SLUDGE DEPOSITION AND DIGESTION PRR

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Sludge accumulation in a wastewater treatment pond can be problematic; reducing holding and treatment capacity, promoting short circuits, shortening life of facility, creating obnoxious odors, and increasing operating costs, among other adverse effects. However, sludge accumulation is an important aspect of wastewater treatment and must be facilitated such that its positive contribution is optimized with the adverse effects. This paper examines the known principles of sludge deposition and digestion and suggests how the controlled recirculation mechanisms by the Sunflo2 technology influences those principles.

Sludge Deposition

Solids in wastewaters may exist in the forms of:

1. settleables,
2. flocculations or coagulations of colloids, and
3. suspendeds.

When these solids are being carried in a river or stream, there is always the possibility that the velocity of flow will drop to some value at which sedimentation will occur. The limiting velocity at which deposition will occur is probably about 0.5-0.6 ft/sec. A detailed mathematical analysis of the settling velocity that takes into account the shape and size of the particles is presented by Crites and Tchobanoglous (1998).(1) Municipal wastewater carried by pipes is designed to flow at velocities sufficient to keep the solids from settling out before it reaches the treatment facility.

However, upon reaching a vessel such as a pond, depending upon the size of the solids and the recirculation taking place in a wastewater treatment pond, sludge will accumulate on the bottom. On the one hand, maintaining conditions that result in the carry-over of solids may have adverse effects on a receiving stream. On the other hand, their accumulation as sludge in a wastewater treatment pond is of concern from the standpoint of displacing aerobic treatment volume, its contribution to obnoxious odors, and its effect on reducing detention times. Yet, the sludge deposition and attendant anaerobic digestion contributes significantly to the overall wastewater treatment performance of a lagoon system.

When sludge is allowed to precipitate naturally and digests thoroughly, more than 60% of the influent BOD may be removed by anaerobic digestion in a properly designed, unassisted facultative pond, without an appreciable reduction in hydraulic detention time due to displaced volume. The characteristics of solids and the manner in which they are conveyed are important as these factors affect the rate of sludge deposition, as well as, its subsequent digestion. The quantity of sludge produced that must be digested is a function of the characteristics of the wastewater, the mean cell residence time (MCRT), the velocity of the water, and the endogenous decay rate.

The rate, quantity, and quality of sludge deposition and the temperature have a significant impact on the oxygen resources. For example, rapidly deposited sludge, under high loading conditions and/or low temperatures, can exert a secondary BOD load when temperatures rise and/or influent loading is reduced. Consequently, in order to ascertain the proper supply of oxygen, it is necessary to account for the rate at which solids are being deposited (sludge) and the effects of sediments being scoured and carried into suspension.

Sludge characteristics of importance include the expected quantity, chemical and nutrient content, and heavy metal content. These characteristics vary with the type of wastewater, the process that produces the sludge, as well as, the wastewater strength.

Sludge quantities vary with the type of wastewater treatment systems as shown in Table 1. For primary sedimentation or Imhoff tanks, the sludge produced is typically 0.6 tons/Mgal of wastewater treated.

Table 1. Sludge production from wastewater treatment.

Operation or process	Dry sludge Range	Tons/Mgal Typical
Primary sedimentation or Imhoff tanks	0.45-0.7	0.60
Activated sludge	0.3 - 0.4	0.35
Trickling filters	0.25-0.4	0.30
Aerated lagoon	0.35-0.5	0.40*
Extended aeration	0.35-0.5	0.40*
Filtration	0.05-0.1	0.07

* Includes primary sludge.

For an activated-sludge system the combined waste activated and primary sludge would amount to 0.95 dry tons/Mgal/day. In contrast, aerated lagoons produce a combined 0.4 dry tons/Mgal/day.

Natural systems such as land treatment, ponds, aquatic treatment, or constructed wetlands produce significantly less sludge than mechanically assisted treatment processes. In land treatment and constructed wetlands, the solids are incorporated into the soil matrix and the vegetation/debris. In stabilization ponds and aquatic treatment systems the solids must be removed, but over a 5- to 10- year period, typically or longer if thoroughly treated.

Reed, et al(2) studied ponds in Alaska and Utah for solids accumulation. They found the sludge production in the facultative ponds to be about 10 percent of the production of a typical primary treatment system. In warmer climates, the solids production would be expected to be lower than in cold climates because the biological stabilization occurs more rapidly in warmer water. The long detention time in ponds allows for the stabilization of organic matter, consolidation of the sludge, and for a significant die-off of fecal coliforms.

