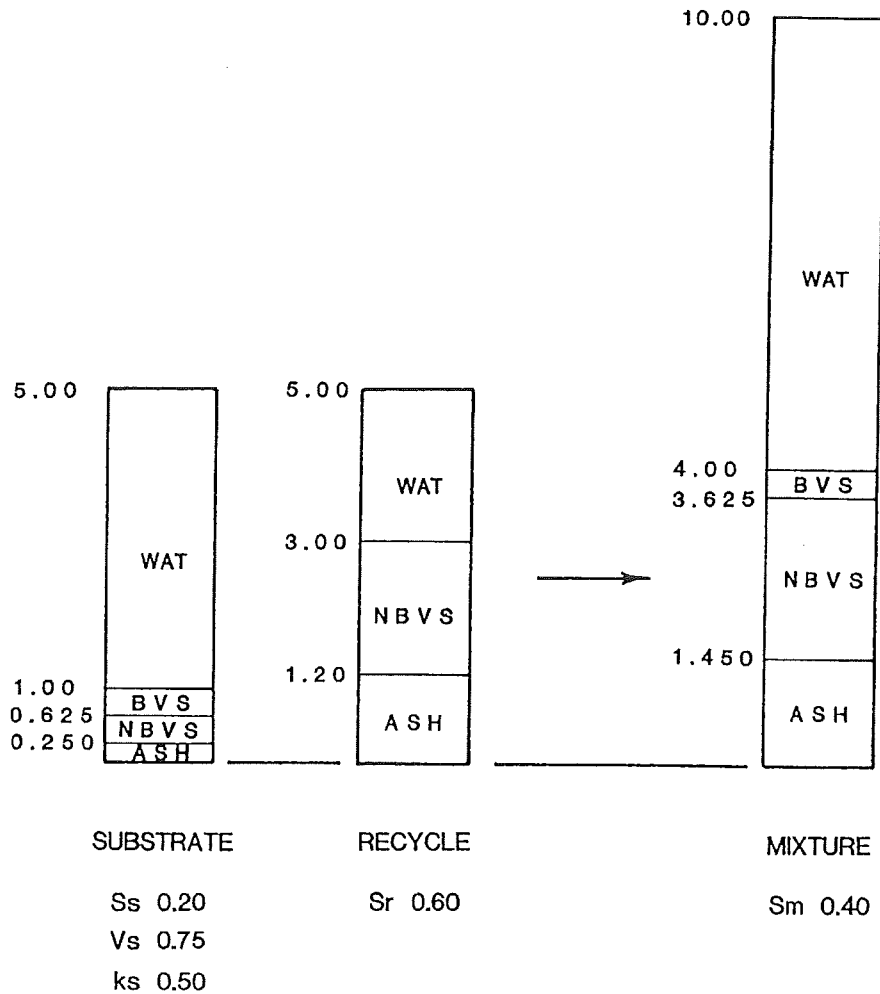


Figure 6.8. Feed conditioning of substrate using recycled compost for the conditions of Example 6.4.

is zero at a substrate solids of 40%. This reflects the fact that a 40% TS mixture was assumed necessary to begin the process. R_w increases as substrate solids decrease below 40%, with the slope depending on the solids content of the recycled product. Obviously, the drier the recycled product, the lower the required recycle ratio. Equation 6.20 can be solved for the case where $S_s = 0$, in other words, no solids in the substrate (i.e., pure water). This is a mathematical anomaly that results from the assumption of a fixed solids content for the recycle product. Valid application of Equations 6.20 and 6.22 depends on the ability to achieve the assumed compost product solids, a subject of discussion in later chapters.

The total quantity of mixed material that must be handled daily is a function of the initial substrate solids. For example, assume a substrate solids of 30% and a compost product of 70% solids. From Figure 6.9, R_w for this case is 0.33. Assuming 100 ton ds/day of substrate, X_s is 333 tpd and X_r 110 tpd, giving a mixture of 443 tpd. If substrate solids are reduced to 20%, R_w increases to 0.67, X_s to 500 tpd, X_r to 335 tpd, and the total quantity of mixed material, X_m , to 835 tpd. Thus, reducing substrate solids from 30 to 20% results in a near doubling of the total weight of mixed materials to be handled each day.

The recycle ratio based on dry weight, R_d , is presented in Figure 6.10. As S_s approaches zero, Equation 6.22 tends toward infinity and the boundary problems associated with Equation 6.20 are not encountered. Based on Figure 6.10 the dry weight of recycled compost can, in

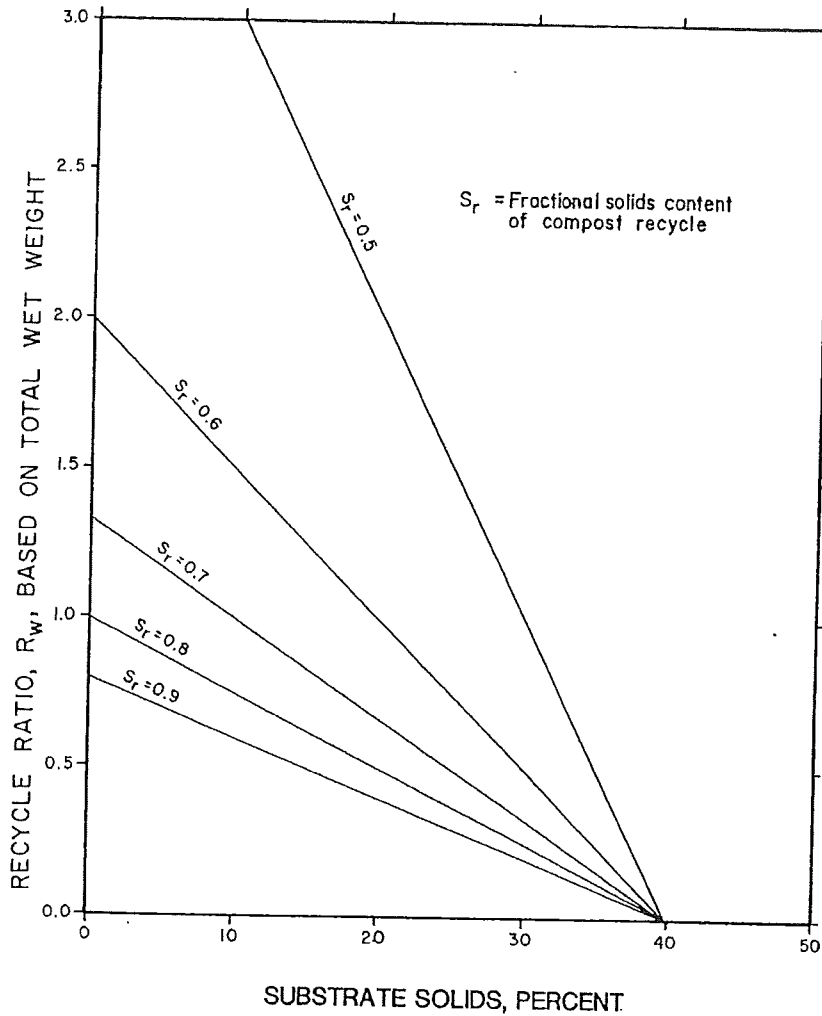


Figure 6.9. Effect of substrate solids content on the wet weight recycle ratio needed to achieve a 40% mixture solids content. From Haug.^{8,10}

certain cases, exceed the quantity of substrate solids. Again, assuming a substrate of 30% solids and a compost product of 70% solids, R_d from Figure 6.10 is 0.78. In other words, 0.78 g ds of compost product must be recycled for each 1.0 g ds of substrate to achieve 40% solids in the mixture. If substrate solids are reduced to 20%, R_d increases to 2.34. Thus, decreasing the substrate solids from 30 to 20% increases the mixture dry weight from 1.78 to 3.34 g and increases the dry weight percentage of recycled compost in the mixture from 44 to 70%. Also, as previously mentioned, the daily mixture wet weight nearly doubles. This is not meant to imply that a substrate with 20% solids cannot be composted. It merely points out the importance of substrate solids in determining both the quantity of material to be handled each day and the relative percentage of compost product in the mixture.

Equation 6.20 was again solved, in this case to determine the effect of mixture solids content on the recycle ratio. Substrate solids were assumed to be constant at 25%, with recycle solids ranging from 50 to 90%. Results are presented in Figure 6.11. Mixture solids content has a significant effect on the required recycle ratio, particularly at lower recycle solids contents. As recycle becomes drier, the effect of mixture solids becomes less pronounced. Assuming recycle at 70% solids, R_w increases from 0.29 to 1.25 as S_m increases from 35 to 50% solids. In practice it is desirable to minimize the mixture solids, S_m to reduce the weight

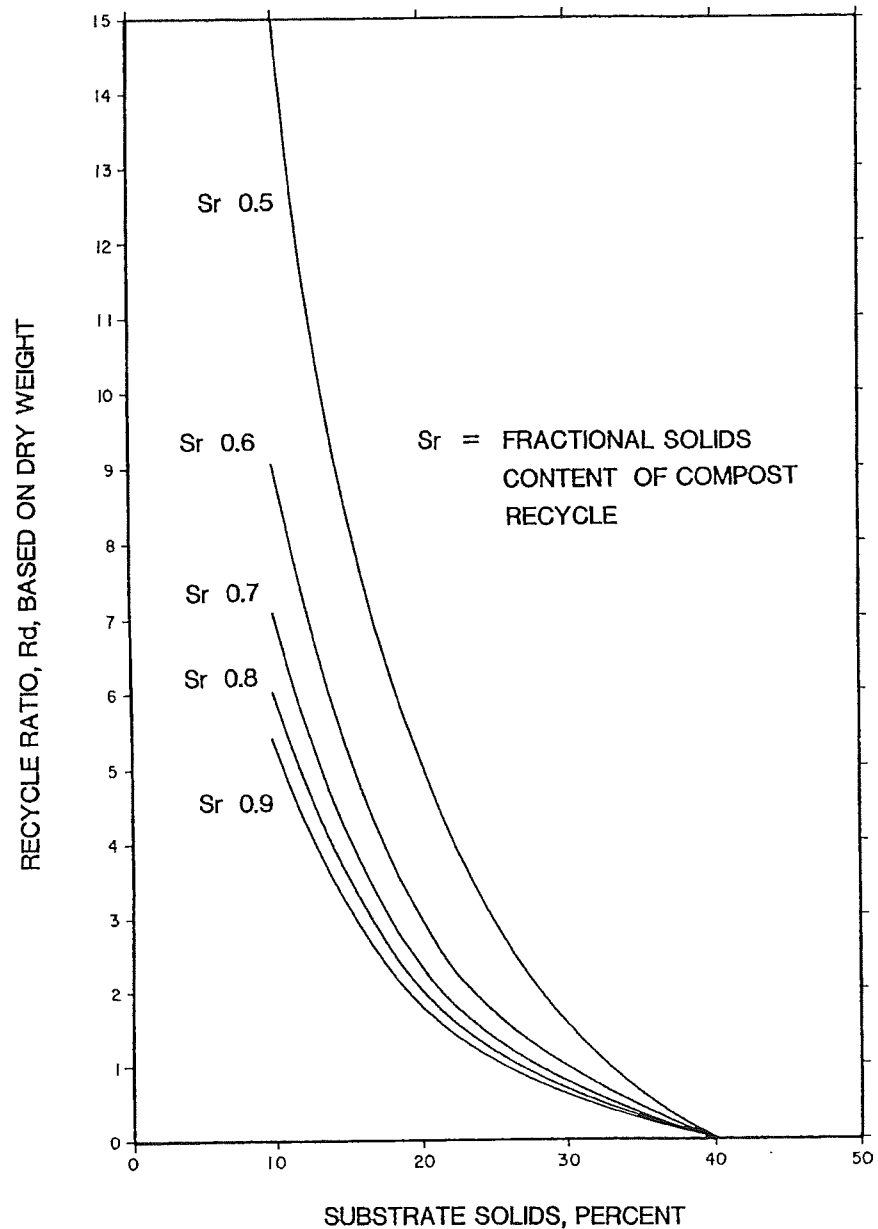


Figure 6.10. Effect of substrate solids content on the dry weight recycle ratio needed to achieve a 40% mixture solids content. From Haug.^{8,10}

and volume of material processed daily. However, care must be taken to avoid decreasing mixture solids to the point that free airspace is reduced below the optimum range. For purposes of planning and design, it is better to err on the side of higher mixture solids and let operations "discover" if lower mixture solids can actually be used in practice.

