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EVALUATION OF LIQUID/SOLID
SEPARATION TECHNIQUES
APPLIED TO SAND-LADEN DAIRY MANURE

presented by

Andrew Walter Wedel

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M.S. degree in Ag. Eng.

William Bickert
Major professor

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EVALUATION OF LIQUID/SOLID SEPARATION TECHNIQUES APPLIED TO SAND-LADEN DAIRY MANURE

By

Andrew Walter Wedel

A THESIS

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ABSTRACT

EVALUATION OF LIQUID/SOLID SEPARATION TECHNIQUES APPLIED TO SAND-LADEN DAIRY MANURE

By

Andrew Walter Wedel

Sand is the bedding material of choice for dairy freestall barns. Although sand possesses many favorable characteristics from a cow health standpoint, it is incompatible with long-term manure storage systems. Separating sand bedding prior to long-term storage would allow the use of conventional manure handling and disposal systems such as irrigation, tanker spreading, and sub-surface injection. An assortment of liquid/solid separation techniques common to wastewater treatment operations as well as the dairy, mining, and petroleum refining industries were applied to sand-laden dairy manure. Separation techniques considered include: i) screening, ii) sedimentation, iii) the hydrocyclone, iv) dissolved air flotation, and v) the belt filter press with polymer conditioning. A sand separator, the batch aerated grit chamber (BAGC), was developed based on the separation techniques previously considered. The BAGC is capable of yielding a dilute manure fraction that can be pumped, stored, and land applied via conventional manure handling techniques, as well as a sand fraction clean enough that it may be reused as bedding.

To my beloved family...Mother, Dad, Kandice, and Kenny.

ACKNOWLEDGMENTS

The date was 30 January 1991. I was studying for a Physics II final exam and faced with a decision; either spend the entire evening studying physics or attend the Cecil County Dairy Night at the Calvert Grange Hall, Calvert, MD, at which I was told the nation's leading expert on dairy facilities from the MSU Department of Agricultural Engineering would be addressing a group of dairy farmers. I opted to forgo studying and attend Dairy Night. Not even in my wildest dreams could I have imagined that such a seemingly inconsequential decision would have a profound impact upon my future, for the speaker that night was Dr. William G. Bickert, my future Major Professor. Thank you Dr. Bickert for granting me the opportunity to study under your guidance. It has been a challenging and truly rewarding experience.

I would also like to thank the following individuals for serving on my guidance committee: Dr. Howard L. Person and Dr. James F. Steffe, MSU Department of Agricultural Engineering; and Dr. Blaine F. Severin, The Michigan Biotechnology Institute (MBI).

I am very appreciative of Dr. Michael Allen, MSU Department of Animal Science, for allowing me access to his laboratory throughout this study as well as David Main and R. Dewey Longuski, for their technical laboratory assistance. Furthermore, assistance afforded to me by the following people proved invaluable: Dr. Dennis Welch and Richard Wolthuis, MSU Dept. of Agricultural Engineering Research Laboratory; George Atkeson, MSU Extension, Ionia County; Jean Steavens and Valerie Geyer, secretaries in the MSU Department of Agricultural Engineering.

I would also like to thank my friends from the MSU Department of Agricultural Engineering and MBI. Their contributions, although oftentimes non-academic, have helped make graduate school an enjoyable experience.

Last but certainly not least I would like to thank DeLynne Anne Vail for her incessant support throughout this study, especially during times when being completely absorbed in my research caused my research to become completely absorbed in me.

Andrew Walter Wedel

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1: Scope of the Industry

As of 1992, there were approximately 338,000 dairy cows in Michigan, a 5.3% decrease since 1988. In 1992, Michigan farms produced 2.5 million kg (5.4 million lb) of milk, a 3.2% increase since 1988. Furthermore, in 1992, milk from Michigan farms accounted for 4.2% of the total U.S. milk production (Michigan Department of Agriculture (MDA), 1993).

A byproduct of milk production is manure. The average 1,400 lb dairy cow produces 52 kg (115 lb) of manure per day (MWPS, 1985) or 18,980 kg (41,980 lb) per year. In terms of the 1992 average milk production per cow of 7,228 kg (15,920 lb) (MDA, 1993), approximately 2.6 mass parts of manure were produced per mass part of milk.

1.2: Statement of the Problem

1.2.1: Purpose of Bedding

Providing an environment conducive to milk production is an essential aspect of dairy herd management. Freestall barns serve this need very well. One aspect of freestall barn management is the implementation and maintenance of an effective freestall bedding material. There is a variety of bedding materials for dairy farmers to choose from including sand, chopped straw, saw dust, or wood shavings. The purpose of bedding is to keep cows free from urine, feces, dripped milk, as well as to act as a comfortable cushion. Hurnick (1981) states that comfortable resting stimulates rumination and thus feed intake, feed conversion efficiency, and milk yield.

1.2.2: Advantages of Using Sand Bedding

In Michigan, it is estimated that sand is used as bedding in more than 50% of the freestall barns (Wedel and Bickert, 1994). Sand is often considered the bedding of choice for freestalls due to a variety of reasons. Sand is an inorganic material that offers little or no nutrients for pathogens since it is not a carbon or nitrogen source (Britten, 1994). Furthermore, Bramley and Neave (1975) report that maintenance of low levels of coliform contamination (less than 10^6/gram bedding) in bedding is the only effective method of mastitis control. Stalls bedded with sand tend to stay drier than those bedded with organic bedding since liquids such as urine and milk are able to infiltrate through the sand (Wedel and Bickert, 1994). Sand improves cow traction in free stall alleys due its abrasiveness (McFarland and Gamroth, 1994). Veterinarians Cox and Marion (1992) used a sand box stall to rehabilitate a cow unable to rise due to a leg injury. They reported that the sand remained free from urine, thus keeping the cow clean, and also provided sure footing while the recuperating cow was attempting to rise.

1.2.3: Disadvantages of Using Sand Bedding

Although sand bedding is very conducive to cow health, it poses significant problems when used in conjunction with long-term manure handling systems. The addition of sand to manure has a negative impact on the physical characteristics of manure. The primary difficulty in handling sand-laden dairy manure (SLDM) is the inability to obtain a homogeneous mixture even during extended agitation. When earthen manure pits are employed, extensive agitation has the potential to cause pit liner damage. If pumping out occurs while the sand is not suspended, only some sand, manure solids, and liquid are removed. If this process is repeated, the sand and manure solids that remain will eventually decrease the storage capacity. From a machinery standpoint, sand is detrimental to moving parts, thus requiring repair and maintenance at shorter time intervals. Pump housings and impellers often require replacement or rebuilding on a yearly basis.

1.3: Approach to the Problem--Sand Separation

One way to facilitate the use of bedding sand in conjunction with a long-term manure handling system is to separate the sand from the manure prior to long-term storage. A sand separator capable of yielding a sand-free manure fraction offers a number of manure handling options associated with long-term storage which are currently not recommended due to the presence of sand. Furthermore, a sand separator capable of yielding reusable sand could offset bedding costs and aid in offsetting the cost of a separator.

Currently, in wastewater treatment operations as well as the dairy, mining, and petroleum refining industries, there exists an assortment of liquid/solid separation and agitation systems. The applicability of these systems to SLDM is investigated. Concepts employed in these systems may offer insight into developing a unique and effective sand separation system.

1.4: Objectives

At the present time, a device specifically designed to separate bedding sand from dairy manure is not commercially available. Therefore, the objectives of this study are as follows:

1. Evaluate some of the physical characteristics of sand-laden dairy manure relevant to handling, treatment, and storage.
2. Evaluate the performance of existing liquid/solid separation techniques.
3. Develop a separator capable of yielding: i) a sand fraction, clean enough that it may be reused as bedding, and ii) a dilute manure fraction, free from sand, that can be pumped, stored, and land applied via conventional manure handling techniques.