The sludge from mechanically assisted primary sedimentation is relatively dilute, with a typical solids concentration of 5 percent. Data on typical sludge quality for primary and waste-activated sludges are shown in Table 2. The fertilizer values of a typical sludge are relatively low with an NPK (nitrogen, phosphorus, potassium) ratio (percent by weight) of 2.5:1.6:0.4. A typical commercially mixed fertilizer will have an NPK ratio of 10:10:10.

Aeration, provided it is not turbulent, has a great beneficial effect on the rate of sludge digestion, especially in the manner in which the sludge is deposited in the first place. Biological slimes develop in aerated organic wastes that contain a considerable proportion of matter in the colloidal and suspended state. For the efficient removal of organic dissolved solids, high floc concentrations are required to provide ample contact surface for accelerated biological activity. The flocs (zoolgleal masses) are living masses of organisms, food, and slime material and are highly active centers of biological life. They require food, oxygen, and living organisms in a delicately controlled environment. Oxygen, provided by aeration, accelerates the formation of flocs.

Constituent	Unit Primary	Untreated
Total solids (TS)	%	5
Volatile solids	% of TS	65
Nitrogen as N	% of TS	2.5
Phosphorus as P2O5	% of TS	1.6
Potassium as K2O	% of TS	0.4
pH		5.0 - 8.0
Iron	%	2.5

* From Tchobanoglous and Burton (1991).

Sedimentation and bioflocculation (the aggregation of small units of biomass into larger and larger “floc” to the point that their density becomes greater than that of water and they precipitate to the bottom) are mainly responsible for the sludge deposition in ponds. While bioflocculation is the predominant mechanism for settling solid particles that float or that may be

suspended, autoflocculation (natural floatation of algae brought about by gas super saturation) and fecal deposition by invertebrates occasionally are significant.

Studies have shown that under natural recirculation conditions by wind and wave action, about 90% of the suspended solids in raw sewage are removed in about three days and 80% of the dissolved solids in about ten days. However, in ponds where algae and bacterial growth has been established, and where incoming wastewater is mixed with pond contents, 85% of both the suspended and dissolved solids are deposited on the bottom within four hours. The studies conclude that bioflocculation brings about a ten-fold increase in the speed of formation and deposition of suspended solids, and more than a hundred-fold increase in the speed of deposition of dissolved solids. Bioflocculation is accelerated as temperature increases from 4° to 25°C, by the gentle recirculation action of waves, or by mechanical re- circulation, and probably, by the movements of invertebrates. The presence of oxygen also greatly increases bioflocculation.

For autoflocculation to be effective the dissolved oxygen (DO) concentration of the pond must exceed about 13 to 15mg/l and the pH must be greater than 11. Autoflocculation occurs in ponds containing a dense algae population, which is generally associated with an increase in temperature and a rise in the pH level. Certain compounds present in “hard” wastewaters, such as magnesium hydroxide, calcium sulfate, and ammonium calcium phosphate, become insoluble (precipitate) when pH level and temperature in a pond are high. As these precipitates enmesh with algae cells, detritus, and bacteria, they form floc particles which readily settle. Coliform removal is known to be enormously enhanced by autoflocculation. Autoflocculation is always followed by a great decrease in dissolved oxygen, because algae are carried to lower strata of limited light and limited access to nutrients.(3)

Fecal deposition also contributes to the sludge bed. Invertebrates such as Rotifera, Cladocera, Ostracods, and Copepods are common in ponds, particularly during the spring and fall. They ingest algae and bacteria, and are capable of cleaning up all suspended solids, except themselves, in only a few days. However, only a small fraction of the algae and bacteria ingested are actually digested. The effect is that the suspended solids are simply added to the sludge bed through fecal pellets. Since only a fraction of the ingested material is stabilized through digestion, the remainder enters the benthal zone to be stabilized through anaerobic decomposition. Remarkable clarification of pond contents is the result of deposition of suspended matter in the form of fecal pellets, or from bioflocculation and autoflocculation brought on by a gentle stirring action.

With regard to sludge deposition, in summary, Oswald found that: in a well seeded, oxygenated and homogenized pond, from 80 to 90% of the suspended and dissolved organic matter becomes fixed in organic solids, which settle to the pond bottom within a few hours. On the other hand, a pond that is not well mixed, oxygenated, or seeded, acts merely as a sedimentation tank. The presence of algae and invertebrates hastens sludge deposition through oxygenation, flocculation, recirculation, ingestion, and defecation.