Conditioning with Amendments

Organic or inorganic amendments can be added to condition the composting mixture either with or without use of product recycle. Using the process diagram of Figure 6.7 and assuming no bulking agent or recycle addition, the following equation can be derived for the required daily weight of amendment X_a :

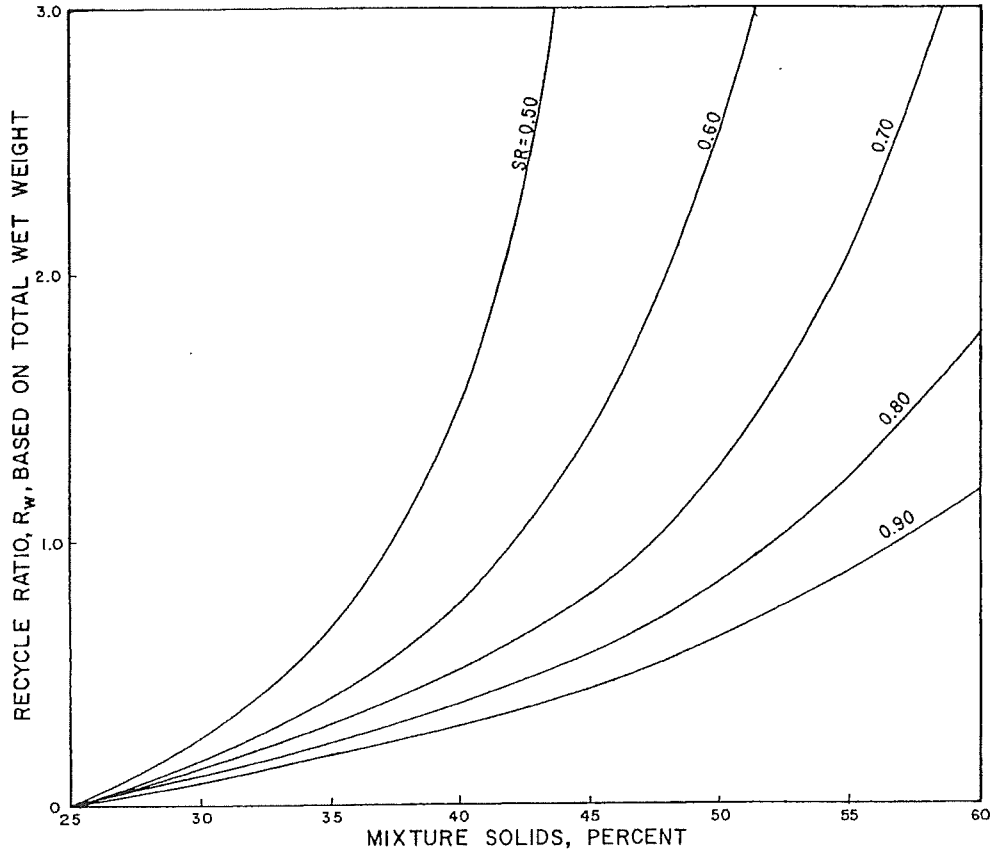


Figure 6.11. Effect of mixture solids content on the wet weight recycle ratio for various recycle solids contents. Substrate solids, S_s , assumed to be 25%.

$$X_a = X_s \frac{(S_m - S_s)}{(S_a - S_m)} \quad (X_r = 0) \quad (6.27)$$

Again, let R_w be defined as the wet weight ratio and R_d as the dry weight ratio. Then,

$$R_w = \frac{X_a}{X_s} = \frac{(S_m - S_s)}{(S_a - S_m)} \quad (6.28)$$

and

$$R_d = \frac{S_a X_a}{S_s X_s} = \frac{[(S_m / S_s) - 1]}{[1 - (S_m / S_a)]} \quad (6.29)$$

Example 6.5

The 10 dmtpd of substrate from Examples 6.3 and 6.4 is to be conditioned using sawdust as a structural amendment. The sawdust is 65% TS, 95% VS, with an estimated 20% degradability of the VS. Desired mixture solids is 40%. Determine the quantity of required amendment and develop a bar diagram showing the substrate, amendment, and mixture conditions.

Solution

1. The quantity of required amendment is determine from Equation 6.27 as

$$X_s = 10 / 0.20 = 50 \text{ tpd}$$

$$X_a = 50(0.40 - 0.20) / (0.65 - 0.40)$$

$$X_a = 40 \text{ tpd}$$

2. From Equations 6.28 and 6.29, the wet and dry mixture ratios are

$$R_w = 40 / 50 = 0.80$$

$$R_d = 40(0.65) / 50(0.20) = 2.60$$

3. Four kg of sawdust are required for each 5 kg of substrate. The WAT, BVS, NBVS, and ASH components of the 4 kg of amendment are determined from Equations 6.23 to 6.26 as

$$\text{BVS} = 0.20(0.95)(0.65)(4) = 0.494 \text{ kg}$$

$$\text{NBVS} = (1 - 0.20)(0.95)(0.65)(4) = 1.976 \text{ kg}$$

$$\text{ASH} = (1 - 0.95)(0.65)(4) = 0.130 \text{ kg}$$

$$\text{WAT} = (1 - 0.65)(4) = 1.400 \text{ kg}$$

4. A bar diagram of the sludge, sawdust and mixture components is presented in Figure 6.12. Again, the mixture is properly conditioned from a structural standpoint, but the energy balance must be checked using procedures in Chapter 8.

The majority of sludge composting facilities condition the wet cake with sawdust or other amendments added to the cake after dewatering. At least one facility, a silo reactor system at Bristol, Tennessee, blends sawdust with the liquid sludge prior to dewatering. Sludge and sawdust at a 1:1 to 1.2:1 ratio by dry weight are metered and blended in a liquid mix tank before belt press dewatering. Dohoney¹¹ reported better water drainage, reduced variability in feed characteristics, reduced polymer consumption, better cake release, and no decrease in liquid loading to the press. A 35 to 37% TS cake is produced compared to 20 to 22% without sawdust addition. The dewatered mixture is then directly fed to the silo reactor.

Conditioning with Recycle and Amendments

Using amendments for structural conditioning without product recycle can result in consumption of considerable quantities of amendment. This can be expensive, depending on local availability of suitable materials. Also, the quantity of final product is increased compared to systems that rely all or in part on compost recycle for conditioning. Whether this is an advantage or not depends on the expected market for the final product. A compromise between use of product recycle alone and use of amendment alone is possible. If recycle is used for part of the structural conditioning, smaller quantities of amendment can be used for the balance.

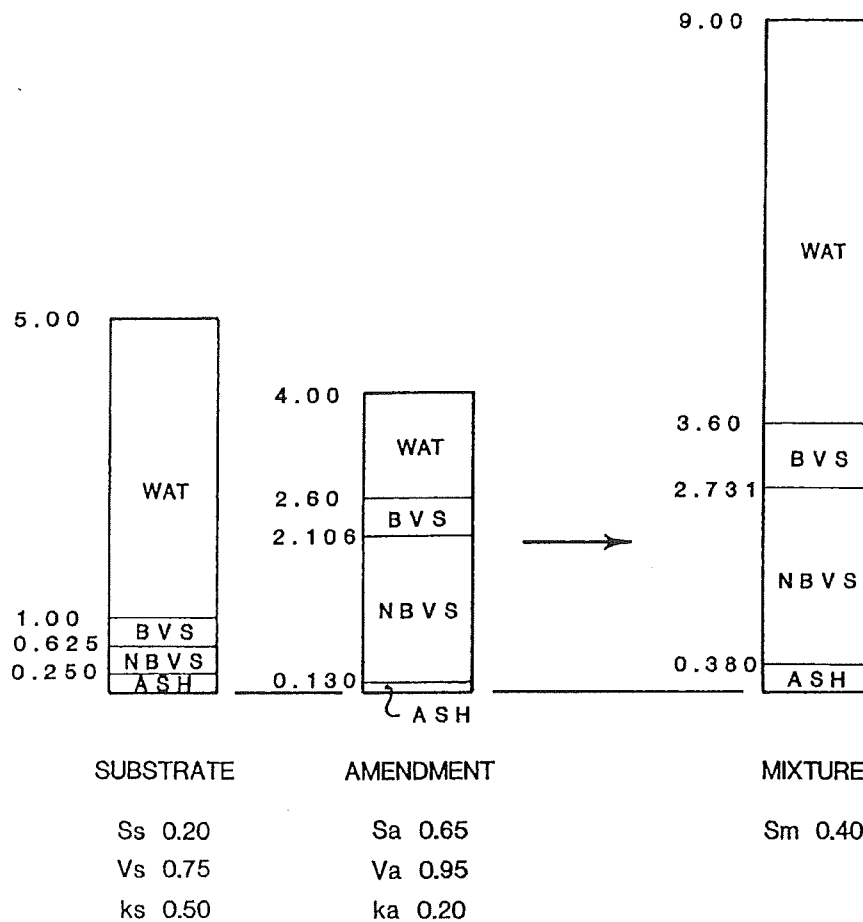


Figure 6.12. Feed conditioning of substrate using amendment for the conditions of Example 6.5.

Approaches to Solution

If both recycle and amendment are added to the infeed mixture, the mass balances for total and dry weight are

$$X_s + X_a + X_r = X_m \tag{6.30}$$

$$S_s X_s + S_a X_a + S_r X_r = S_m X_m \tag{6.31}$$

The mass balance cannot be uniquely solved because there are three unknowns (X_r , X_a , and X_m) and only two mass equations (wet weight or water and dry weight balances). A unique solution is possible if a third equation can be developed. Three approaches to a third equation are possible: (1) a mass balance on volatile solids, (2) assuming a value for X_a or X_r , and (3) an energy balance on the system. The first two approaches are considered here. The third approach of using the system energy balance to develop a third equation is considered in Chapter 8.

Referring to the system diagram in Figure 6.7, a volatile solids balance gives a third equation as

$$V_s S_s X_s + V_a S_a X_a + V_r S_r X_r = V_m S_m X_m \tag{6.32}$$

Combining Equations 6.30, 6.31, and 6.32 and rearranging gives the following solutions:

$$X_a = \frac{X_s [S_r (S_s / S_m - 1)(V_r - V_m) + S_s (S_r / S_m - 1)(V_m - V_s)]}{S_r (1 - S_a / S_m)(V_r - V_m) - S_a (S_r / S_m - 1)(V_m - V_a)} \quad (6.33)$$

$$X_r = \frac{S_s X_s (V_m - V_s) + S_a X_a (V_m - V_a)}{S_r (V_r - V_m)} \quad (6.34)$$

The procedure for a problem of this type is to assume all input variables and consecutively solve Equations 6.33, 6.34, and 6.30 for X_a , X_r , and X_m , respectively.

Alternative to the above approach, a third equation can be developed by assuming a value for either the amendment, X_a or recycle, X_r , i.e., $X_a = \text{constant}$ or $X_r = \text{constant}$. If X_r is assumed, Equations 6.30 and 6.31 can be solved for X_a as follows:

$$X_a = \frac{X_r (S_m - S_a) + X_s (S_m - S_r)}{(S_a - S_m)} \quad (6.35)$$

If X_a is assumed, the solution for X_r is

$$X_r = \frac{X_s (S_m - S_a) + X_a (S_m - S_r)}{(S_r - S_m)} \quad (6.36)$$

Example 6.6

Ten dtpd of substrate at 20% solids is combined with 20 wtpd of sawdust at 65% solids. These substrates are further conditioned with recycle compost at 60% TS. Other characteristics are the same as in previous examples. Determine the quantity of recycle required to achieve a 40% TS mixture.

Solution

1. The total weight of substrate = $10/0.20 = 50$ tpd.
2. The quantity of required recycle is determined from Equation 6.36 as

$$X_r = \frac{50(0.40 - 0.20) + 20(0.40 - 0.65)}{(0.60 - 0.40)}$$

$$X_r = 25 \text{ tpd}$$

3. The quantity of mixed materials is determined from Equation 6.30.

$$X_m = 50 + 20 + 25 = 95 \text{ tpd}$$

4. Referring to Example 6.3, the recycle is reduced from 50 to 25 tpd and the mixture weight reduced from 100 to 95 tpd by use of the combination of sawdust and recycle. Referring to Example 6.5, amendment use is reduced from 40 to 25 tpd.

5. A bar diagram showing the mixture and individual components is presented in Figure 6.13.

Particle Size Distribution

The particle size distribution of the amendment can be important to the structural conditioning of wet substrates. If the amendment is too fine, it may not provide the expected increase in free air space even though the mixture solids content is acceptable. As an example, some sludge composting facilities have noted that very fine sawdust, termed wood "flour", tends to produce a muddy consistency in the mix. The saturated condition can produce anaerobic conditions due to lack of free air space. As a result, several agencies have revised their amendment specifications to define the desired particle size distribution. Lancaster, Pennsylvania, specifies sawdust with a minimum 65% TS, with 95% passing a 12.5 mm screen opening but <50% passing a 2.23 mm opening. Cape May, New Jersey, specifies a coarser sawdust between 50 and 70% TS, with 95% passing a 12.5 mm screen opening but <20% passing a 4.75 mm opening.¹² The limit on fines is designed to avoid problems with wood flour. The limit on larger sized particles is applied to avoid the need to screen the final compost. The maximum particle size should be ≤ 10 mm if the compost product is intended for general horticultural use or as a top dressing on lawns and gardens.

The particle size distribution is also important to energy conditioning, which is discussed in Chapter 8. Generally, the biodegradability of amendments such as sawdust is favored by small particle size. Too many fines may be undesirable from a structural standpoint, but very attractive for energy conditioning. The demands for structural and energy conditioning should both be considered when developing amendment specifications.

Moisture Control by Drying

Air Drying

In lieu of using compost recycle or amendments to provide all of the structural conditioning, some wet substrates can be dried to further reduce the moisture content before composting. Air drying is used at both Phoenix, Arizona, and Austin, Texas, to reduce the moisture content of digested sludges before windrow composting. Liquid digested sludge is sent to decanting/evaporation lagoons. Free water is decanted as supernatant from the liquid surface. Evaporation then continues to remove water until a cake is formed. Mobile turning equipment is used during the evaporation period to prevent a crust from forming, which would reduce the surface evaporation rate. Cake is generally removed from the drying beds when it reaches ~30% solids and is conditioned with recycle or other amendments before windrow composting. Little if any composting occurs during the drying process because of the limited aeration. Therefore, biodegradable solids are largely conserved for use in the composting process.