1.5: Organization of the Thesis

Chapter 2 describes liquid/solid separation and agitation systems employed in wastewater treatment operations, as well as the dairy, mining, and petroleum refining industries. Chapter 3 describes the laboratory methods used to test SLDM physical characteristics as well as its individual components (sand and manure). The procedures used to test existing sand separation systems are also presented. Chapter 4 offers the results of the tests performed in Chapter 3 and a discussion of the results. Chapter 4 also presents the development and the results of testing a novel sand separation technique. Chapter 5 summarizes the study and offers conclusions.

CHAPTER 2
LITERATURE REVIEW

2.1: General Comments

In wastewater treatment operations as well as the dairy, mining, and petroleum refining industries there exists a host of liquid/solid separation and agitation techniques that may be directly applied to separating sand from dairy manure. Separation systems considered include: i) screening, ii) sedimentation, iii) the hydrocyclone, iv) dissolved air flotation, and v) the belt filter press with polymer preconditioning. Applications of aeration which may be directly applicable to separating sand from dairy manure, such as the pachuca tank and air-lift pumping, are also investigated.

2.2: Screening

Screening is a technique that separates particles on the basis of size differences. Stationary and vibrating screens are commonly used in the dairy industry to separate organic solids from dilute manure slurries (Merkel, 1981 and Schutt et. al., 1972). In the mining industry, screening is used to classify aggregates (Taggart, 1945). In wastewater treatment, coarse screens are used to remove large debris such as pieces of wood, plastic materials, and rags from wastewater influent (Reynolds, 1982).

2.2.1: Stationary Screens

Figure 2.1 is a schematic diagram of a stationary screen. Stationary screens operate by allowing manure to flow over an inclined sloping screen. Liquids pass through the screen and the manure solids are retained. As the solids collect on the screen, they slowly slide downward due to gravity and the suction created behind the screen by the flowing liquid (Merkel, 1981). Some difficulties are experienced with clogging due to film formation on the screen. The problem is remedied by periodically cleaning the screen by brushing away the film.

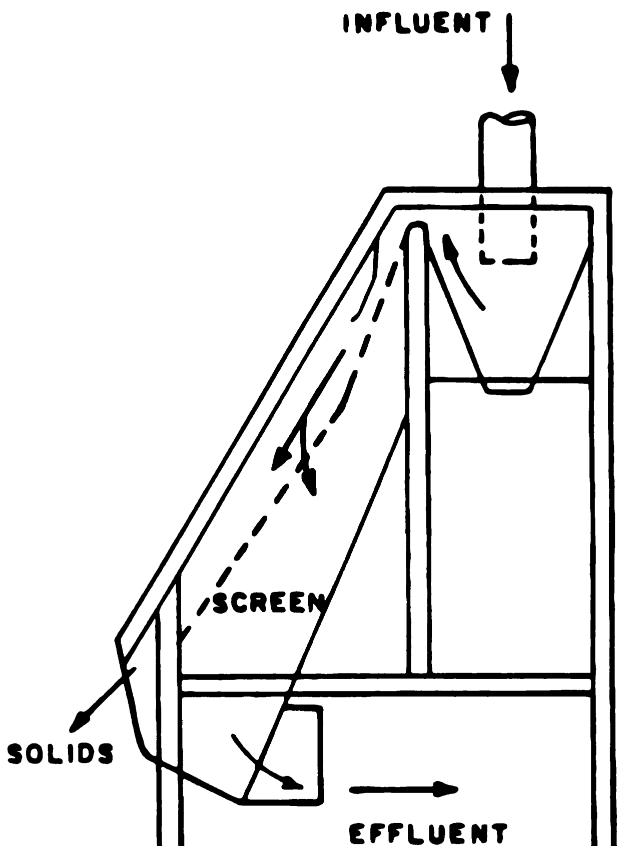

FIGURE 2.1: Stationary Screen Schematic (Shutt et al., 1972).

2.2.2: Vibrating Screens

Vibrating screens (Merkel, 1981 and Schutt et al., 1972) operate similarly to stationary screens due to the fact they both separate solids from liquids on the basis of particle size. The primary difference between vibrating and stationary screens is that, as the name implies, vibrating screens are subjected to reciprocal shaking in order to encourage solids to move across the screen, thereby reducing clogging. Figure 2.2 is a schematic diagram of a vibrating screen.

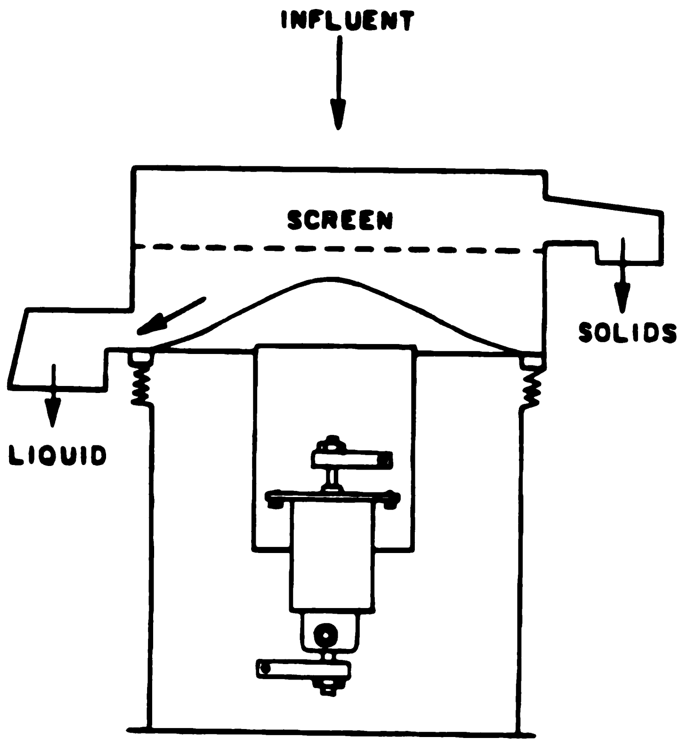

FIGURE 2.2: Vibrating Screen Schematic

2.3: Sedimentation

A number of sand separation devices function on the basis of settling, such as aerated grit chambers and sedimentation basins. The principles of sedimentation also apply to the classification of the settling behavior, under quiescent conditions, of raw manure and SLDM. Therefore, a general discussion pertaining to sedimentation theory is pertinent to this thesis. Sedimentation theory is presented in most journal articles pertaining to removing grit (sand) from sewage (Camp, 1946, Kivell and Lund, 1940, Tark and Gilbert, 1940) as well practically all environmental engineering texts (Davis and Cornwell, 1991, Metcalf and Eddy, Inc., 1979, and Reynolds, 1982).

Sedimentation is the separation from water, by gravitational settling, of suspended particles that are heavier than water (Metcalf and Eddy, 1979). Reynolds (1982) states that sedimentation is used extensively in wastewater treatment for grit (sand) as well as silt removal. Consider the free-body diagram of a discrete particle settling in a quiescent fluid (Figure 2.3). When a particle is released in a still fluid, it will accelerate until the drag force (upward) plus the buoyant force (upward) equals the weight of the particle (downward) and the buoyant forces (downward). At which time, the particle has reached its terminal or settling velocity. Assuming spherical, discrete particles and a Reynolds number less than 0.3, Stokes' law,

$$V_s = \frac{g(\rho_s - \rho_m)d_s^2}{18\mu} \quad [2.1]$$

where: v_s = terminal settling velocity of a discrete particle, m/s

d_s = diameter of settling particle, m

g = acceleration due to gravity, 9.81 m/s^2

ρ_s = density of settling particle, kg/m^3

ρ_m = density of medium, kg/m^3

μ = dynamic viscosity of medium, Pa s

is used to calculate terminal settling velocity. See Davis and Cornwell (1991), Metcalf and Eddy (1979), or Reynolds (1982) for the derivation of Stokes' law.