From the above, one can conclude that sludge deposition, which is the prerequisite for the effective separation of biological solids in the first stages of treatment, and contributes greatly to overall BOD reduction is significantly enhanced by low velocity currents and by the formation of a satisfactory floc. Flocculation is influence by gentle circulation, and the presence of oxygen and algae.

Sludge Digestion

The organic fraction of sludge deposits decomposes. If the overlying water contains dissolved oxygen, the surface of the deposits remains aerobic subtracting some quantity of the typically scarce dissolved oxygen from the pond. But oxygen will penetrate into the mud only as far as its diffusion and the sludge composition will permit. Ordinarily, the downward diffusion of oxygen is not sufficiently vigorous to reach below the superficial layers. In the deeper strata, anaerobic conditions stake hold.

Upward diffusion of products of anaerobic decomposition also consumes some oxygen. In deposits of significant thickness, therefore, decomposition is forced to proceed both aerobically and anaerobically, The course of benthal decomposition is further complicated by the activities of worm and insect larvae which ingest subsurface mud and deposit fecal pellets upon the mud surface or which burrow into the mud and expose its lower strata to the flowing water.

When decomposition is vigorous, bubbles of gas (principally carbon dioxide and methane) break through the sludge and rise through the supernatant water. In warm weather, the evolution of gas bubbles may become sufficiently intense to bring sludge particles to the water surface where they may form unsightly, floating islands of sludge. Floating sludge that contains volatile soluble matter may impose a sudden, sometimes overpowering, oxygen demand in the upper stratum. The magnitude of this demand cannot be predicted, but it must be noted that fresh sludge suspended in water has a 5-day, 20oC BOD in excess of 0.7 lb per lb of volatile matter. Even deep sludge deposits that have undergone decomposition for a year or more may still possess a demand of 0.1 lb per lb of volatile solids. Much of this demand is exerted as a chemical demand during the first few hours of suspension in the supernatant water.

All these phenomena may be observed while the supernatant water retains some DO, but only when the reaeration mechanisms are able to meet the increased demands for free oxygen. Heavy sludge banks, however, may become so active, especially in the early summer, that the DO content of the supernatant water is fully depleted.

Problems of dealing with sludge is complicated by the fact that: (1) it is composed largely of substances responsible for the offensive character of untreated sewage, (2) a portion of the sludge produced from biological treatment requiring disposal is composed of the organic matter contained in the raw sewage, but in another from, which eventually will decompose and also become offensive, and (3) only a small part of sludge is solid matter.

Whether in a stream or in a quiescent pond, deposition of organic solids results in a temporary reduction in the BOD load in the stream or pond waters. Almost as soon as organic matter is deposited, the deposits will start undergoing biological decomposition that results in some reduction in the dissolved oxygen concentration in the water adjacent to the sediment material. As the deposited organic matter increases in volume, the rate of decomposition also increases. Ultimately, equilibrium will be established. Velz (1958)(4) has shown that at equilibrium the rate of decomposition, or the exertion of a BOD, equals the rate of deposition.

Because of the typical absence of DO in the lower stratum of a facultative wastewater treatment pond, sludge accumulations must undergo digestion through the work of anaerobic life forms, and attendant chemical reactions, including acid forming decomposition and methane fermentation. The rate of decomposition is dependent upon

the constituency of the sludge, its density, the type of bacteria present, age of the deposit, ambient temperature, pH, and the manner in which it was deposited, among other factors.

Sludge accumulations from primary sedimentation is usually gray and slimy with an offensive odor. Partially digested sludge is dark brown to black and contains a large quantity of gas. When thoroughly digested, it is not offensive. Its odor being relatively faint like hot tar, burnt rubber, or sealing wax.

Without aerobic “buffer zones” of sufficient depth, or other reactions promoted by adding other chemicals, the sludge digestion process will produce odors. The application of nitrate to supply oxygen and raise the redox potential in industrial waste ponds has been recommended as a control of odors resulting from sulfate reduction. However, practical experience has shown that this chemical has very little effect on odor reduction in domestic sewage, stabilization ponds. The best assurance against odors is maintenance of aerobic conditions, or loading at a rate sufficient to permit optimum decomposition of influent organic matter.

Oswald(5) concluded that in a heavily loaded pond, particularly during periods when methane fermentation either is nonexistent or is limited by temperature, and algal photosynthesis is not taking place at the surface, a buildup of organic acid occurs. Subsequent lowering of the pH level permits the emission of hydrogen sulfide from the pond. However, if methane fermentation becomes established in the bottom deposits, high rates of BOD removal may be obtained without appreciable odors. He suggested that unassisted ponds in which both photosynthetic oxygenation and methane fermentation occur (facultative ponds), must be restricted to about 50 pounds of BOD per acre per day, because at times conditions are unfavorable for either process.