Air drying of wet substrates prior to composting is a form of conditioning, just as adding recycle or other amendments. Removal of water by air drying effectively increases the solids content of the feed substrate. From the previous discussions, this will in turn reduce the amount of recycle or amendment needed for supplemental conditioning. Obviously, air drying is only effective in arid regions where evaporation exceeds precipitation and where relatively large land areas are available. If the climate is characterized by wet and dry seasons, the composting process will experience peak loads, because sludge will essentially be stored in the wet season and subsequently dried during the dry season. Finally, air drying is usually restricted to relatively stable substrates, such as digested sludge and some manures, because of the odor potential associated with putrescible substrates, such as raw sludge. Given these constraints, air drying is an extremely effective and often low cost method of structural

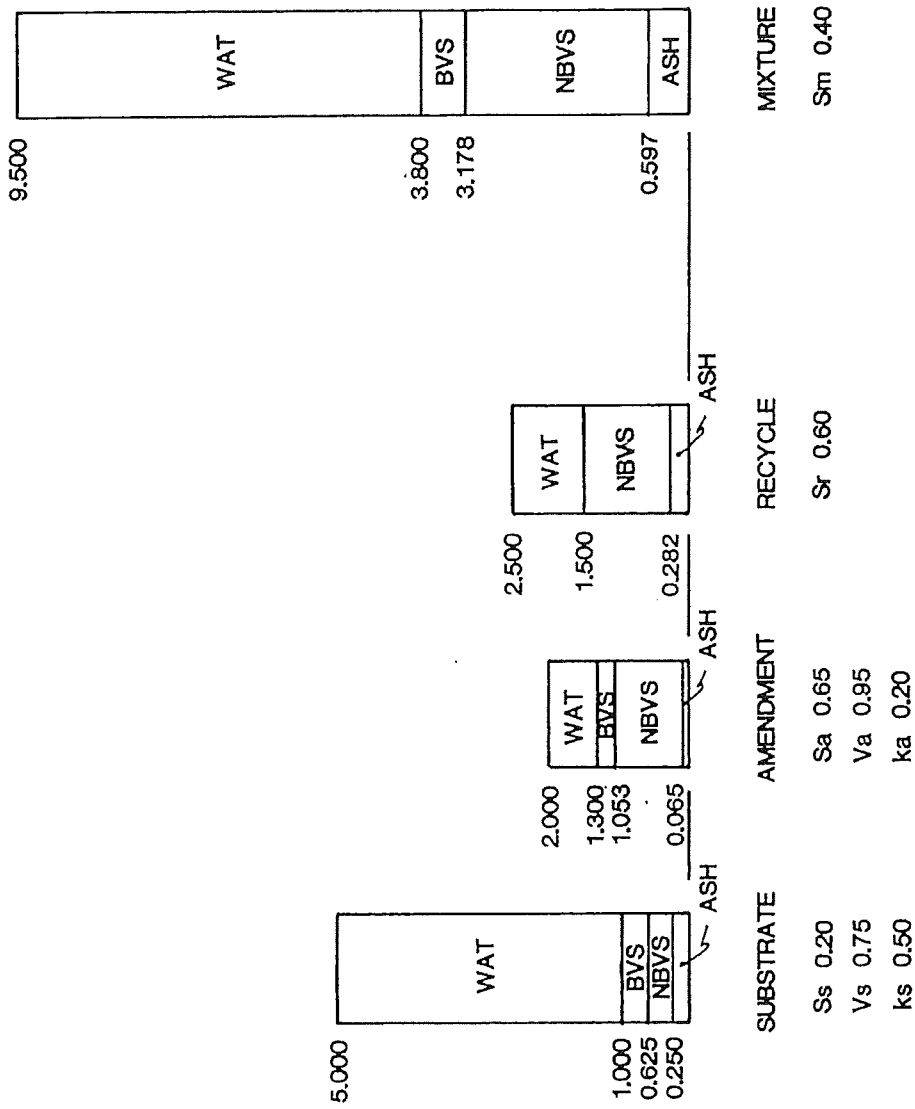


Figure 6.13. Feed conditioning of substrate using amendment and recycle for the conditions of Example 6.6.

conditioning. Because air drying removes water from the process, it is also a form of energy conditioning.

The time required for evaporative drying can be estimated by considering a layer of wet substrate of initial depth, d_{si} , and unit surface area. The substrate is to be dried from an initial solids content, S_{si} , to a final solids content, S_{sf} . Assuming that the substrate remains homogeneous throughout its depth as water evaporates from the surface, the following equation can be developed:

$$t_a = \frac{d_{si} \delta_{si}}{(E - P) \delta_w} (1 - S_{si} / S_{sf}) \quad (E > P) \quad (6.37)$$

where

- t_a = time required for air drying, days
- d_{si} = initial depth of the wet substrate, cm
- δ_{si} = initial bulk weight of the substrate, g/cm³
- δ_w = bulk weight of water, g/cm³
- E = average evaporation rate over the drying period, cm/day
- P = average precipitation rate over the drying period, cm/day
- S_{si} = initial solids content of the wet substrate, fraction
- S_{sf} = final solids content of the dried substrate, fraction

The area required for drying can then be determined knowing the daily weight of sludge cake.

$$\text{area} = \frac{\text{volume / day}}{\text{depth}} (t_a)$$

$$\text{area} = \frac{X_s / \delta_{si}}{d_{si}} (t_a) \quad (E > P)$$

Substituting Equation 6.37 for t_a and applying unit conversions:

$$A = \frac{X_s (1 - S_{si} / S_{sf})}{(E - P) \delta_w (10^5)} \quad (E > P) \quad (6.38)$$

where

- A = required drying area, hectares
- X_s = substrate wet weight, kg/day

Should precipitation exceed evaporation during any period, no drying will result. Thus, Equations 6.37 and 6.38 apply to periods of the year when evaporation exceeds precipitation or to situations where the drying area is covered to prevent rainfall from reaching the substrate.

The most readily available information on evaporation rates is usually pan evaporation data recorded at a weather station near the proposed facility. However, evaporation rates from a wet organic substrate may not necessarily equal the pan evaporation rate. This would obviously

be true if a dry crust were allowed to form, restricting passage of water to the surface. It is important that the substrate be turned frequently to reduce the likelihood of such a rate limitation. Even so, evaporation rates per unit surface area are likely to be less than pan evaporation rates, particularly as the cake moisture content decreases. On the other hand, surface area of cake per unit of ground surface is probably greater than unity because of the irregular surface of the dry cake. In the absence of actual field data and for purposes of estimation, pan evaporation rates can be assumed over the ground surface area occupied by the wet substrate.

Equations 6.37 and 6.38 represent a rather simplified approach to analysis because both evaporation and precipitation are assumed constant over time. Obviously, this is a simplified model of the actual case. In real situations, both the time required for drying and the land area will vary dynamically throughout the year. Simulation models have been developed to predict the drying time and area requirements in response to changing weather conditions.¹⁴

Heat Drying

Another approach to increasing the solids content of wet substrates is to heat dry either all or a portion of the substrate before composting. This is sometimes referred to as "thermal dewatering". Consider a substrate at 25% TS. If the substrate is thermally dewatered to 40% solids, about 2.5 g of water are removed per gram of solids. Thermal dewatering can accomplish the same feed conditioning benefits as air drying, namely biodegradable solids are conserved and excess water is removed. In addition, the heat drying process is not subject to outside climatic conditions. The downside is the fuel demand of the dryer and its capital cost.

A factor that may limit the application of heat drying prior to composting is that a dry product can be produced directly from the dryer with only modest additional energy input. For example, further drying of the above substrate to 90% solids requires removal of only 1.4 g additional water. Essentially complete drying can be obtained with only modest increases in the energy investment over that required for thermal drying. The number of required dryers is increased significantly, however. Today, there are no known applications of thermal dewatering prior to composting, but its possible use in selected situations should not be discounted.

Another potential application of heat drying is to dry the compost product and/or recycled compost to better assure a proper moisture content. If compost product is dried from 50 to 70% solids, about 0.57 g additional water must be removed per gram of compost solids, significantly less than that calculated for complete drying of the above substrate. The moisture removal that can be achieved during composting is determined by the thermodynamic balance of the system, which is discussed in Chapter 8. The compost process can remove significant quantities of water using the heat of biological decomposition. Heat drying can then be used to "polish" the composted product to the desired moisture content. This can be an attractive concept because energy requirements for heat drying can be significantly reduced without placing the total drying burden on the compost process or on the uncertainties of open-air drying. Postdrying was used at the Fairfield Hardy composter at Altoona, Pennsylvania, during composting of sludge cake and paper.¹³ A materials balance for that facility is shown in Figure 6.14. Postdrying facilities were also designed into the Delaware Reclamation Project which composts MSW heavy fraction (see Chapter 2). However, the heat dryers have seen only limited service.

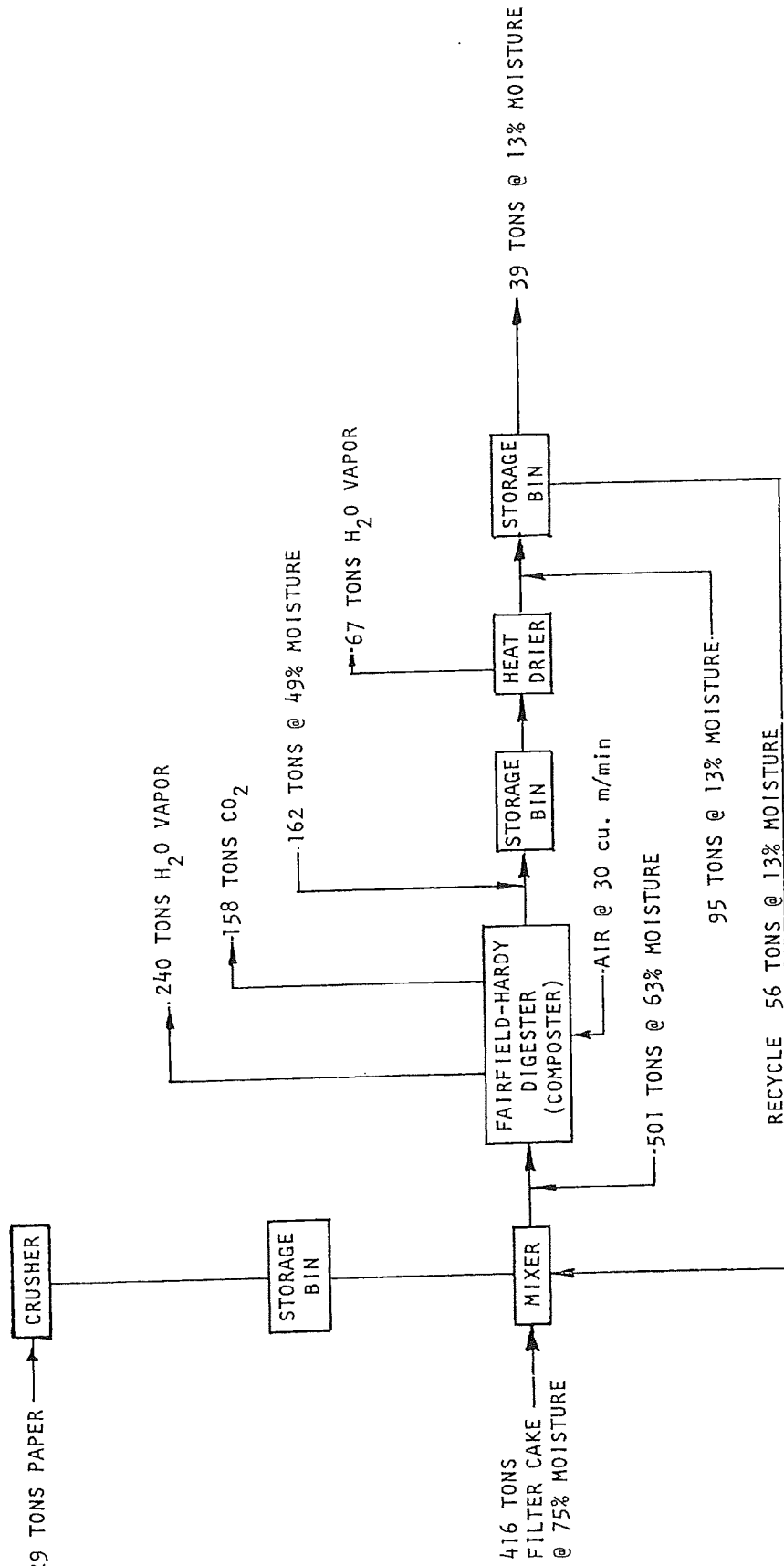


Figure 6.14. Process flow diagram and materials balance during composting of raw sludge cake at the Fairfield Hardy digester in Altoona, Pennsylvania. The system included a pelletizer ahead of the heat drier which was not used in the study. At the start of the study, shredded paper was the only amendment used at a ratio of 4.0 tons ds cake to 1.6 tons ds paper. Later in the study, compost product that had been heat dried to 13% moisture was used as the sole amendment.

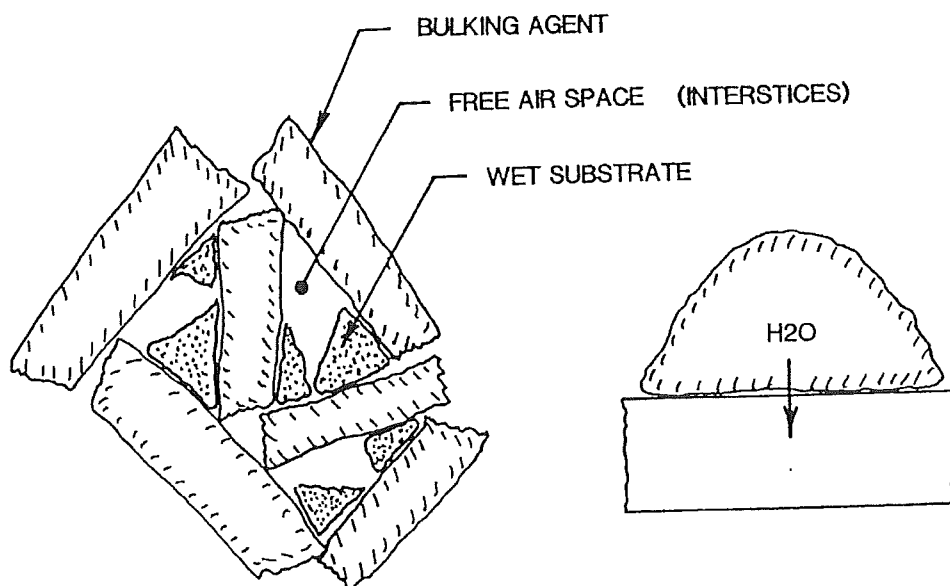


Figure 6.15. Schematic illustration of substrate/bulking agent mixture showing water absorption from wet substrate into bulking particles.