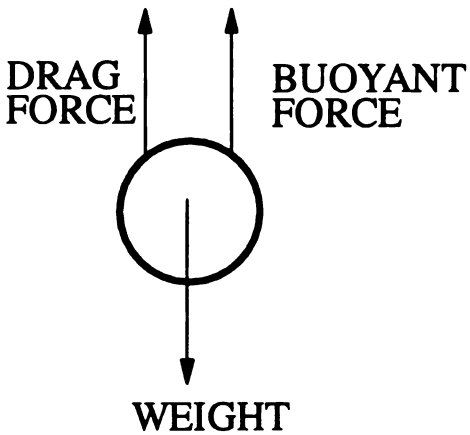

FIGURE 2.3: Force Balance About a Particle Settling in a Quiescent Fluid.

There are four different classes of settling: i) discrete, ii) flocculant, iii) hindered, and iv) compression (types 1, 2, 3, and 4, respectively). To complicate matters, all types of settling phenomena may occur simultaneously. See Table 2.1 for a description of the four types of settling phenomena.

2.3.1: Continuous Flow Aerated Grit Chamber (CAGC)

CAGC's are used to remove grit, sand, cinders and other inorganic materials from municipal wastewater in order to prevent excessive wear on pumps, comminutors, and settling tank scrapers. Furthermore, if allowed to enter a wastewater treatment plant, grit will settle in piping, clarifiers, and digesters, resulting in the need for frequent and expensive cleaning.

A CAGC consists of either a circular or rectangular concrete tank with air diffusers positioned 0.45 to 0.6 m (1.5 to 2 ft) above the bottom of the tank (Metcalf and Eddy, 1979). Figure 2.4 is a schematic diagram of a CAGC. Typical design data are presented in Table 2.2. A CAGC operates as follows: i) influent wastewater containing water, organic matter, and grit enters the tank (into the cross-section depicted in Figure 2.4) and flows in a circular or rolling pattern, ii) grit settles out of the 'roll' as organic material is suspended and carried out of the tank, iii) grit accumulates in the grit hopper and is removed from the tank via air-lift, screw conveyors, or grab buckets, and iv) effluent containing water and suspended organic matter flows out of tank. Flow into and out of the chamber is in a direction perpendicular to the rolling motion. Influent and outfluent conduits are located on opposite ends of the tank.

CAGCs are capable of removing sand particles as small as 0.2 mm (0.008 in). The velocity of the tank roll is crucial to effective grit removal. Data indicate that a velocity of 0.23 m/s (0.75 fps) is required to move a 0.2 mm sand particle along the tank bottom toward the grit trap (see Figure 2.4) (Kappe and Neighbor, 1950). In addition, a vertical fluid velocity of 1.8 m/s (6 fps) is necessary to elevate sand particles. Therefore, this should be considered the absolute maximum roll velocity since, if the roll velocity exceeds 1.8 m/s, sand particles are carried

TABLE 2.1: Types of Settling Phenomena in Wastewater Treatment (Metcalf and Eddy, 1979).

Type of Settling Phenomenon	Description	Application
Discrete particle (type 1)	Refers to the sedimentation of particles in a suspension of low solids concentration. Particles settle as individual entities, and there is no significant interaction between particles (Stokes' law).	Removal of grit and sand
Flocculant (type 2)	Refers to dilute suspensions of particles that coalesce, or flocculate, during the sedimentation operation. By coalescing the particles increase in mass and settle at a faster rate than would an individual particle.	Removal of chemical floc
Hindered, also called zone (type 3)	Refers to suspensions of intermediate concentration, in which interparticle forces are sufficient to hinder the settling of neighboring particles. The particles tend to remain in fixed positions with respect to each other. The mass of the particles settle as a unit. A solids-liquid interface develops at the top of the settling mass.	Occurs in secondary settling facilities used in conjunction with biological treatment facilities (activated sludge).
Compression (type 4)	Refers to settling in which the particles are of such concentration that a structure is formed and further settling can occur only by compression of the structure. Compression takes place from the weight of the particles, which are constantly being added to the structure by sedimentation from the supernatant liquid.	Usually occurs in the lowest layers of a deep sludge mass, such as in the bottom of secondary settling facilities.

TABLE 2.2: Typical Aerated Grit Chamber Specifications (Metcalf and Eddy, 1979)

Item	Range
Dimensions:	
Depth, m	2-5
Length, m	7.5-20
Width, m	2.5-7.0
Width to depth ratio	1:1-5:1
Detention time at peak flow, min	2-5
Air supply, m^3/(min*m of length)	0.15-0.45

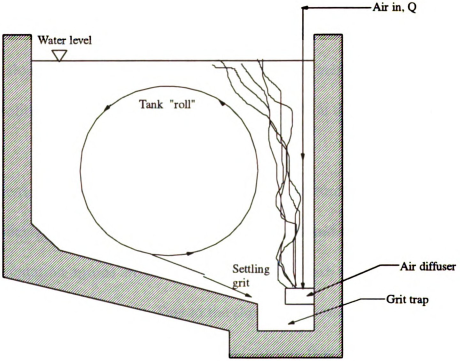

FIGURE 2.4: Cross-sectional view of a continuous-flow aerated grit chamber.

out of the tank. Also, from data it has been determined that air supplied at a rate of 280 L/min per meter (3 cfm per foot) of tank length creates a flow velocity of 0.6 m/s (2 fps) (Kappe and Neighbor, 1950).

2.3.2: Sedimentation Basins and Aprons

Sedimentation basins (Figure 2.5), when used in conjunction with a flush manure handling system, are commonly used to separate sand from manure. Sand settles in the basin as the scouring (horizontal) velocity along the floor slows to less than 0.3 m/s (1 fps) (Fairbank, et al., 1984). The liquid fraction passes through a vertical porous dam with 1.3 cm (0.5 inch) spacing and into an additional pit. A skimmer board may be placed before the vertical porous dam to retain any floating solids. The walls of the sedimentation basin are constructed of concrete and slope inward to enable front-end loaders to enter and remove the sand and manure solids. These basins have a hydraulic detention time of approximately four days.

Sedimentation aprons (Figure 2.6) are similar structures except they are conceptually designed to settle out solids from lot runoff and milking center wash water. Sedimentation aprons are designed to retain the wash water from one milking for no less than one hour. Due to the short detention time, sedimentation aprons lack the capacity to handle the water and manure from flush systems.

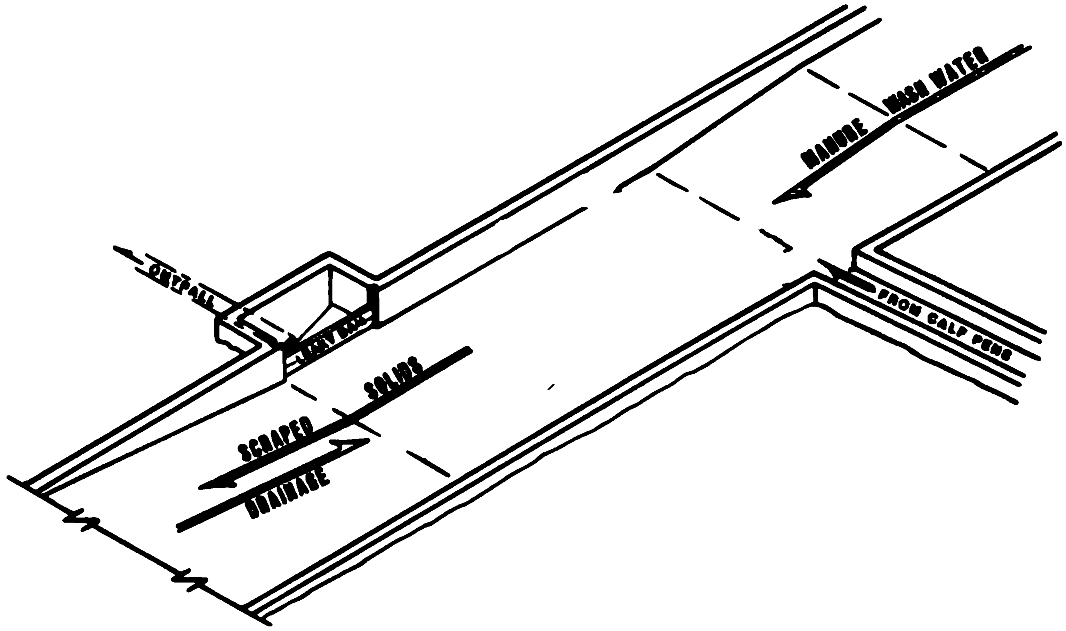

FIGURE 2.5: Sedimentation Basin (Fairbank et al., 1984).