A new facultative stabilization pond may initially become very odorous. The only biological activity that can occur in newly deposited sludge layers is putrefaction. Odors tend to endure until methane fermentation becomes established, or until aerobic conditions exist throughout the pond depth. However, if started in the fall, aerobic conditions may not occur until the following spring when warmer temperatures permit accelerated algal growth and methane fermentation. Seeding of such ponds with digested sludge and algae may be necessary to initiate aerobic and fermentation conditions in order to minimize odor problems.

Sludge deposits decompose: when a suitable seed is present, when there is a relatively high pH, in the absence of inhibiting substances, and in warmer temperatures. Sludge deposited in a new pond will require some time before the seed develops to a sufficiently large population to effect decomposition. Once a population is established, decomposition proceeds with the production of carbon dioxide, hydrogen sulfide, and organic acids. Frequently these acids accumulate and cause a decrease in the pH to a point below the optimum environment for bacterial activity. Substances that inhibit bacterial decomposition are: strong acids, strong bases, and various organic and inorganic salts.

Although aeration and recirculation by mechanical means can accelerate the formation of floc and thereby increase the rate of sludge deposition, if the velocity of the recirculation action provided by the aeration equipment is sufficiently high (1.5 – 2.0 ft/sec.) to keep solids and colloidal material in suspension, the sludge deposit may be thinly disbursed throughout the zone of influence of the aeration equipment. Thin layers of sludge are more vulnerable to fluctuations in pH and temperature than sludge deposited at slower velocities. These fluctuations disrupt the biological and chemical processes that may have been established.

Also, higher velocities will reduce the rate of successful flocculation, as the turbulence will tend to cause shear forces that will disaggregate or reduce the size of the flocs. A high rate of auto- and bioflocculation contributes significantly to a sludge deposit that can be digested efficiently.

When sludge digestion is fast, as in activated sludge processes, ciliated and flagellated protozoa, as well as bacteria prevail. When the BOD loading is very high or very low, flagellates replace the ciliates, despite the level of oxygen present. When oxygen supply is inadequate, only bacteria are observed in the sludge.

One of the advantages of using conventional surface aerators in a facultative pond is that higher organic loads can be applied. However, the organic load must not exceed the amount of oxygen that can be supplied by the aerator(s) without completely recirculation the pond contents, otherwise the benefits to be derived from anaerobic decomposition will be lost.

The most common cause of sludge accumulation is thermal inhibition. The rate of sludge

decomposition declines with declining temperature and practically ceases at 4C. Under these conditions, sludge deposition exceeds decomposition and sludge accumulates until temperature conditions permit active decomposition.

Nuisance odors seldom occur in ponds when sludge decomposition is totally inhibited. Odor from sludge is frequently a problem when biological and chemical reactions are “slower” than their optimal natural rate.

Partial decomposition of a sludge bed may decrease the pH to a point where the material “pickles” itself. In this case, the pond is said to be “stuck." Recovery from this state requires an effective increase in the pH throughout the sludge bed and rehabilitation of the bacteria colonies.

It is apparent that recirculation of the aerobic and facultative zones, depending on the velocity, enhances BOD reduction, both by expanding the aerobic volume, as well as, promoting more digestible sewage depositing conditions. Recirculation the anaerobic zone upsets that type of bacteria and chemical contribution to BOD removal.

Acid Forming Decomposition

The uncontrolled occurrence of acid formation in heavy sludge deposits built up over a period of time is the primary cause of objectionable odors. The reaction, described by Lackey and Hendrickson,(6) produces carbon dioxide, hydrogen, ammonia, organic acids, and many odorous compounds such as indole, skatol, cadaverin and hydrogen sulfide. Some of these compounds, particularly gases, escape into the atmosphere, and may constitute a severe odor nuisance.

The organic matter in sewage may contain from 5 - 20 ppm of organic sulfur, which if converted entirely into hydrogen sulfide would be a relatively high concentration. Evolution of hydrogen sulfide is not ordinarily a problem in stabilization ponds because the compound dissociates to hydrogen and sulfide ions when in solutions of high pH or because it is oxidized in the presence of molecular oxygen. Hydrosulfide is almost entirely dissociated at pH 8.5, where as only 50% dissociated (and will liberate odors) at pH 7.0. Even an anaerobic pond of pH above 8.5 will not emit odors. Aerobic and facultative ponds of pH 8.5 usually indicates the production of oxygen by algae, which combines readily with hydrosulfide ions, also scrubbing odors from the reactions.