Conditioning with Bulking Agents

Functions of a Bulking Agent

As discussed previously, the free airspace of wet substrates, such as sludge cake and wet manures, can reasonably be assumed to be zero. The function of a bulking agent is to provide structural support for the wet substrate, to provide free airspace within the voids between particles, to increase the size of pore spaces, and to allow easier air movement through the mixture. A bulking agent can be viewed as a three-dimensional matrix of solid particles capable of self-support. The void volume and size of the pore spaces is determined by the shape and size of the bulking particles. Conceptually, the wet substrate can be viewed as occupying part of the void volume in the bulking agent, as shown schematically in Figure 6.15.

If the substrate is assumed to occupy the void spaces, limits must exist on the ratio of bulking agent to substrate. If too little bulking agent is added the individual bulking particles will not be in contact with each other. Instead they will be immersed in the substrate and no practical increase in FAS or pore size will result. On the other hand, addition of bulking agent beyond that required to assure adequate FAS will increase the quantity of material to be handled daily, increase the consumption of bulking agent (assuming it to be degradable), and result in greater land requirements and higher costs.

Numerous bulking agents have been used in practice, including wood chips, straw, pelleted refuse, shredded tires, rice hulls, peanut shells, and other materials. Most of these are composed of cellulosic material and are degradable to some extent during composting. Decomposition will use up a portion of the bulking agent and size reduction will allow an additional fraction eventually to pass through the screening process with the composted sludge. Thus, continual makeup of bulking agent is necessary to balance that which is degraded and that which becomes part of the final product. Certain bulking agents, such as shredded tires and plastic materials, are extremely resistant to microbial decomposition and are probably not affected by the composting process. Hence, they should act almost as conservative substances. Assuming that the bulking agent can be screened efficiently from the compost mixture and reused, little or no makeup would be required in such a case.

Bulking agents can also be classified as to their moisture-absorbing characteristics. Most natural cellulosic materials are porous and capable of significant moisture absorption. Non-porous materials, such as plastics, can be assumed to be nonabsorptive for all practical purposes. Similarly, a porous bulking material that is saturated with water is not capable of further absorption unless it is dried before reuse.

The moisture-absorptive capacity of the bulking agent is important in determining the quantity required for structural conditioning. Assume the bulking agent to be dry and porous before mixture with the wet substrate. Once mixed, moisture will be drawn from the substrate into the bulking agent. Thus, a volume of water will penetrate the bulking agent, leaving an equivalently greater void volume. If the bulking agent is nonporous or water-saturated, a greater quantity of bulking agent will be required to produce the same FAS.

The quantity of moisture that can be absorbed by a bulking agent such as wood chips is considerable. For example, assume 1 m³ of dry wood chips with a bulk weight of 288 kg/m³ (18 lb/ft³) is saturated with water to a final moisture content of 60%. In such a case, the 288 kg of dry chips will absorb 434 kg of water, i.e., $(288/0.4) - 288$, or 0.43 m³. Thus, a volume of moisture greater than 40% of the wood chip volume can be absorbed. Considering that the porosity of randomly piled wood chips is probably on the order of 40%, the importance of moisture absorption can easily be seen.

Development of a Conceptual Model

A mass balance diagram for the addition of bulking agent to wet substrate is presented in Figure 6.16. The required ratio of bulking agent to substrate can be determined from analysis of the mass balance diagram provided certain assumptions are made. First, the substrate is semifluid in nature and occupies the interstices of the mixture. Second, sufficient bulking agent must be added so that contacts between the bulking particles provide structural support for the mixture. In general, this condition is satisfied as long as the substrate/bulking agent mixture remains porous. If insufficient bulking agent is added, bulking particles will be suspended in the substrate and will not provide structural support. Third, moisture absorption by the bulking agent is limited to a maximum moisture content (i.e., minimum solids content). Fourth, moisture release from the substrate is limited to a maximum solids content. Fifth, if other amendments or recycled compost are added to the mixture, the quantities added are sufficiently small to not violate the first assumption. Sixth, the individual bulking particles are solid with no internal FAS. Any free airspace that might exist in the cellular matrix of a wood chip or other porous particle is of little value to the substrate in the void space between particles, at least in terms of oxygen transfer to the substrate.

Moisture relationships with absorption limited by the bulking agent (bulking agent limited) are shown in Figure 6.17, and the case for moisture absorption limited by the substrate (substrate limited) is shown in Figure 6.18. Nomenclature used in Figures 6.17 and 6.18 and in the subsequent discussion, which has not been previously defined, is as follows:

- S_{sm} = fractional solids content of substrate in the substrate/bulking agent mixture after moisture absorption
- S_{sm}^m = maximum fractional solids content of substrate achievable by absorption of moisture from substrate to bulking agent
- S_{bm} = fractional solids content of bulking agent in substrate/bulking agent mixture after moisture absorption
- S_{bm}^m = minimum fractional solids content of bulking agent achievable by absorption of moisture from substrate to bulking agent

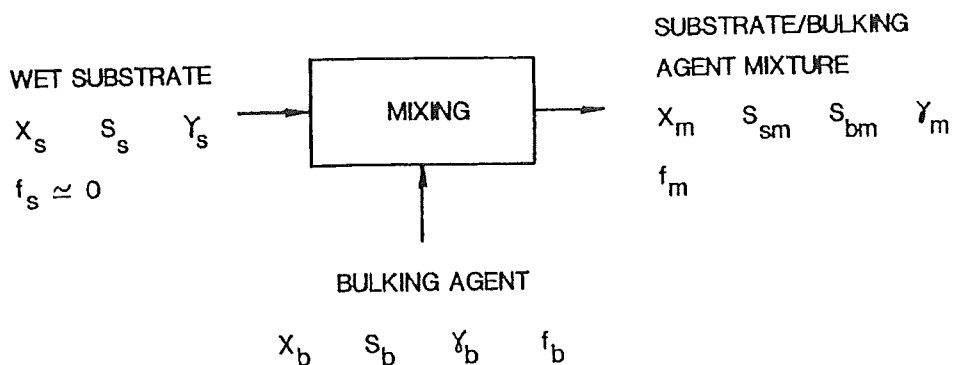


Figure 6.16. Mass balance diagram for bulking agent addition to a wet substrate.

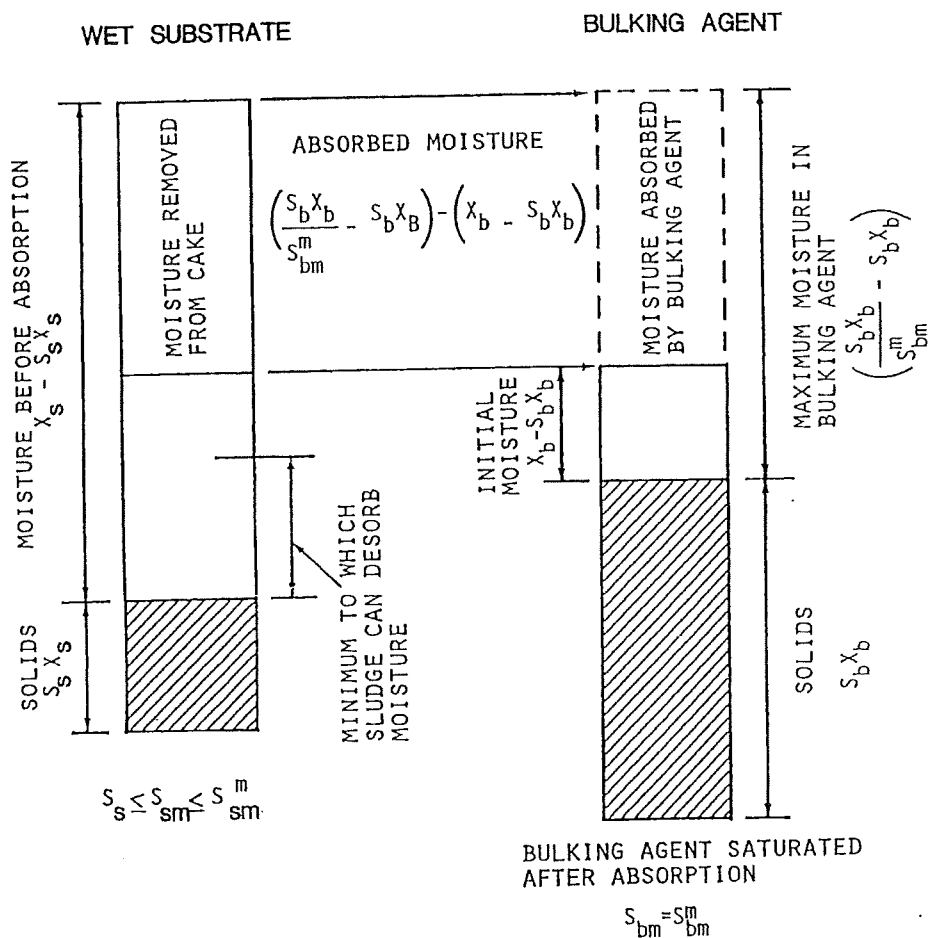


Figure 6.17. Moisture relationships for a substrate/bulking agent mixture with water absorption limited by the bulking agent. From Haug.⁴

- f_b = FAS within the interstices of a bulking agent before substrate addition
- f_s = FAS within the interstices of a wet substrate, usually assumed to be zero
- f_m = FAS within the interstices of a substrate/bulking agent mixture
- δ_b = unit bulk weight of bulking agent, wet weight per volume

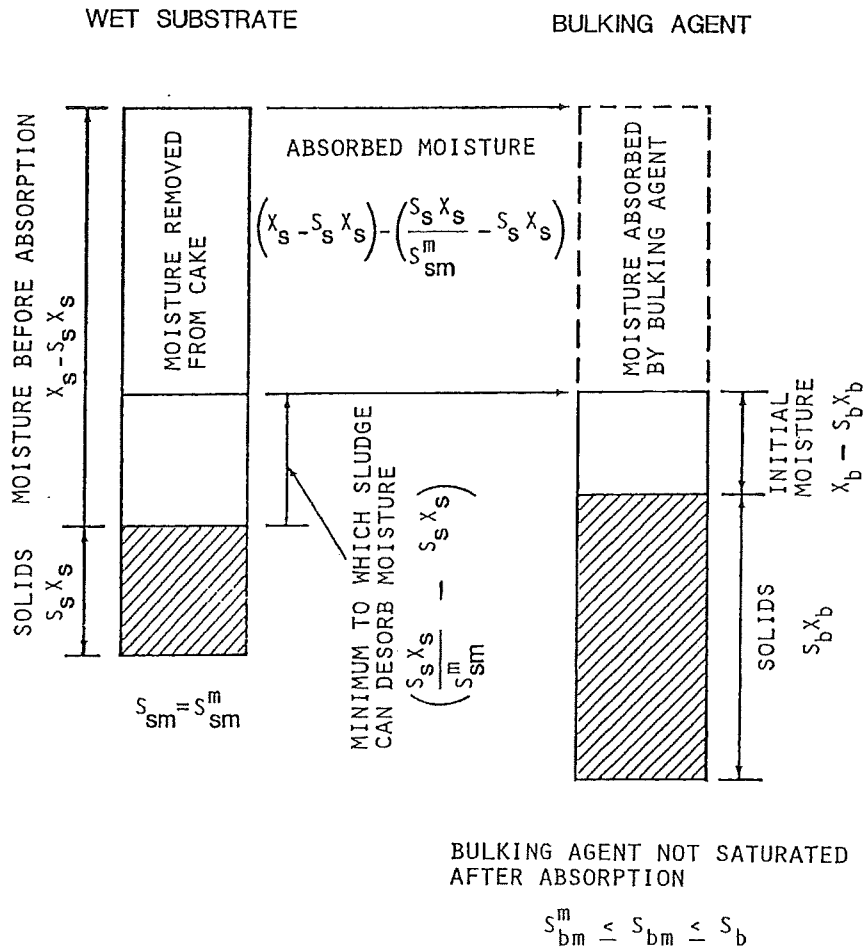


Figure 6.18. Moisture relationships for a substrate/bulking agent mixture with water absorption limited by the substrate. From Haug.⁴

For the case where moisture transfer is limited by absorption into the bulking agent (bulking agent limited), the following equation describes the volume of substrate in the void spaces after moisture absorption:

$$\begin{aligned} &(\text{initial substrate volume}) - (\text{absorbed moisture volume}) = \\ &(\text{mixture volume}) - (\text{bulking particle volume}) - (\text{mixture FAS}) \end{aligned} \tag{6.39}$$

Substituting terms from Figure 6.17 into Equation 6.39:

$$\begin{aligned} &(X_s / \delta_s) - (1 / \delta_w) \left\{ \left[(S_b X_b / S_{bm}^m) - S_b X_b \right] - (X_b - S_b X_b) \right\} = \\ &(X_m / \delta_m) - (X_b / \delta_b) (1 - f_b) - (X_m / \delta_m) f_m \end{aligned} \tag{6.40}$$

Let the volume of bulking agent to substrate be defined as the volumetric mixing ratio, M_{bs} , as follows:

$$M_{bs} = \text{volumetric mixing ratio} = \frac{X_b / \delta_b}{X_s / \delta_s} \quad (6.41)$$

If the substrate is very fluid it will occupy only the interstices of the mixture and will not add significantly to the total mixture volume. As the substrate solids increase, however, the structural strength also increases. The substrate then becomes capable of partially supporting its own weight. Therefore, as substrate solids increase the substrate begins to add to total mixture volume. To account for this, let M_{mb} be defined as the volume ratio of mixed materials to bulking agent:

$$M_{mb} = \frac{\text{volume of mixture}}{\text{volume of bulking agent}} = \frac{X_m / \delta_m}{X_b / \delta_b} \quad (6.42)$$

$$M_{mb} = f(S_s, M_{bs})$$

M_{mb} equals 1.0 if mixture volume equals the bulking agent volume, i.e., the substrate occupies only void space in the initial bulking agent. M_{mb} will be greater than 1.0 if the mixture volume is greater than that of the initial bulking agent.