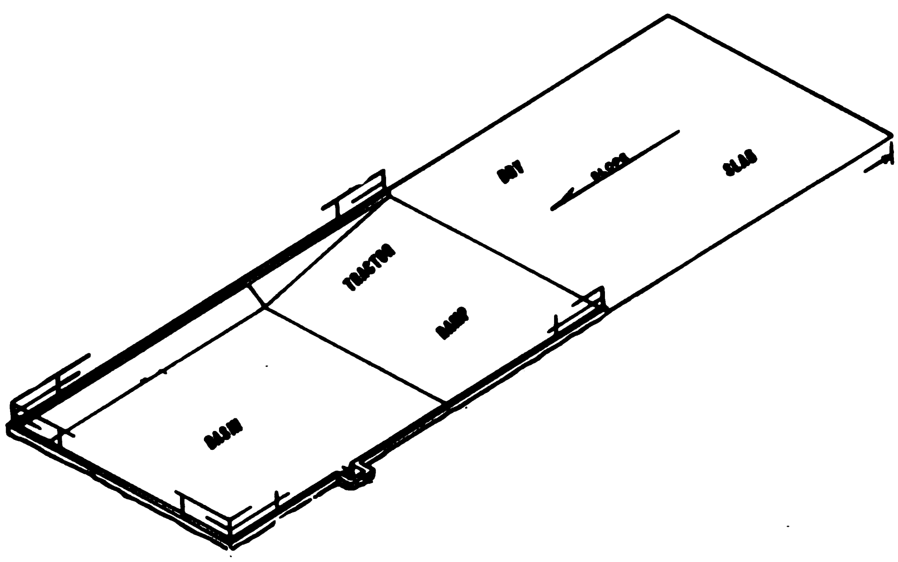

FIGURE 2.6: Sedimentation Apron (Fairbank et al., 1984).

2.4: Hydrocyclones

A hydrocyclone is a device which separates solid particles on the basis of differences in specific gravity between particles and a carrier fluid. Hydrocylones are used extensively in mining operations to separate organic slimes from fine aggregates (sand). Hydrocyclones are also used to degrit sludge in wastewater treatment plants where grit chambers are not used, or where grit removal capability is exceeded at peak flow (Metcalf and Eddy, 1979). Metcalf and Eddy (1979) note that cyclone separation is the most effective method of degritting sludge.

Figure 2.7 is a schematic diagram of a hydrocyclone. A hydrocyclone functions as follows: i) a dilute suspension of solid particles is pumped tangentially into the top of the hydrocyclone cylinder, thus subjecting the solid particles to centrifugal force, ii) particles with relatively higher specific gravities such as grit are forced to the walls of the hydrocyclone and exit through the lower opening, or underflow, and iii) particles of relatively lower specific gravities such as organic solids remain in the center, or inner spiral of the hydrocyclone and, in addition to water, are forced out of the upper opening, or overflow.

Currently, on a commercial dairy, a hydrocyclone separator is being used to separate sand from dairy manure. Theoretically, hydrocycloning lends itself well to separating sand from manure since the specific gravity of sand is approximately 2.5 times the specific gravity of manure. However, in order for a hydrocyclone to operate effectively, the solids feed concentration must remain constant or separation efficiency will fluctuate (Metcalf and Eddy, 1979).

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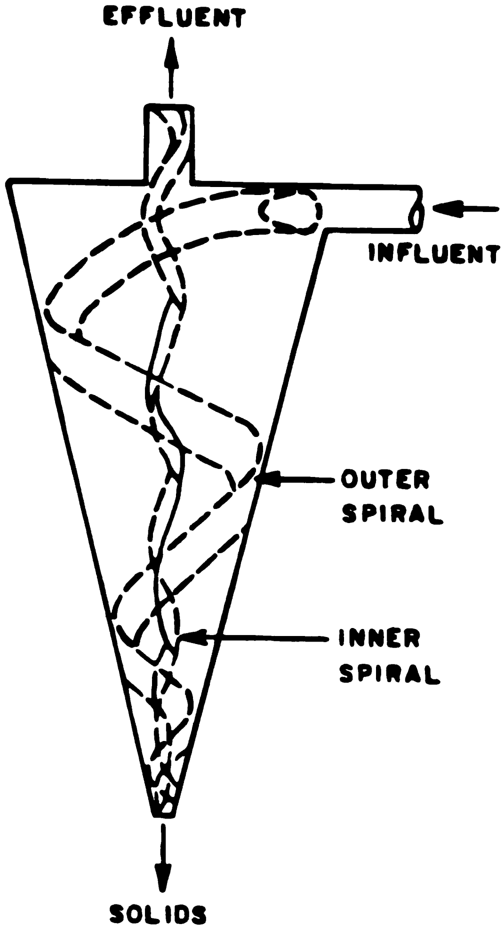

FIGURE 2.7: Hydrocyclone Schematic (Schutt et al., 1972).

2.5: Dissolved Air Flotation (DAF)

Dissolved air floatation (DAF) systems are used to separate low density solid or liquid particles from liquid (Reynolds, 1982). This type of liquid/solid separation system is utilized extensively in water and wastewater treatment operations, primarily to thicken sludges and/or remove oil emulsions. In a DAF system (Figure 2.8), the entire waste stream is pressurized to, and held at 275 to 350 kPa (40 to 50 psig) for several minutes, causing air bubbles to become dis

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dissolved in the liquid. The air saturated mix is then released via a pressure reducing valve into a flotation tank at atmospheric pressure in which the air comes

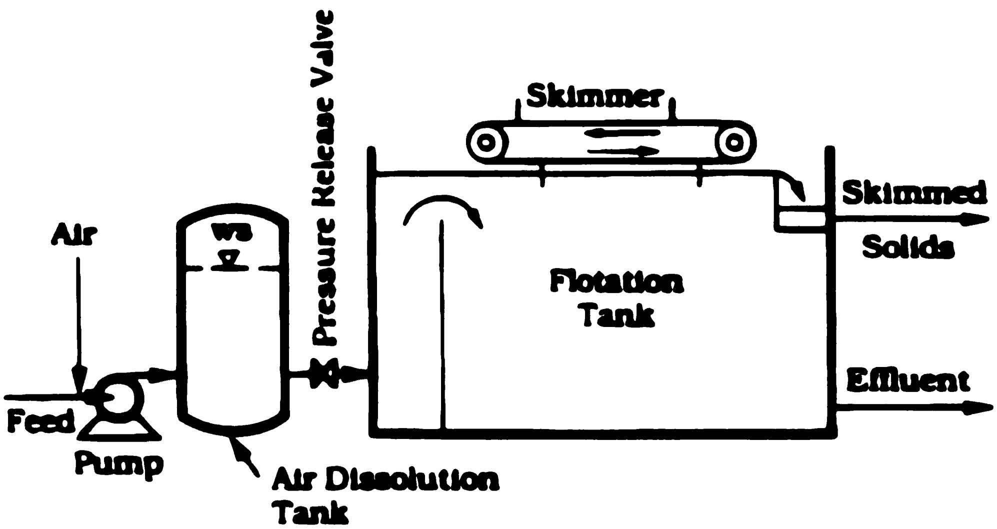

FIGURE 2.8: Dissolved Air Flotation System--Entire Flow Pressurization (Reynolds, 1982).