Decomposition of organic matter is not the only source of hydrogen sulfide. Under extreme (stimulated) anaerobic conditions, sulfate-reducing bacteria can become established and carry out a reaction in which sulfate serves as a hydrogen acceptor for bio-oxidation, and hydrogen sulfide is produced. Sulfate reduction is greatly stimulated by the presence of high concentrations of sulfate in the wastewater influent and by a large concentration of organic matter such as might accumulate during low temperature or low pH.

Methane Fermentation

Methane fermentation is a significant factor in sludge digestion. All of the materials which settle to the bottom of a stabilization pond through the various processes of sludge deposition are subject to methane fermentation, provided proper conditions exist or become established. Conditions for methane fermentation are:

- abundance of organic matter being continually converted to fermentable organic acids
- adequate population of methane bacteria
- pH level within the range of 6.5 - 7.5 (preferably 7.0)
- alkalinity in quantities sufficient to buffer the organic acids
- temperatures from 5˚C - 60˚C
- lack of toxic substances
- sustained absence of oxygen

Although not always spontaneously established, should the required conditions exist in the sediments for a sufficient period of time, eventually methane fermentation will become established. When it is, fermentation will contribute significantly to BOD removal. For example, Oswald calculated that each pound of volatile matter destroyed in anaerobic process gives rise to about 15 ft.3 of gases, which set the stage for an indirect measure of oxygen required, or not required in this case, due to the anaerobic digestion process in the sludge bed.

In an experiment, Oswald measured 315 ft.3 of gas evolved per acre which indicates the dissipation of about 33 lbs. of BOD per acre, per day, using the ratio of 1.56 for oxygen required to organic matter oxidized. This experiment shows that the oxygen demand which would otherwise have to be met in the pond through absorption of oxygen from the atmosphere or photosynthesis is diminished to about 1 lb. for each 10 ft.3 of gas evolved. In other words, evidence of methane production is evidence of sludge digestion and a corresponding relief in the demand for oxygen. Small bubbles surfacing in a pond is generally a strong indication of methane fermentation. However, as pointed out earlier, volatile floating sludge that may be soluble will exert an additional demand on DO resources.

If the rate of sludge deposition and accumulation exceeds that of digestion, the sludge will become acid and putrefaction will take place. On the other hand, if a sludge blanket is permitted to accumulate near the pond influent by limiting re-circulation, dissolved oxygen will be absent, and due to its proximity to the entering sewage which is normally warm, a constant and relatively high temperature and a uniform pH will prevail. If such an area is seeded with methane producing organisms, methane fermentation will be initiated in the sludge mass. It will continue, providing loading is neither excessive nor too light. As a result, high BOD removal will be obtained (in the sludge blanket) and the pond will be free of odors.

The Progressive Reaeration and Recirculation Process (PRR™ Process) incorporating the Sunflo2 technology contributes to sludge deposition and digestion through the following functions:

- Gentle circulation and recirculation (1ft/sec. or less), thereby enhancing the conditions for bioflocculation, resulting in efficient precipitation of undissolved, suspended solids for anaerobic digestion.

- Reareation and recirculation of controlled volume thereby establishing and maintaining an aerobic zone of a given depth, resulting in a buffer zone for evolving H_2S gasses, and replacing facultative digestion with aerobic biological activity, while depriving the anaerobic zone of oxygen.

- Surface stripping and renewal, thereby controlling algal growth resulting in stabilized algae-carbonate interactions contributing to pH stability and enhanced conditions for methane fermentation.

Evidence derived from sludge profiles and analyses in ponds prior to the installation of Sunflo2 units compared with data gathered at those sites after one and two years of operation generally support the theoretical concepts and mechanisms described above. Where there were volatile constituents in the sludge, where the sludge had accumulated to depths greater than 12", or where sludge had been rapidly deposited by aggressive mechanical aeration equipment, sludge depths have been reduced by more than 50%. Analyses have indicated greater than 95% reduction of volatile constituents.

If sludge buildup is apparent, typically, Sunflo2 recommends that a sludge profile and analysis be conducted before the number and placement of the units are determined. Sunflo2 treatment of a partially digested sludge bed increases the demand for oxygen that must be accounted for in estimating the oxygen supply for simultaneous treatment of the influent and the sludge. The rate of sludge digestion can be controlled somewhat by the depth setting of the Sunflo2 intake dish and/or by the depth of the water above the sludge bed. As sludge digests, there are attendant odors. Generally, the odor events, resulting from the Sunflo2 treatment of sludge, are short in duration and diminish in frequency and intensity as the sludge is stabilized.

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