The value of M_{mb} should be a function of substrate solids and the volumetric mixing ratio, M_{bc} . The effect of substrate solids is illustrated in Figure 6.19 for blends of wood chips and sludge cake. FAS was not measured at the different test points in these studies. Some of the variation in M_{bs} may have been caused by differences in FAS. Nevertheless, the tendency is for M_{bs} to decrease as substrate solids increase. This results from the increasing structural strength of the substrate, which then increases M_{mb} above 1.0. Exact relationships between these variables have not been determined experimentally, and additional work is needed in this area. Limited data¹⁶ suggest an M_{mb} of about 1.2 for a 20% TS sludge cake.

Substituting Equations 6.41 and 6.42 into Equation 6.40 and rearranging:

$$1 / M_{bs} = (\delta_b / \delta_w) [S_b / S_{bm}^m - 1] + M_{mb} (1 - f_m) - (1 - f_b) \quad (6.43)$$

Equation 6.43 can be used to estimate the volumetric mixing ratio, M_{bs} , required to achieved a desired mixture free airspace, f_m , when the quantity of moisture removed from the substrate is limited by that which the bulking agent can absorb (bulking agent limited).

Because Equation 6.43 assumes that moisture absorption is limited by the bulking agent, the solids content of the bulking agent in the mixture, S_{bm} , must equal the minimum solids content, S_{bm}^m . The solids content of the wet substrate, on the other hand, will increase to a level between the initial substrate solids, S_s , and the maximum solids, S_{sm}^m . The actual value of S_{sm} can be determined as

$$S_{sm} = \frac{\text{wt solids}}{\text{wt solids} + \text{wt initial water} - \text{wt water absorbed}}$$

Substituting terms from Figure 6.17:

$$S_{sm} = \frac{S_s X_s}{S_s X_s + (X_s - S_s X_s) - [(S_b X_b / S_{bm}^m) - S_b X_b] - (X_b - S_b X_b)}$$

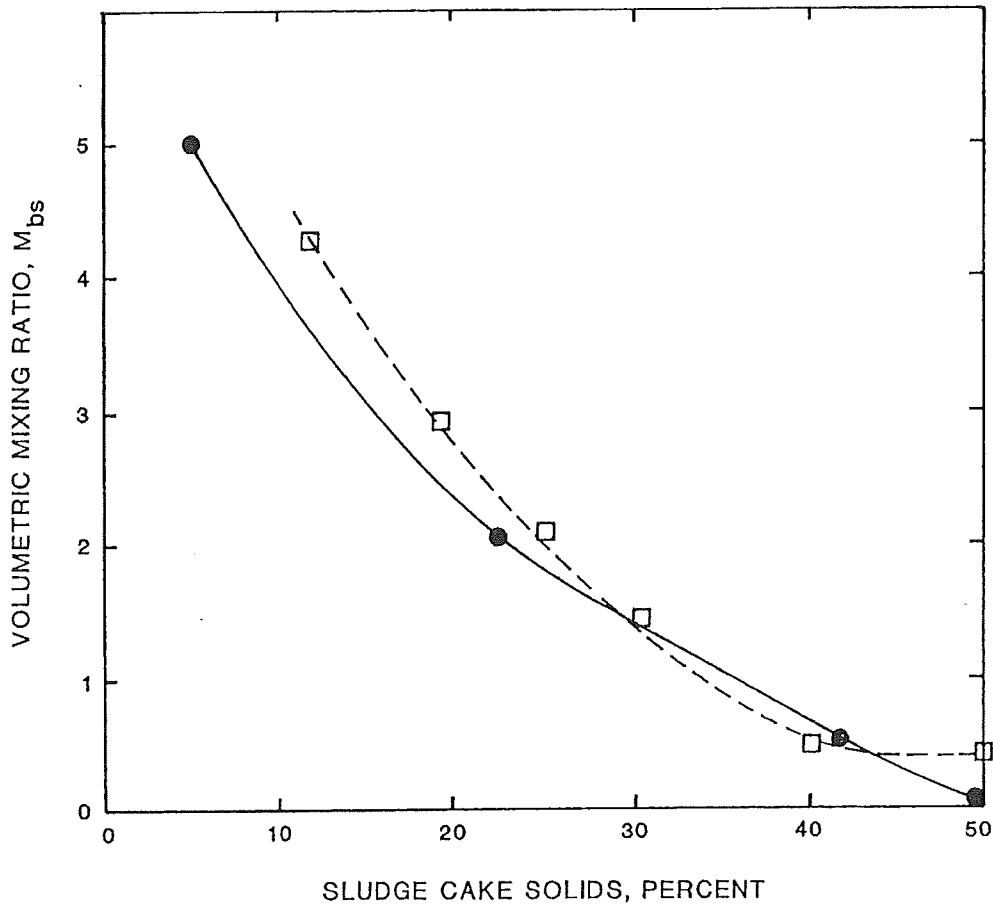


Figure 6.19. Effect of sludge cake solids on the volumetric mix ratio of woodchips to sludge. Solid line represents Willson's data¹⁵ and dashed line represents that of Epstein.¹⁶ FAS was not measured in these tests, so values may have varied at the different test points.

Substituting Equation 6.41 and rearranging:

$$S_{sm} = \frac{S_s}{1 + M_{bs}(\delta_b / \delta_s)[1 - (S_b / S_{bm}^m)]} \quad S_s \leq S_{sm} \leq S_{sm}^m \quad (6.44)$$

The wet substrate cannot give up unlimited quantities of water. Thus, a situation can exist where moisture transfer is limited by the amount that the substrate is capable of yielding (substrate limited), a situation illustrated in Figure 6.18. Substituting appropriate terms from Figure 6.18 into Equation 6.39 yields

$$\begin{aligned} (X_s / \delta_s) - (1 / \delta_w)\{(X_s - S_s X_s) - [(S_s X_s / S_{sm}^m) - S_s X_s]\} = \\ (X_m / \delta_m) - (X_b / \delta_b)(1 - f_b) - (X_m / \delta_m)f_m \end{aligned} \quad (6.45)$$

Substituting Equations 6.41 and 6.42 into Equation 6.45 and rearranging:

$$M_{bs} = \frac{1 - (\delta_s / \delta_w)[1 - (S_s / S_{sm}^s)]}{M_{mb}(1 - f_m) - (1 - f_b)} \quad (6.46)$$

With moisture absorption limited by the substrate, the substrate solids content, S_{sm} , will equal the maximum substrate solids, S_{sm}^m . The bulking agent solids content, S_{bm} , will decrease to a value less than the initial solids content, S_b , but greater than the minimum solids content with maximum moisture absorption, S_{bm}^m . The value of S_{bm} can be estimated as

$$S_{bm} = \frac{\text{wt of bulking agent solids}}{\text{wt solids} + \text{wt initial water} + \text{wt water absorbed}}$$

Substituting terms from Figure 6.18:

$$S_{bm} = \frac{S_b X_b}{S_b X_b + (X_b - S_b X_b) + \{(X_s - S_s X_s) - [(S_s X_s / S_{sm}^m) - S_s X_s]\}}$$

Substituting Equation 6.41 and rearranging:

$$S_{bm} = \frac{S_b}{1 + (1/M_{bs})(\delta_s / \delta_b)[1 - (S_s / S_{sm}^m)]} \quad S_{bm}^m \leq S_{bm} \leq S_b \quad (6.47)$$

For a porous bulking agent the bulk weight, δ_b , is a function of the moisture content and, hence, the solids content, S_b . Because both terms appear in Equation 6.43, the relationship between the two must be known. Wood chips are the most commonly used bulking agent. Available data suggest a bulk weight of about 0.288 g/cm³ for oven-dried wood chips. Bulk weight at other moisture contents can be estimated as

$$\delta_b = \frac{0.288 \text{ g/cm}^3}{S_b} \quad (6.48)$$

For a wet substrate the bulk weight, δ_s , and solids content, S_s , both appear in Equation 6.46. The relationship between these two can be determined from Equations 6.1 and 6.3.

Because either of the above cases may be limiting, the procedure for calculating the required M_{bs} for a given situation is as follows:

1. Calculate M_{bs} and the corresponding S_{sm} from Equations 6.43 and 6.44, respectively.
2. Calculate M_{bs} and the corresponding S_{bm} from Equations 6.46 and 6.47, respectively.
3. Determine the required mixing ratio as the greater of the two calculated values. If M_{bs} calculated by Equation 6.43 is greater, moisture transfer is limited by the amount that can be absorbed by the bulking agent, therefore, $S_{bm} = S_{bm}^m$. If M_{bs} calculated by Equation 6.46 is greater, absorption is limited by the amount released from the wet substrate, therefore, $S_{sm} = S_{sm}^m$. Equations 6.43 and 6.46 will calculate to the same M_{bs} if $S_{sm} = S_{sm}^m$ and $S_{bm} = S_{bm}^m$.

Example 6.7

A wood chip bulking agent is to be used to provide airspace for composting 40 dmtpd of raw sludge cake at 25% TS and 70% VS. The bulking agent has a porosity of 35% and a moisture content of 40%

(60% TS). The minimum FAS to be maintained in the mixture is 15%. It is expected that the sludge can further dewater to a maximum of 35% TS ($S_{sm}^m = 0.35$) and the bulking agent absorb water to a maximum of 60% moisture ($S_{bm}^m = 0.40$). M_{mb} is estimated at 1.10. Determine the required volumetric mixing ratio, the moisture contents of the cake and bulking agent in the mixture, and the total volume and weight of mixed materials to be processed daily.

Solution

1. Specific gravity of sludge solids from Equation 6.1 is

$$1/G_s = (0.70/1.0) + (1 - 0.7)/2.5$$

$$G_s = 1.22$$

2. Bulk weight of the sludge solids from Equation 6.3 is

$$\delta_s = \frac{1.00}{[(0.25/1.22) + 1.0 - 0.25]}$$

$$\delta_s = 1.047$$

3. Estimate the bulk weight of wood chips from Equation 6.48 as,

$$\delta_b = 0.288/0.60 = 0.48 \text{ g/cm}^3$$

4. Calculate M_{bs} by Equation 6.43:

$$1/M_{bs} = (0.48/1.00)[(0.60/0.40) - 1] + 1.10(1 - 0.15) - (1 - 0.35)$$

$$M_{bs} = 1.91$$

5. Calculate M_{bs} by Equation 6.46:

$$M_{bs} = \frac{1 - (1.047/1.00)[1 - (0.25/0.35)]}{1.10(1 - 0.15) - (1 - 0.35)}$$

$$M_{bs} = 2.46$$

The required M_{bs} is 2.46 and moisture absorption is limited by the sludge cake. Therefore,

$$S_{sm} = S_{sm}^m = 0.35$$

6. S_{bm} is then given by Equation 6.47:

$$S_{bm} = \frac{0.60}{1 + (1/2.46)(1.047/0.48)[1 - (0.25/0.35)]}$$

$$S_{bm} = 0.479$$

Note that $S_{bm}^m \leq S_{bm} \leq S_b$ because $0.40 < 0.479 < 0.60$

7. Calculate the total daily volume of mixed material as follows:

$$\text{volume sludge cake} = 40(1000 \text{ kg / mt})(1 / 0.25)(1 \text{ m}^3 / 1047 \text{ kg}) = 153 \text{ m}^3 / \text{day}$$

$$\text{volume of bulking agent} = 2.46(153) = 376 \text{ m}^3 / \text{day}$$

$$\text{total volume} = 376(1.10) = 414 \text{ m}^3 / \text{day}$$

8. Calculate the total daily weight of mixed materials as

$$\text{wt sludge cake} = 40(1 / 0.25) = 160 \text{ mtpd}$$

$$\text{wt bulking agent} = 376 \text{ m}^3 / \text{day} (480 \text{ kg/m}^3)(1 \text{ mt} / 1000 \text{ kg}) = 180 \text{ mtpd}$$

$$\text{total wt} = 160 + 180 = 340 \text{ mtpd}$$

Example 6.8

If a nonporous bulking agent is substituted for the wood chips in Example 6.7, calculate the required volumetric mixing ratio if all other conditions remain the same.

Solution

1. Because no moisture is absorbed by the bulking agent the following conditions hold:

$$S_{bm}^m = S_{bm} = S_b = 1.0 \text{ for the nonporous case}$$

$$S_{sm} = S_s$$

2. Calculate M_{bs} from Equation 6.43:

$$1 / M_{bs} = (0.48 / 1.00)[1.0 / 1.0] - 1] + 1.10(1 - 0.15) - (1 - 0.35)$$

$$M_{bs} = 3.51$$

3. M_{bs} calculated from Equation 6.46 will remain at 2.46 as in Example 6.7. Therefore, the required M_{bs} is 3.51 as calculated above.

4. Note that use of a nonporous bulking agent, or one that is already saturated with water, significantly increases the required mixing ratio over that calculated in Example 6.7. This in turn would increase the daily volume of material to be handled and the land area required for composting.

Example 6.9

The following data¹⁶ represent the mass flow of materials for a mixture of sludge cake and wood chips to be composted by the aerated static pile technique. Estimate the FAS of the mixture.