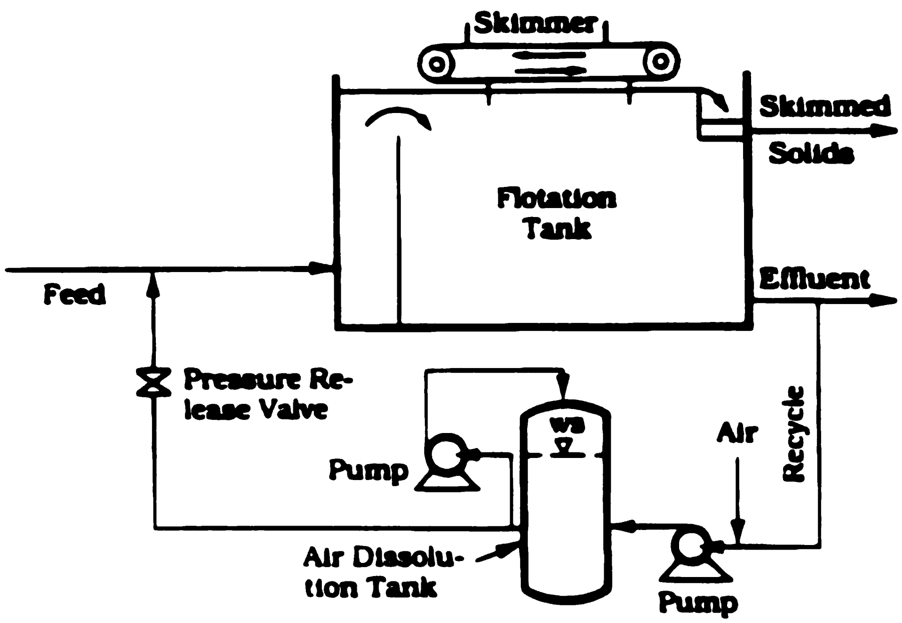

FIGURE 2.9: Dissolved Air Flotation (DAF)--Recycled Flow Pressurization (Reynolds, 1982).

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out of solution in the form of minute bubbles. As the bubbles rise they become attached to solid particles causing them to float to the top of the tank. The floating solid mat is removed from the top of the tank by a mechanical skimmer mechanism. The entire DAF process may be enhanced by polymer preconditioning the inflow

A variation of this system (Figure 2.9) is the recycled flow pressurization method in which, instead of pressurizing the entire feed flow, part (5 to 10%) of the effluent is diverted to a pressurization tank prior to being released back into the flotation tank. The remainder of the system functions the same as the entire waste stream pressurization method.

2.6: Belt Filter Press (BFP) With Polymer Conditioning

The purpose of a belt filter press (BFP) (Figure 2.10) is not to degrit sludge, but instead to dewater sludge. Prior to the actual dewatering operation it is necessary to condition the sludge. The object of sludge conditioning is to coagulate the solid particles into larger masses, or flocs. Detailed accounts of coagulation chemistry are presented by Davis (1991) and Metcalf and Eddy (1979). Coagulation is enhanced by the addition of coagulants such as polymers. Typically, solid particles in wastewater are repelled due to their surface charges. The object of coagulation is to reduce the surface charge to a point where the particles are no longer repelled from each other. Since the colloids are negatively charged, the addition of coagulant aids such as cationic polymers cause a reduction of surface charge.

Polymers are long-chain anionic, cationic, or polyamphotype (no charge) organic compounds of high molecular weight that have many active sites. The active sites adhere to the flocs, thus joining them together. Polymer type and

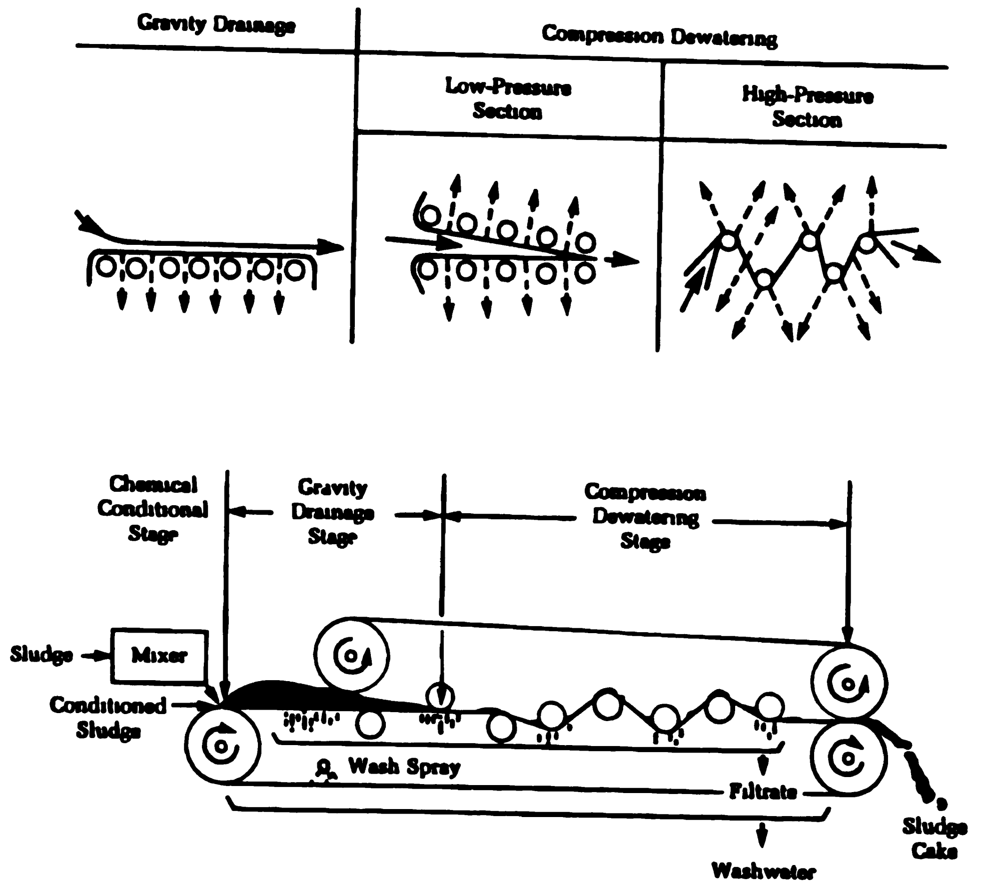

FIGURE 2.10: Belt Filter Press Schematic (Davis and Cornwell, 1991).

dosage vary based on the individual wastewater, as well as on a seasonal basis (Davis and Cornwell, 1991).

The belt filter press consists of two continuous and converging belts. In addition to preconditioning, a BFP operation consists of two zones: i) draining and ii) compression (Davis and Cornwell, 1991). In the first zone, the sludge is allowed to drain by gravity. The sludge then enters the compression zone where pressure is applied to the sludge due to the converging belts. The belts continue to converge, resulting in increased pressure being applied to the sludge. A wash spray is also applied to the lower belt in order to remove solids and, therefore, prevent belt clogging. As the sludge cake exits the converging belts, it is removed by a scraper. Reynolds (1981) notes, when applied to raw primary sludge, a belt filter press in conjunction with polymer conditioning is capable of yielding sludge cakes of 28 to 44 percent dry solids.