	Bulk wt kg/m ³	wet tpd	% TS
Raw sludge	1068	600	20.0
New chips	297	58	67.1
Recycled chips	415	444	62.8
Mixed blend	726	1102	39.7

Solution

1. Calculate the average solids content and bulk weight of the new and recycled wood chips and sludge:

$$S_b = \frac{58(0.671) + 444(0.628)}{58 + 444} = 0.633$$

$$\delta_b = \frac{58(297) + 444(415)}{58 + 444} = 401 \text{ kg / m}^3$$

$$\delta_s = 1068 \text{ kg / m}^3 \text{ from the above table}$$

2. Calculate the volumetric mixing ratio as

$$M_{bs} = \frac{\text{volume bulking agent}}{\text{volume sludge}}$$

$$M_{bs} = \frac{444(1000) / 415 + 58(1000) / 297}{600(1000) / 1068} = 2.25$$

3. Assume S_{sm}^m to be 0.40, S_{sm}^m as 0.40, and f_b as 0.40. First consider the case where moisture transfer is limited by that which the bulking agent can absorb and estimate f_m from Equation 6.43.

$$1/2.25 = (0.401/1.00)[(0.633/0.40) - 1] + 1.10(1 - f_m) - (1 - 0.40)$$

$$f_m = 0.263$$

The corresponding S_{sm} is determined from Equation 6.44:

$$S_{sm} = \frac{0.20}{1 + 2.25(0.401/1.068)[1 - (0.633/0.40)]} = 0.394$$

$$S_{sm} = 0.394 < 0.40; \quad S_{sm} < S_{sm}^m \text{ which is OK}$$

4. Now consider the case where moisture transfer is limited by that which can be released by the sludge cake. Estimate f_m from Equation 6.46.

$$2.25 = \frac{1 - (1.068 / 1.00)[1 - (0.20 / 0.40)]}{1.10(1 - f_m) - (1 - 0.40)}$$

$$f_m = 0.266$$

The corresponding value of S_{bm} is determined from Equation 6.47.

$$S_{bm} = \frac{0.633}{1 + (1 / 2.25)(1.068 / 0.401)[1 - (0.20 / 0.40)]} = 0.397$$

$$S_{bm} = 0.397 < 0.40; S_{bm} < S_{bm}^m \text{ which is not OK}$$

5. The condition $S_{bm} < S_{bm}^m$ cannot exist, so the conditions as determined in part 3 are correct and

$$f_m = 0.263$$

$$S_{sm} = 0.394$$

$$S_{bm} = 0.40$$

Other Model Results

Examples 6.7 and 6.8 highlight the importance of moisture absorption by the bulking agent in determining the required volumetric mix ratio. The same calculation procedures were used to prepare the results shown in Figure 6.20. The bulking agent was assumed to be wood chips with a porosity of 0.40, capable of absorbing water to a maximum 60% moisture, $S_{bm}^m = 0.40$. The wet substrate was assumed to release moisture to a maximum solids content of 40%, $S_{sm}^m = 0.40$. Specific gravity of the substrate solids was assumed to be 1.43 and 1.00 for water. For convenience, M_{mb} was assumed to be 1.0 for all calculations.

Analysis of published data for the aerated static pile process suggests a typical FAS of about 20% in the mixed materials. Referring to Figure 6.20, therefore, consider a mixture, f_m , of 0.20. Reading upward, the first intercepted curve is for a cake solids of 10%. All of the solid curves, which represent different bulking agent solids contents, lie above the line for $S_s = 0.10$. Under these conditions, moisture transfer is limited by the absorptive capacity of the bulking agent (solid lines). If $S_b = 0.80$, for example, the required M_{bs} is about 1.8, increasing to $M_{bs} = 2.9$ if $S_b = 0.50$. If substrate solids increase to 20%, M_{bs} is determined by moisture release from the substrate if $S_b > 0.60$. In other words, the dashed curve for $S_s = 0.20$ lies above the solid curves for $S_b \geq 0.60$ at $f_m = 0.20$. In this case, drying the bulking agent beyond 60% solids does not decrease the required M_{bs} of ~ 2.3 . If $S_b < 0.60$, M_{bs} is determined from the solid curves. Considering an S_b of 0.40, for example, M_{bs} is ~ 5.0 , decreasing to ~ 2.9 at $S_b = 0.50$.

As seen above, moisture content of the bulking agent can have a significant influence on the total quantity of mixed material to be processed each day. Drying the bulking agent before recycling can be considered as a way to reduce the required M_{bs} . The facility shown in Figure 6.21 has implemented a storage silo with forced aeration to provide further drying of screened wood chips prior to recycle. This should be an effective strategy to reduce the required M_{bs} within certain limits. For the assumptions of Figure 6.20, drying beyond an S_b of ~ 0.60 with

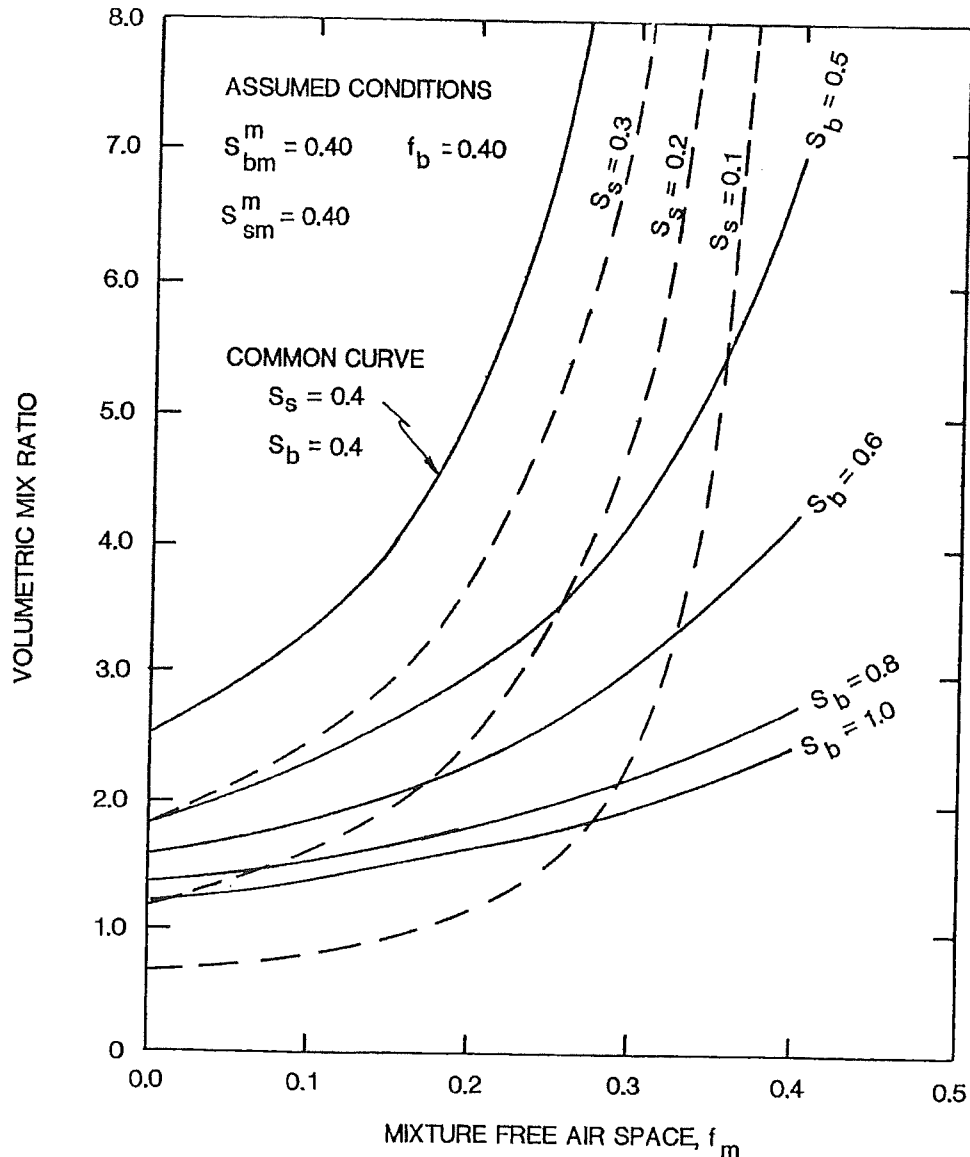


Figure 6.20. Volumetric mixing ratio for bulking agent/substrate mixtures as a function of mixture FAS for various values of substrate solids, S_s , and bulking agent solids, S_b . From Haug.⁴

a substrate of 20% solids may no longer reduce M_{bs} , because moisture removal from the substrate becomes limiting at about that point.

Remember that the curves in Figure 6.20 are based on assumed values for a number of variables. Although the values assumed are reasonable, variations should be anticipated depending on conditions specific to a particular problem. The examples discussed above are intended to illustrate the factors involved in determining the volumetric mixing ratio. If better input data are available for a specific case, the procedures of Example 6.7 can be used to develop curves similar to those presented in Figure 6.20.

Even though assumed values have been used in the previous analysis, it is interesting to note that the general range of M_{bs} values is in good agreement with values reported in practice. With wood chips as a bulking agent and sludge cake solids of ~20%, volumetric mix ratios of 1.0 to 4.0 have been reported.¹⁸⁻²⁰ Based on the model results in Figure 6.20, M_{bs} will likely range between 1.5 and 3.0 if the bulking agent is capable of some moisture absorption and

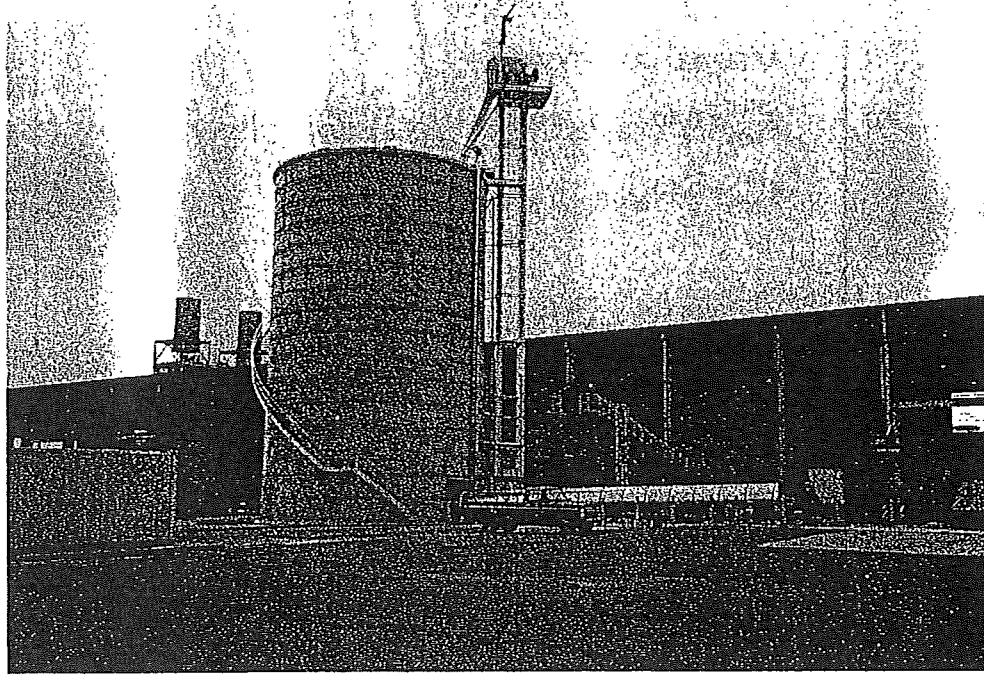


Figure 6.21. Vertical, aerated silo used to store and provide supplemental drying for screened wood chips. Site is the Montgomery County Composting Facility operated by the Washington Suburban Sanitary Commission, Maryland. The facility composts raw sludge with wood chips as a bulking agent using the aerated static pile process.

substrate solids are between 15 and 30%. The general agreement is encouraging and suggests that the model is a reasonable representation of the physical events that occur when using bulking agents for control of FAS.

CONDITIONING OF DRY SUBSTRATES

Dry substrates are generally friable with available free airspace and usually do not need the extensive structural conditioning required for wet substrates. Bulking agents are seldom required for dry substrates. Preprocessing for size reduction or separation of undesirable materials may be required and may have some structural benefits. The present discussion will focus on the need for water addition to adjust dry substrates to a proper range of moisture content.

Referring to Figure 6.7 and assuming water is added to the mixture at a rate, X_w , the mass balance on total weight becomes

$$X_s + X_a + X_r + X_w = X_m \quad (6.49)$$

The mass balance on dry weight remains the same as Equation 6.31:

$$S_s X_s + S_a X_a + S_r X_r = S_m X_m \quad (6.31)$$

S_m in Equation 6.31 is interpreted as the desired solids content after moisture addition. Combining and solving for X_w :

$$X_w = \frac{X_s(S_s - S_m) + X_a(S_a - S_m) + X_r(S_r - S_m)}{S_m} \quad (X_w > 0) \quad (6.50)$$

If $X_w < 0$ the mixture does not require water addition and the actual mixture solids are less than the desired S_m . In such a case, the actual S_m can be calculated from simultaneous solution of Equations 6.30 and 6.31.

Example 6.10

50 tpd of air dried manure at 60% TS is blended with 25 tpd of yard waste at 55% TS and 25 tpd of compost recycle at 65% TS. Calculate the water required to bring the initial mix to 50% moisture.

Solution

1. The desired solids content in the initial mix, S_m , is $1 - 0.50 = 0.50$.
2. The required water rate, X_w , to achieve $S_m = 0.50$ is determined from Equation 6.50:

$$X_w = \frac{50(0.60 - 0.50) + 25(0.55 - 0.50) + 25(0.65 - 0.50)}{0.50}$$

$$X_w = 20 \text{ tpd water} = 20(2000) / (8.34 \text{ lb / gal}) = 4795 \text{ gal / day}$$

3. Without water addition the mixture would have an S_m determined from Equations 6.30 and 6.31 as

$$X_m = 50 + 25 + 25 = 100 \text{ tpd}$$

$$S_m(100) = 50(0.60) + 25(0.55) + 25(0.65)$$

$$S_m = 0.60 = 60\% \text{ TS or } 40\% \text{ moisture}$$

4. As will be seen in later chapters, rate limitations become significant at moisture contents below 40 to 50%. Thus, it is important to consider water addition whenever dry substrates are used for composting.

Adjusting the initial mixture to a proper moisture content does not guarantee that the moisture content stays within an acceptable range throughout the composting process. Composting tends to be a dehydrating environment. Supplemental water addition may be required during the composting cycle to compensate for moisture lost in the exhaust gases. Determining the required rate of supplemental water addition is a considerably more difficult problem because it depends on both process kinetics and thermodynamics. This subject is revisited in Chapters 11 and 14 as part of the analysis of simulation models.

CHEMICAL CONDITIONING

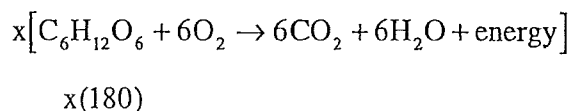
Some substrates may require additional conditioning beyond adjustment of free airspace and moisture. Cellulosic rich substrates, such as some yard wastes and MSW fractions, may lack the nutrients necessary to sustain rapid microbial growth rates. Other substrates may have

extremely low or high pH levels which will also impede microbial growth. Feed conditioning may be necessary to remove these potential limitations to microbial growth.

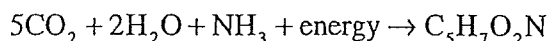
Nutrients

As discussed in Chapter 4, a number of inorganic nutrients are required to support microbial synthesis in biological systems. Nitrogen has received the most attention in composting systems, because higher concentrations are required than for any other inorganic nutrient. The composting industry generally uses the carbon/nitrogen ratio (C/N) as the measure of a proper nitrogen balance. The C/N ratio has a fundamental significance because nitrogen is necessary to support cellular synthesis and carbon makes up the largest fraction of organic molecules in the cell.

During active aerobic metabolism, microbes use about 15 to 30 parts of carbon for each part of nitrogen, i.e., C/N = 15 to 30. To understand this ratio consider a microbe using a starch or cellulosic substrate as an energy source. Glucose is the base monomer of both starch and cellulose, and the energy reaction can be written as



As discussed in Chapters 3 and 4, this reaction yields free energy that the cell can apply to drive the synthesis of new microbial mass. Assuming an average cell formulation of $\text{C}_5\text{H}_7\text{O}_2\text{N}$ and ammonia as the source of cell N, the synthesis reaction is



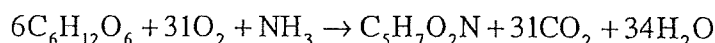
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The maximum yield of cells is limited by thermodynamics to ~ 0.4 g cells/g glucose. The actual yield is usually lower, particularly in systems with long residence times where endogenous respiration is significant. Let us assume a net yield in the range of 0.1 to 0.2 g cells/g glucose as typical for composting of relatively degradable substrates. Using 0.1 as the yield coefficient, the moles of energy reaction required per mole of synthesis reaction can be determined as

$$1/[x(180)] = 0.1/113$$

$$x = 6.3, \text{ say } 6 \text{ moles / mol}$$

Multiplying the energy reaction by 6 and adding to the synthesis reaction gives the net metabolic reaction:



36 mol of carbon are used for each 1 mol of N. Thus, the required C/N ratio is $36(12)/1(14) = 30.9$. If the cell yield were higher, say 0.2 g cells/g glucose, the required C/N ratio decreases to ~ 15 . Hence, rapid composting is favored by maintaining a C/N ratio of ~ 30 or less.

The theoretical arguments are supported by actual field experiments. McGaughey and Gotass² composted mixed refuse materials with initial C/N ratios from 20 to 78. An initial C/N between 30 and 35 was recommended as optimum for rapid composting of the refuse materials. Below this range, rapid composting was accompanied by increasing losses of excess nitrogen from ammonia volatilization. Above this range, composting time increased with increasing C/N ratio. The composting activity accomplished in 12 days with a C/N ratio of 20 required about 21 days with a C/N of 78.

The effect of low nitrogen concentration is due to growth limitations imposed by lack of this particular nutrient. With growth limited, the overall process kinetics become limited in turn. Referring back to Equation 4.10, nitrogen can be a limiting substrate as well as oxygen or another solubilized organic substrate. Problems associated with high C/N ratios can be alleviated by removing a portion of the carbonaceous material (high C/N ratio substrates) and/or by adding nitrogen. If the C/N ratio is ≤ 15 to 30, nitrogen is present in excess and no rate limitation is imposed. This is often misunderstood in the composting literature. It is not necessary that the mixed substrates have a C/N ratio within the range of 15 to 30. It is only required that C/N be < 15 to 30 to remove nitrogen from being rate limiting. Below a C/N of 15 to 30, excess nitrogen will be available and some will likely be lost as volatilized ammonia in the exhaust gases. Kayhanian and Tchabanoglous²² noted some problems with ammonia toxicity during anaerobic composting of MSW fractions. However, this problem is unique to the anaerobic environment and probably would not be a problem with aerobic composting.

MSW =
municipal
solid waste

Nitrogen (N), phosphorus (P), potash (K), and C/N ratios for various organic substrates are presented in Table 6.2. Many composting substrates have high nitrogen contents including night soil, manures, sludges, and grass clippings. Others are quite low in nitrogen and these tend to be cellulosic materials such as sawdust, straw, leaves, and the paper fractions of refuse. It is often advantageous to blend high nitrogen substrates with low nitrogen substrates. Ammonia released from the nitrogen rich substrate can be captured for synthesis by microbes using the nitrogen poor substrate. Thus, more of the nutritive value is conserved and less ammonia is released to the atmosphere. If a nitrogen rich substrate is not available, supplemental nitrogen is usually added in the form of urea, ammonium sulfate, or ammonium chloride. Ammonium phosphate can also be used if a phosphorus deficiency is suspected or if it is desired to fortify the final product.

Determining the C/N ratio requires knowledge of the chemical composition of the substrate. Total Kjeldahl nitrogen can be determined by most wastewater laboratories, however, the necessary test for carbon may not be a routine practice. New Zealand researchers²⁴ have suggested the following relationship between carbon content and ash fraction:

$$\% \text{ carbon} = (100 - \% \text{ ash}) / 1.8 \quad (6.51)$$

The ash fraction can be analyzed by most labs. Equation 6.51 provided results accurate to within 2 to 10% during the New Zealand field studies and should be sufficiently accurate for most practical purposes.

One caution with using C/N ratios should be noted. It is assumed that both the carbon and nitrogen sources are relatively degradable. If the nitrogen were present in a nondegradable organic molecule, the nitrogen would not be available regardless of the C/N ratio. Fortunately, most of the nitrogen in naturally occurring substrates is present in protein molecules, which are relatively degradable. Alternatively, a relatively nondegradable carbon source would not experience rate limitations even with a high C/N ratio. This is because there would be little decomposition and therefore little synthesis to be supported. Kayhanian and Tchabanoglous²² recommended that the C/N ratio should be based on biodegradable carbon, particularly for

Table 6.2. Nutrient Content of Various Composting Substrates

Material	Nitrogen as N (% dw)	Phosphorus as P ₂ O ₅ (% dw)	Potash as K (% dw)	C/N ratio
Night soil	5.5-6.5			6-10
Urine	15-18			0.8
Blood meal	10-14	1-5		3.0
Animal tannage				4.1
Cow manure	1.7-2	1.0	2.0	18
Poultry manure	5-6.3	1.9	1.2	15
Sheep manure	3.8			
Pig manure	3.8			
Horse manure	1.2-2.3	1.0	1.6	25
Raw sewage sludge	4-7			11
Digested sewage sludge	2-4	1.5	0.2	
Activated sludge	5			6
Grass clippings (green)	2.4-6			12-15
Grass clippings and weeds	2.0	1.1	2.0	
Mixed grasses	2.4			19
Nonlegume vegetable wastes	2.5-4			11-12
Bone meal	2.0	23		
Coffee grounds	2.1	0.3	0.3	
Cottonseed meal	6.6	2.0-3.0	1.0-2.0	
Eggshells	1.2	0.4	0.1	
Fish scraps	2.0-7.5	1.5-6.0		
Garbage	2.0-2.9	1.1-1.3	0.8-2.2	
Meat scraps	5-7			
Potato tops	1.5			25
Seaweed	1.7	0.8	4.9	
Salt marsh hay	1.1	0.3	0.8	
Straw, wheat	0.3-0.5			128-150
Straw, oats	1.1			48
Leaves, fresh	0.5-1.0	0.1-0.2	0.4-0.7	41
Sawdust	0.1			200-500
Food wastes	3.2			15.6
Mixed paper	0.19			227
Yard wastes	1.95			22.8
Wood ashes		0.1-2.0	4.0-10	

Source: Adapted from Golueke,¹ Poincelot,²³ and Kayhanian and Tchobanoglous.²²

MSW feedstocks. Based on their pilot plant testing, almost all of the nitrogen in the organic material was available. Assuming that all nitrogen is available, the C/N ratio should be based on the nitrogen content of the total organic mass and the carbon content of the biodegradable organic mass. Biodegradable fraction was determined using Equation 9.1 based on the lignin content of each substrate.

Estimates of the C/N ratio for various MSW fractions based on biodegradable and total carbon are presented in Table 6.3. C/N ratio based on biodegradable carbon is always lower than the value based on total carbon. Kayhanian and Tchobanoglous also noted that the C/N ratio in the organic fraction of MSW will change as new mandated recycling programs are initiated. For example, recycle of the paper fraction will remove this high C/N component from the MSW, resulting in a lower C/N ratio in the remaining material. They determined that 70% recycle of paper would reduce the biodegradable C/N ratio of from about 34 to 17 based on the MSW characteristics at Folsom, California. This would cause a significant increase in ammonia release if the remaining feedstocks are composted. The lesson here is that feedstock characteristics should be carefully reviewed to determine the effect of seasonal changes and changes resulting from societal activities such as recycling.

Table 6.3. C/N Ratios for MSW Fractions Based on Biodegradable and Total Organic Fractions

Component	C/N Ratio Based On	
	Biodegradable Organic Carbon ^a	Total Organic Carbon ^b
Food wastes	12.4	15.6
Mixed paper	143.1	227.1
Yard wastes	14.5	22.8
Mixed waste	34.4	59.9

Source: Kayhanian and Tchobanoglous.²²

^a Biodegradable organic carbon is obtained by correcting the total dry weight carbon value for the ash content and then multiplying by the biodegradable fraction determined from Equation 9.1.

^b Total organic carbon is obtained by correcting the total dry weight carbon value for the ash content.

Example 6.11

Estimate the C/N ratio for raw sewage sludge.

Solution

1. Assume a chemical composition of $C_{10}H_{19}O_3N$ for raw sludge:

$$C/N = 10(12) / 1(14) = 8.6$$

2. Using the New Zealand formula, Equation 6.51, and assuming an ash content of 25%, the percentage carbon is estimated as

$$\% \text{ carbon} = (100 - 25) / 1.8 = 41.7\% \text{ of TS}$$

If nitrogen is 5% of TS from Table 6.2:

$$C/N = 41.7 / 5 = 8.3$$

3. Based on the above, municipal sludges should have more than sufficient nitrogen to satisfy the growth requirement. In fact, considerable volatilization of ammonia is usually observed because of the excess of nitrogen.

Example 6.12

Your firm has been retained to design an MSW composting facility. Refuse is to be received and preprocessed to recover 100 tpd of an "organic rich" fraction which will then be composted. The organics are expected to have a formulation of $C_{99}H_{148}O_{39}N$, contain 25% inert or ash fraction, and have 30% moisture content. Determine the quantity of nitrogen which must be added to the refuse fraction to adjust the feed mixture to a C/N ratio of 25. The nitrogen is to be added as either ammonium sulfate $(NH_4)_2SO_4$ or in the form of raw sludge cake with characteristics per Example 6.11. Determine the quantities of each required.

Solution

1. The C/N ratio of the refuse organics is

$$C / N = 99(12) / 14 = 85$$

Additional nitrogen will be needed to achieve the desired 25 C/N in the feed substrate.

2. The additional nitrogen can be estimated as follows:

The molecular weight of the organics is

Carbon	99(12)	=	1188
Hydrogen	148(1)	=	148
Oxygen	56(16)	=	896
Nitrogen	1(14)	=	14
Total		=	2246

The daily weight of refuse organics is

$$100(1 - 0.25)(1 - 0.30) = 52.5 \text{ tpd of organic solids}$$

Nitrogen content in the feed substrate is

$$52.5(14) / 2246 = 0.33 \text{ tpd nitrogen}$$

Carbon content in the feed substrate is

$$52.5(1188) / 2246 = 27.8 \text{ tpd carbon}$$

The nitrogen required at a C/N ratio of 25 can then be estimated as

$$N = C / 25 = 27.8 / 25 = 1.11 \text{ tpd nitrogen}$$

The required additional nitrogen is then

$$1.11 - 0.33 = 0.78 \text{ tpd additional N}$$

3. If the 0.78 tpd of N is added as ammonium sulfate, the feed requirement is determined as follows:

The molecular weight of ammonium sulfate is

Nitrogen	2(14)	=	28
Hydrogen	8(1)	=	8
Sulfur	1(32)	=	32
Oxygen	4(16)	=	64
Total		=	132

The weight of required ammonium sulfate is then determined as

$$0.78(132) / 28 = 3.7 \text{ tpd}$$

4. If raw sludge is used as the nitrogen source, the quantity required to achieve a combined mixture C/N of 25 can be determined as follows.

Molecular weight of the raw sludge is

Carbon	10(12)	=	120
Hydrogen	19(1)	=	19
Oxygen	3(16)	=	48
Nitrogen	1(14)	=	14
Total		=	201

Let x be the required dtpd of sludge organics. x can then be determined from the desired C/N in the combined mixture:

$$C/N = 25 = \frac{52.5(1188/2246) + x(120/201)}{52.5(14/2246) + x(14/201)}$$

$$x = 17.1 \text{ dtpd of sludge organics}$$

Accounting for the ash and water fractions, the wet weight of sludge cake required can then be determined as

$$17.1 / [1 - 0.25](0.25)] = 91.2 \text{ wtpd sludge cake}$$

5. As can be seen by this example, the requirement for additional nitrogen can be significant if the substrate is nitrogen poor. Combining substrates with low and high nitrogen contents can be advantageous and can avoid the need to add outside sources of nitrogen.