2.7: Aeration

Aeration has long been used in industry for the purpose of agitation and mixing. It is most commonly used with slurries which posses high solids concentrations and are either abrasive or corrosive in nature. Besides for industrial applications, aeration has also been used to agitate harbors and channels in the winter to prevent freezing (Railsback, 1992). In addition to agitation and mixing, aeration is capable of promoting aerobic biological decomposition of organic matter and removal of odors and toxic gasses (Szabo, 1971).

2.7.1: Aeration Applications

2.7.1.1: Mining Industry

The Brown or pachuca tank is an example of aeration applied to the mining industry. In the mining industry pachuca tanks are used to: i) suspend solids, ii) scrub films from solid particles, and iii) aerate pulp. In South Africa, pachuca tanks are used for leaching (purifying) gold ores, a process which takes advantage of each application mentioned above (i-iii). In Canada, pachuca tanks are used for acid leaching of Uranium ores. In the acid leach process, aeration is used to suspend solids. Pachuca tanks are very desirable for this operation since there are no moving parts exposed to the acid pulp (Lamont, 1958). Pachuca tanks are circular vessels with conical bottoms. The mineral processing literature lacks typical design values (diameter, depth, and air flow rate) for pachuca tanks. However, Lamont (1958) refers to a tank 13.7 m (45 ft) deep and 6.9 m (22.5 ft) in diameter, operated at 8,500 L/min (300 cfm) of air. The tank was being used to agitate a suspension with a specific gravity equal to 1.6. Typically, the included angle of the conical bottom is 60 degrees. Air is introduced at the apex of the conical bottom. The purpose of the conical bottom is to redirect settled solids into the upward flowing fluid so that they may be returned to the top of the tank (resuspended) (Lamont, 1958). Figure 2.11 shows four different pachuca tank configurations: i) full-center column, ii) full-center column, with shallow air introduction, iii) stub-column tank, and iv) free-airlift tank.

The BAGC proposed in this thesis is an example of a free-airlift pachuca tank (iv). Based on an analysis of energy transfer in pachuca tanks, Lamont (1958) states that the full-center column (i) and the stub-column (iii) configurations are superior to the free-airlift tank (iv) since they are both capable of developing higher pulp flow rates at tank bottoms.

An additional application of the airlift principle is the airlift pump. They are commonly used in the petroleum industry to clean materials such as boring debris from around oil well heads. Some characteristics of airlift pumps which render them desirable for this type of operation are: i) good reliability (minimal equipment needed-only a dependable air compressor), ii) low maintenance

requirements (few or no moving parts), and iii) the ability to handle hazardous materials safely (Vargas, 1992).

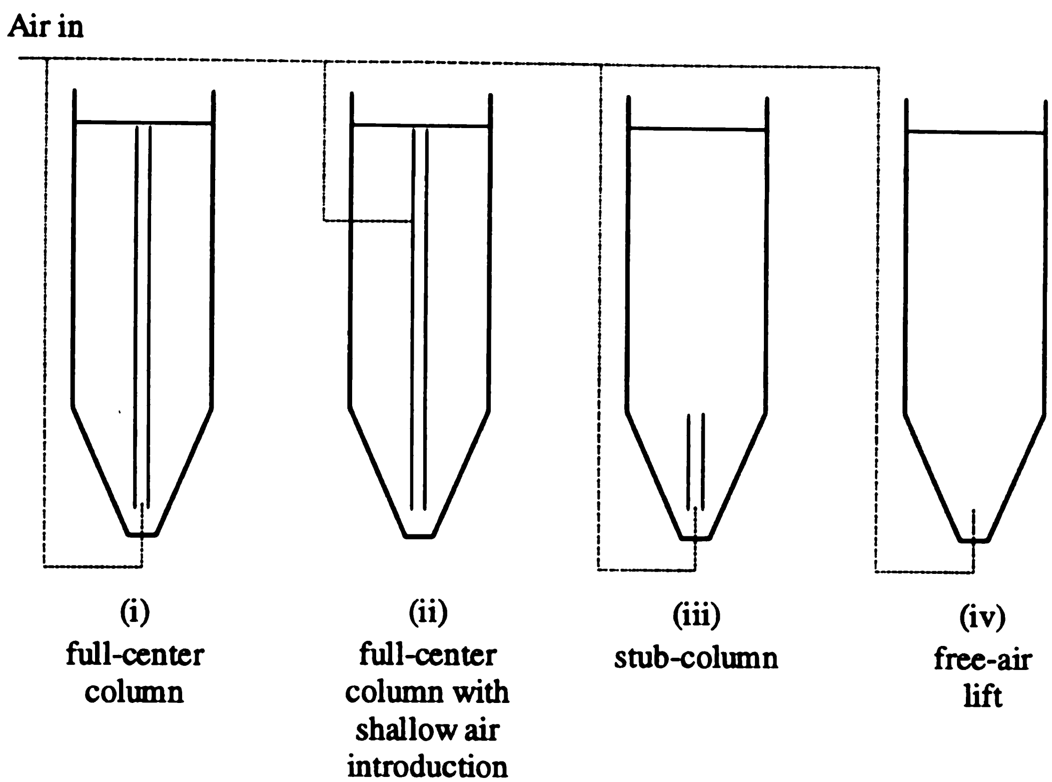

FIGURE 2.11: Pachuca Tank Configurations (Lamont, 1958).

Figure 2.12 is a schematic diagram of an airlift pump, which consists of a vertical tube partially submerged in liquid and an air pipe connected near the bottom of the vertical tube. An airlift pump works as follows: i) air is pumped via compressor and air pipe into the bottom of the vertical tube, ii) air mixes with the slurry, decreasing its bulk density, and iii) the air-liquid-solid mixture moves upward in slug flow and is discharged above the liquid surface.

For this application, the lift and air supply pipes were 15 cm (6 in) and 4 cm (1.5 in), respectively. In order to raise the slurry to the required height (H_S + H_L) of 60 m (200 ft) a 256 kW (343 hp) air compressor was required.

Compressed air for agitation plays an important role in the refinement of petroleum products (Kaufman, 1930). In the refining process, air is used for blending of light oils, kerosene, and gasoline.

Kaufman (1930) concludes that increased agitation is achieved with deep rather than shallow tanks using the same air flow rate for each case. This is due to the fact that agitation is caused by the expansion of rising air and the speed at which the air rises. Both of these factors are greater in deep rather than shallow tanks. In a specific example, the author notes that in order to achieve the same degree of agitation in both a 0.91 m (3 ft) and a 2.7 m (9 ft) deep tank, the shallow tank would require twice the air flow compared to the deep tank. For this study, the author neglects to indicate tank geometry other than height.

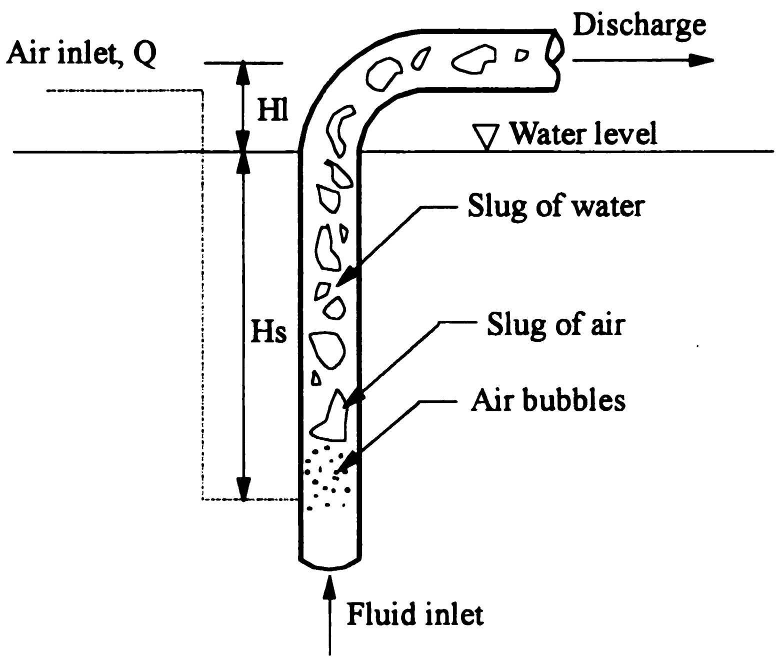

FIGURE 2.12: Airlift Pump Schematic (Vargas, 1992).

2.7.2: Aeration Modeling

2.7.2.1: Mixing intensity

Mixing is an essential aspect of water and wastewater treatment operations. Some operations require a certain regulated degree of agitation. A measure of mixing intensity, or velocity gradient (G), was developed by Camp and Stein (1943). Velocity gradient or G, depends upon: i) the amount of power dissipated by the fluid, ii) the volume being agitated, and iii) the fluid viscosity. The equation for the velocity gradient in mechanically or pneumatically agitated vessels is

$$G = \sqrt{\frac{P}{\mu V}} \quad [2.2]$$

where: G = Velocity gradient or mixing intensity, s^{-1}

P = Input power, W

μ = Dynamic viscosity, Pa s

V = Active volume, m^3

The velocity gradient is related to the shear forces in a fluid. Therefore, large velocity gradients produce high shear forces which, in turn, result in a high degree of agitation. For instance, to preserve water softening floc, relatively low velocity gradients are required in order to minimize the shearing effect between the fluid and the floc, as well the rate of particulate collisions. The operation of air agitated tanks is most economical when velocity gradients range between 30 and $300 s^{-1}$ Szabo (1971).

Mixing may also be characterized by Gt (dimensionless), the product of the velocity gradient and detention time. The values G and Gt may be related to the number of particle collisions per unit time and the total number of particle collisions in a vessel, respectively (Reynolds, 1981). Typical G an Gt values for a variety of water and wastewater treatment operations are reported by Davis and Cornwell (1991).

2.7.2.2: Power Dissipation

Knowing the amount of power dissipated in air induced mixing and agitating is useful in appropriately sizing air supply units. The following equation is used to calculate the power dissipated by rising bubbles in pneumatic mixing and stirring Reynolds (1982); the derivation of which can be found in (Fair et al., 1971)

$$P = 1.689Q \ln\left(\frac{H+10.33}{10.33}\right) \quad [2.3]$$

where: P = Power dissipated by air bubbles, W

H = Height of fluid over air discharge point, m

Q = Air flow rate, L/min

From this equation, it is evident that power dissipated, P is directly proportional to the natural logarithim of the height of fluid over the air discharge point, H and air flow rate, Q.

2.7.2.3: Agitation Time

Machina and Bewtra (1987) conducted an extensive study of bulk mixing using diffused air in circular and rectangular vessels. The circular vessels were 1.5 m (5.0 ft) in diameter and fluid depth was varied from 0.45 to 1.1 m (1.5 to 3.5 ft). Dimensional analysis was used to obtain the following equation for agitation time required to achieve m-percent uniformity of dye and salt solutions in circular vessels.

$$t_m = 117 + \frac{14,900}{G} - 210\frac{H}{D} \text{ ....}$$

where: t_m = Mixing time required to achieve m-percent uniformity, s

G = Mixing intensity, s^{-1}

D = Vessel diameter, cm

H = Depth of air inlet, cm

The authors note that the most cost effective air agitation system is one which minimizes mixing time, t_m and G. Therefore, the dimensionless parameter Gt_m should be minimized. As expected, percent uniformity increased with mixing time.

2.7.2.4: Pick-Up Velocity and Gas Bubble Dynamics

Recognizing that dimensional analysis is the most common approach used to determine the suspension characteristics of solid-liquid mixtures in mechanically agitated vessels, Narayanan et al. (1969a) derived an analytical expression for pick-up velocity, or the minimum fluid velocity required to elevate a particle. The author states that an equation for pick-up velocity based on fluid dynamics and vertical transport phenomena would be more rigorous than one derived empirically from dimensional analysis.

Once again, considering a force balance analysis about a solid particle, this time in a vertically flowing medium, the minimum fluid velocity required to initiate the suspension of a solid particle is

$$V_P = \left\{ 2g(\rho_P - \rho_M)\left[\frac{2d_P}{3\rho_M} + \frac{H_S H_H}{\rho_P + H_S\rho_L}\right]\right\}^{1/2} \text{ .... [2.5]}$$

where: d_p = Particle diameter, cm

g = Acceleration due to gravity, 981 cm/s^2

H_H = Fluid depth, cm

H_S = Mass basis solids concentration, unitless

ρ_M = Density of fluid medium, g/ml

ρ_S = Density of suspended particle, g/ml

V_P = Fluid pick-up velocity, cm/s

This equation assumes no slip between the particle and the fluid. But when dealing with solids of high density, the slip between the two phases is inevitable (Narayanan, et al., 1969b). Even dilute SLDM slurries possess high concentrations of particles of high density (sand), flowing in a medium composed of concentrated low-density solids (manure). Therefore, the analytical equation for pick-up velocity is not applicable to SLDM slurries.

2.7.2.5: Summary of Aeration Tank Design Considerations

1. Pneumatic agitation and separation systems are ideal for slurries which posses high solids concentrations and are either abrasive or corrosive in nature.

2. Deep, instead of shallow tanks are preferred since, as bubbles rise, they also expand. The result is a higher degree of agitation.

3. For the most economical operation of aeration tanks, design G-values should range from 30 to 300 s^{-1}.

CHAPTER 3
EXPERIMENTAL METHODS

3.1: General Comments

This chapter is dedicated to describing the experimental methodology used to test an assortment of sand separation systems as well as the physical properties of sand and manure samples. Initially, the standard analytical techniques used to determine physical properties such as total solids (TS), organic or volatile solids (VS), and sand content (S) are discussed. These analytical techniques were then used throughout the study to evaluate the efficacy of the separation systems considered.

3.2: Standard Techniques and Procedures

The experimental procedures used to determine total solids TS, VS, and S were adopted from Van Soest and Robertson's (1985) guide to analyzing the physical and chemical properties of forages. These methods are described as a "hot basis" analyses since all mass measurements are performed on hot samples, as opposed to a cool basis method in which samples are cooled in a desiccator prior to weighing.

3.2.1: Hot Weighing Samples

The "hot basis" technique is preferred over the "cool basis" technique in which a desiccator is used to cool samples prior to weighing, since it decreases the possibility of samples gaining additional moisture from the atmosphere and/or faulty desiccant.

3.2.1.1: Materials

The following equipment is required for hot weighing samples:

American Scientific Products Constant Temperature Oven (±1 ^{o}C)
Mettler AE 200 Balance ±0.0001 g
Lotus Measure data acquisition program
IBM PS2/Model 20 computer
50 ml beakers

3.2.1.2: Methodology

The procedure for hot weighing samples includes the following steps: i) empty 50 ml beakers, stored in the drying oven, are weighed on a the Mettler AE 200 Balance, ii) the balance is tared in order to take into account any moisture the beaker may have absorbed from the atmosphere, iii) samples are placed in the 50 ml beakers and the mass ($m_{initial}$) each is recorded. All data is recorded using the Lotus Measure data acquisition program. After placing a sample on the balance pan, the Lotus Measure program records the sample weight twenty times and then stores the minimum value. The beaker is then removed from the pan and Lotus M1easure records the average of twenty tares. The minimum sample weight is then corrected using the average tare.