Hydrogen Ion Concentration

Both hydrogen ion (H^+) and hydroxide ion (OH^-) are very toxic to microorganisms. For example, most bacteria will not survive in a pH 3 solution, but at pH 3 the H^+ concentration is only about 1 mg/L. Similarly, most bacteria begin to succumb at high pH levels, above 10.5, with significant kills above ~ 11.5 .²¹ The high and low pH causes a change in the ionization state of various protein components such as amine and carboxyl groups. This in turn causes changes in the physical structure of the protein and hence a loss of enzymatic activity.

Extremes of low or high pH are most often encountered with municipal sludges. Most raw sludges have a pH in the range of 5 to 6.5, while digested sludges are well buffered in the range of 7 to 8 pH. High pH values above 10 are encountered when lime is used for coagulation or precipitation in the wastewater treatment process or as a conditioning chemical during dewatering. Similarly, low pH values may be encountered when ferric chloride or alum are used for sludge conditioning. It is more common in modern practice to encounter high pH sludges because lime conditioning and lime stabilization are widespread practices. Under low or high pH conditions, an initial lag in the composting rate can be expected.

Composting has a rather unique ability to buffer both high and low pHs back to a neutral range as composting proceeds. This is because both a weak acid (CO_2) and a weak base (NH_3) are produced as a result of microbial decomposition. CO_2 is an end product in all organic decomposition, while NH_3 is an end product of protein decomposition. The CO_2 effectively neutralizes high pH conditions (excess OH^-) and the NH_3 low pH conditions (excess H^+).

Thus, it is common to observe a gradual neutralization of low or high pH as composting proceeds.

Using a well-mixed reactor, Shell and Boyd⁹ composted digested sludge conditioned with 4.5% ferric chloride and 15.5% lime based on dry weight. The filter cake pH averaged 11.0 while pH of the compost product averaged 6.5. Obviously, sufficient CO₂ was produced to neutralize the lime content. It was also noted in this study that sludge conditioned with lime and ferric produced compost that mixed and handled better than sludge conditioned with organic polymers. With batch processes a lag period is usually observed until the persistent microbial activity neutralizes the high or low pH. The batch, static pile process has been applied to many lime conditioned sludges. A lag period of a few days to one week is typically observed before sufficient CO₂ is evolved to neutralize the excess lime.

Davis et al.²⁵ studied the pH changes of lime/ferric conditioned and polymer conditioned sludge cakes during composting and subsequent use of the composts in plant growth experiments. Initial pH of the lime/ferric cake was about 12.1 and about 8.4 for the polymer cake. Both sludge types were composted by both windrow and static pile processes using subtropical yard wastes for amendment. A decreasing pH trend was observed during the composting and curing periods. All final composts had pH levels between 7.7 and 7.9. The composts were then used alone and blended with pine bark and sand to produce a potting soil for the growth experiments. During an 8-week growth period the composts alone showed a continued decrease in pH to a range of 6.6 to 7.2. Similar levels were observed with the potting blend. There were no observed pH increases from the initial lime in the sludge. The authors concluded that (1) the conditioning method for dewatering did not affect growth of short-term crops, (2) once neutralized the high pH should remain neutralized, and (3) lime conditioning should not limit marketability even on calcareous soils.

For material not conditioned with lime, it is common in the early stages of batch composting to observe a decrease in pH from CO₂ and organic acid production. pH as low as 4.5 to 5.0 may at times be observed. However, the pH sag is rapidly overcome as organic acids are further decomposed and temperature rises. Protein decomposition will contribute NH₃ which will also tend to neutralize the acids. Increased rates of aeration will tend to decrease CO₂ levels in the compost, which in turn will tend to increase pH. pH usually stabilizes in the near-neutral range of values. McGaughey and Gotaas² examined the effect of calcium carbonate addition to reduce the normal pH sag observed during windrow composting of refuse. Although a slight reduction in the pH sag was observed, it was concluded that the practice was of limited value to process kinetics and that pH control was not necessary in the composting of garbage and municipal refuse.

Based on the above, it is not common to adjust the pH conditions of the feed substrates for composting. However, some cautions should be noted to this general rule. High lime dosages, such as those that occur with lime stabilization processes, could impose an extensive lag period on a batch composting process. If an extended lag period is undesirable, a number of approaches can be used to condition the starting substrate. First, acid can be added, but this is usually difficult to properly control. Second, CO₂ rich gases from the actively composting material can be recycled and passed through the starting substrate to neutralize the excess lime. This is usually quite effective and avoids the problem of accidentally producing low pH conditions from oversupply of acid. The latter can occur when strong, mineral acids (sulfuric, hydrochloric, and phosphoric) are used for neutralization. Third, a well-mixed process can be used so that the new substrate is mixed with actively composting material, which is already neutralized.

One other caution is noted for substrates that are both low in nitrogen and low in pH. For example, an industrial sludge could be mostly cellulosic with low pH from residual acids used

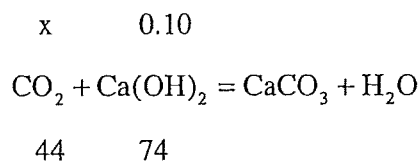
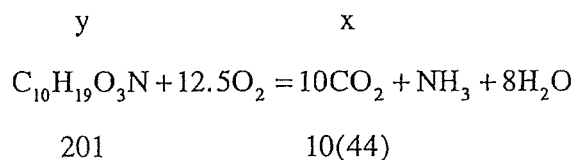
in the process. If this were the case, neutralization of the low pH may not occur because ammonia is not available from the substrate. The only recourse in this case would be to neutralize the substrate pH. Lime, calcium carbonate, sodium hydroxide, sodium bicarbonate, or ammonia could be used for this purpose.

Example 6.13

Assume $C_{10}H_{19}O_3N$ as the chemical composition of the organic fraction of a raw sludge. The sludge is 30% ash by weight and is conditioned with 10% lime as $Ca(OH)_2$ based on dry weight. Estimate the fraction of organics that must degrade to produce sufficient CO_2 to neutralize the lime. Neglect any neutralization reactions that may occur during initial lime addition to the sludge.

Solution

1. Oxidation of the organics and neutralization by the produced CO_2 can be represented as



Consider 0.10 g lime/g dry solids. The CO_2 requirement is then given by

$$\begin{aligned} x/44 &= 0.10/74 \\ x &= 0.0595 \text{ g } CO_2 \end{aligned}$$

To supply this CO_2 the following organic decomposition is required:

$$\begin{aligned} y/201 &= 0.0595/[10(44)] \\ y &= 0.027 \text{ g} \end{aligned}$$

2. The fraction of substrate organics that must decompose can be estimated as

$$0.027/0.70 = 0.0386 \text{ g/g VS} = 3.9\%$$

Thus, only a small fraction of the substrate must decompose to neutralize the initial high pH. Lime doses as high as 30 to 40% are used for stabilization. Even these large amounts would not overly tax the neutralizing capacity of the composting process. Rate limitations in the early stages of composting might occur until sufficient organic decomposition is realized to lower the pH.

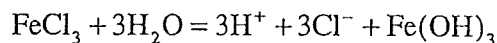
3. The reader should note that a portion of $\text{Ca}(\text{OH})_2$ added to sludge will react with CO_2 and bicarbonate alkalinity naturally present to form CaCO_3 . Thus, the above calculations are conservative and tend to overestimate the required organic decomposition.

Example 6.14

Assume the sludge in Example 6.13 is conditioned by adding 2% FeCl_3 based on dry weight. Estimate the fraction of organics that must degrade to produce sufficient ammonia to neutralize acids produced from the addition of ferric chloride. Neglect any neutralization reactions that may occur during initial ferric addition to the sludge.

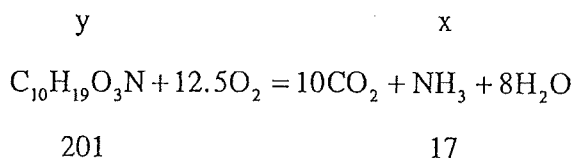
1. Production of acid from addition of ferric chloride can be described as

$$0.02$$

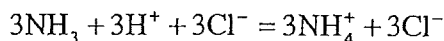


$$162.5$$

2. Oxidation of organics and neutralization by produced NH_3 can be represented as



$$x$$



$$3(17)$$

3. Consider 0.02 g $\text{FeCl}_3/\text{g ds}$. The NH_3 requirement is then given as

$$x/[3(17)] = 0.02/162.5$$

$$x = 0.0063 \text{ g NH}_3$$

To supply this NH_3 the following organic decomposition is required:

$$y/201 = 0.0063/17$$

$$y = 0.0745 \text{ g}$$

4. The fraction of substrate organics that must decompose is then estimated as

$$0.0745/0.70 = 0.106 \text{ or about } 10.6\%$$

The organic decomposition required to neutralize low pH conditions will depend largely on the degradable protein content of the feed substrate, because this is the primary form of organic nitrogen. Substrates low in degradable protein will produce less ammonia and have a reduced neutralizing capacity against low pH conditions.

SUMMARY

Conditioning of the feed substrates is important to successful operation of the composting process. Feed conditioning is a process by which potential process limitations imposed by lack of moisture, free airspace, nutrients, or energy are selectively removed. Three types of conditioning can be defined: physical or structural, chemical, and energy or thermodynamic conditioning. Physical or structural conditioning is defined as conditioning of the substrates to remove potential rate limitations caused by lack of moisture and/or free airspace. Chemical conditioning is defined as conditioning of the substrates to remove potential rate limitations caused by lack of nutrients or other chemical imbalances. Thermodynamic conditioning is defined as conditioning of the feed mixture to assure that sufficient energy is available to drive the process.

Moisture is essential to maintain microbial activity. Lack of moisture can impose severe rate limitations on the process. Moisture content should generally be as high as possible without saturating the substrate and removing all available free airspace. Free airspace (FAS) is important in maintaining aerobic conditions within a composting material. There is considerable evidence that the optimum moisture content for a particular substrate is related to maintenance of a certain minimum FAS. Reported optimum moisture contents tend to fall in the range of FAS between about 20 and 35%.

Wet substrates, such as municipal and industrial sludges and wet manures, often contain little or no FAS. Because of the high moisture content, these materials generally lack the structural strength to maintain a properly shaped windrow or pile and the friability to assure aerobic conditions in the composting material. It is necessary to reduce the bulk weight and increase the structural strength of these materials to produce free airspace within the composting matrix. Four techniques have been demonstrated in commercial practice to deal with the problem of high moisture content:

1. recycle of dry, previously composted material
2. addition of dry amendments either with or without product recycle
3. use of bulking agents such as wood chips
4. drying the wet substrate before composting to reduce the moisture content

Recycle of compost product has been used in the windrow and many reactor systems. In some cases it is the only conditioning material added to the wet substrate; however, it is more common to combine product recycle with supplemental amendments, such as sawdust. Bulking agents are usually used in the aerated static pile process. Predrying has been used with digested sewage sludges and may be combined with the use of product recycle. A fifth technique, the use of nearly constant agitation to achieve aeration, has been successful only in bench scale applications and is not considered a feasible alternative for full scale practice.

Product recycle and amendments are effective in physical (structural) conditioning because they (1) decrease the bulk weight of the wet substrate and (2) increase the structural properties of the mixture to the point that it can be piled without consolidating or losing its free airspace. Bulk weights for most wet substrates begin to decrease from the theoretical maximum at solids

contents between about 30 to 40%. Using product recycle and/or amendments to adjust mixture solids contents to the range of 35 to 45% is the common practice with wet substrates.

By comparison, bulking agents provide structural conditioning by maintaining a three-dimensional matrix of particles whose strength is provided by particle-to-particle contacts. The wet substrate occupies part of the void spaces between bulking particles. Sufficient bulking agent must be added to assure that the wet substrate volume does not exceed the available void volume. Use of dry porous bulking agents is advantageous because moisture is absorbed from the wet substrate, thus increasing the FAS. Use of a nonporous bulking agent, or one that is already saturated with moisture, increases the required quantity of bulking agent because no moisture is absorbed from the substrate.

Dry substrates usually do not require the structural conditioning provided by product recycle, amendments, or bulking agents. Recycle and amendments may be used for other than structural reasons, however, such as for energy conditioning or microbial inoculation of the dry substrate. Water addition is important to the conditioning of dry substrates to remove rate limitations from lack of moisture. Generally, the moisture content of the initial mixture should be at least 50%. Composting tends to be a dehydrating environment. Supplemental water addition may be required during the composting cycle to compensate for moisture lost in the exhaust gases.

Nutrient additions may be required for some substrates, particularly high cellulosic ones that lack sufficient nitrogen. The C/N ratio of the feed mixture should normally be less than 30 to assure that nitrogen does not become rate limiting. Blending with other high-nitrogen substrates or addition of supplemental chemical nitrogen can be used to condition a low-nitrogen substrate. With some substrates the potential exists that other macronutrients, such as phosphorus and potassium, or micronutrients, such as iron and magnesium, could be present in low enough concentrations to be rate limiting. Fortunately, such cases are rare and limitations can easily be avoided by adding a small quantity of a nutrient rich substrate such as sewage sludge, garbage, or manure.

Very low or very high pH levels can impose rate limitations to microbial activity. High pH levels are commonly encountered with municipal sludges because of the practice of lime conditioning. Fortunately, composting has a rather unique ability to buffer both high and low pHs back to a neutral range as composting proceeds. This ability to buffer extremes of pH is caused by the fact that both carbon dioxide (a weak acid) and ammonia (a weak base) are released as a result of organic decomposition. These compounds will tend to neutralize extremes of low or high pH. Therefore, pH adjustment of the starting substrates is usually not required and is not a common practice. Two cautions to this general rule are noted. The first applies to sludges conditioned with very high lime dosages which may exhibit an excessively long lag period before neutralization. The second applies to low pH, low nitrogen substrates which may lack sufficient protein to supply the ammonia needed to neutralize the acidic conditions.

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