3.2.2: Dry Matter Content (TS)

Total solids content (TS) is a measure of the dry matter remaining after drying a sample to equilibrium at 106 ^{o}C. TS is directly related to moisture content in that the sum of the TS and moisture content equal 100% (Sobel, 1966).

3.2.2.1: Materials

The equipment required for TS analyses is identical to that which is required for hot weighing.

3.2.2.2: Methodology

The procedure for determining TS is as follows, i) samples are weighed out into 50 ml beakers using the hot weigh method, ii) samples are allowed to dry at

106 ^{O}C for 12 hours, and iii) the masses of the dried samples are then recorded using the hot weigh method. The TS of a sample is a ratio of the mass of the solid material remaining after drying, over the initial mass of the sample (wet), or

$$TS = \frac{m_{dry}}{m_{initial}} * 100 \qquad [3.1]$$

where: TS = Total solids content, %

m_{dry} = sample mass after drying at 106°C, g

$m_{initial}$ = initial (wet) mass of sample, g

3.2.3: Fixed Solids (FS) and Volatile Solids (VS) Content

Total solids are composed of both fixed (FS) and volatile solids (VS). The FS, or inorganic matter content, is a measure of the material remaining after igniting a sample at 500 ^{O}C. Similarly, the VS, or organic matter content, is a measure of sample weight loss after ignition.

3.2.3.1: Materials

The equipment required for this analysis is the same as that which is required for hot weighing, and TS determination with the exception of a muffle furnace capable of attaining a temperature of 500 ^{O}C. For this study the following muffle furnace was used:

Thermolyne Type 30400 Furnace (±1 ^{O}C)

3.2.3.2: Methodology

The experimental procedure for determining FS or VS (Van Soest and Robertson, 1985) is the following: i) hot weigh and dry samples as previously outlined, ii) ignite samples in Thermolyne muffle furnace at 500 ^{O}C for six hours (complete ignition), iii) record sample mass after ignition using the hot weigh method. The ashes that remain after ignition are the fixed solids. The FS of a sample can be expressed as:

$$FS = \frac{m_{ash}}{m_{initial}} * 100 \quad [3.2]$$

where: FS = Fixed (inorganic) solids, %

m_{ash} = sample mass after ignition at 500°C, g

$m_{initial}$ = initial (wet) sample mass, g

Conversely, the VS of a sample is the weight loss after ignition over the original mass of the sample prior to drying (wet),

$$VS = 1 - \frac{m_{final}}{m_{initial}} * 100 \quad [3.3]$$

where: VS = Organic or volatile solids, %

m_{ash} = sample mass after ignition at 500°C, g

$m_{initial}$ = initial (wet) sample mass, g

Recognizing the relationship between TS, FS, and VS,

$$TS = FS + VS \quad [3.4]$$

VS can also be expressed as

$$VS = TS - FS \quad [3.5]$$

Note that in this instance, FS, and VS are calculated on a wet basis. To convert VS to dry basis simply divide VS by TS,

$$VS(db) = \frac{VS}{TS} * 100 \quad [3.6]$$

where: VS(db) = Dry basis volatile or organic solids content, %

3.2.4: Sand Content (S):

Sand content (S) is a mass basis measure of the amount of sand contained in a sample. In the previous analysis, the total amount of fixed solids in a sample was determined. However, in the case of SLDM, both sand and manure contribute to the fixed solids. For SLDM the FS mass balance can be expressed as:

$$FS_T = FS_{manure} + FS_{sand} \quad [3.7]$$

where: FS_T = Sum total of fixed solids, %

FS_{manure} = Fixed solids of manure component, %

FS_{sand} = Fixed solids of sand component, %

Therefore, in order to determine S, a test capable of distinguishing between FS_{manure} and FS_{sand} is required. The analyses used in this study assume that the sand is free from organic matter. Therefore, FS_{sand} is equal to S. An acid digestion procedure outlined by Van Soest and Robertson (1985) was used to distinguish between FS_{manure} and FS_{sand}. The goal of the acid digestion is to eliminate the FS_{manure} so that FS_{sand}, or S remains.

This test assumes the following:

- FS_{sand} are non-digestible.
- FS_{manure} are completely digestible.

3.2.4.1: Materials

To perform the acid digestion analysis, the following items are required:

50 ml, 40-60 micron filter crucibles
Vacuum pump
1 L of 0.1 M HCl
Distilled water at 100 ^{o}C

3.2.4.2: Methodology

The steps for determining S are as follows: i) hot weigh filter crucibles, ii) place previously ignited samples into filter crucibles (stored in oven) and hot weigh, iii) using an eye dropper, soak the contents of the filter crucibles with 0.1 M HCl, and let stand for fifteen minutes, iv) vacuum filter each sample while liberally rinsing the walls of the beaker and the undigested beaker contents using 100 ^{o}C distilled water, and iv) oven dry for twelve hours, then hot weigh. The material remaining after digestion and drying is sand, m_{sand}. The sand content of a sample is then expressed as:

$$S = \frac{m_{sand}}{m_{initial}} * 100 \quad [3.8]$$

where: S = Sand content, %

m_{sand} = Sand mass, g

$m_{initial}$ = Initial (wet) sample mass, g

Again, note that in this instance S is calculated on a wet basis. To convert to dry basis simply divide S by TS.

3.2.5: Sand Particle Size Analyses (Dry Sieving, Wet Sieving, and Hydrometer Test)

Particle size analyses generate particle size distribution curves for different bedding sands. For the purpose of this study, three particle size determination techniques are utilized: i) dry sieving, ii) wet sieving, and iii) hydrometer (sedimentation) test. Sieve analyses (dry and wet) are used for samples composed of particles greater than 0.053 mm. For particles smaller than 0.053 mm (a clay particle), the hydrometer test is used.

3.2.5.1: Materials

These analyses were conducted in accordance to the American Standards for Testing and Materials (ASTM, 1991) standard Dry Sieving Fine Aggregates (C136) and Particle Size Analysis of Solids (D422). The following is required in order to perform these analyses:

US Sieve Series (6, 10, 12, 14, 16, 20, 30, 50, 100, 140, and 270)
Sieve shaker
ASTM Standard Hydrometer (ASTM 152H)

1000 ml graduated cylinder
Plastiseal, 10 cm x 10 cm
Ohaus TS4KS Balance (±0.1 g)
500g sample, dry
Distilled water

TABLE 3.1: U.S. Standard Sieve Series

U.S. Sieve Number	Opening Size (mm)
6	3.66
10	2.00
12	1.68
14	1.41
16	1.19
20	0.84
30	0.59
50	0.30
100	0.15
140	0.11
270	0.053

3.2.5.2: Methodology

The experimental procedure to determine the particle size distribution of sand and silt particles is as follows: i) oven dry a 500 g sand sample at 106 ^{o}C, ii) weigh empty sieves, iii) assemble the sieve series in the order of decreasing size, top to bottom, iii) place sample in top sieve and cover, v) activate sieve shaker for ten minutes, and vi) weigh sieves and maintain the fraction which passed through the last sieve (US 270).

The hydrometer test predicts particle concentrations based on the buoyancy of the liquid phase in a settling column. The procedure for the hydrometer test used to determine clay content is as follows: i) place the material which passed through the last sieve (US#270) into a 1000 ml beaker and fill to the 1000 ml mark with distilled water, ii) seal the end of the column with Plastiseal, iii) mix by inverting the column several times, iv) allow the sample to settle for 8 hours then place the hydrometer into the suspension and record its depth, and v) refer to

ASTM D422 and determine the particle concentration (clay content) that corresponds to the previously recorded hydrometer depth, and vi) plot a cumulative particle size distribution for each sand tested.

The wet sieve analysis is used to determine the particle size distributions of paste-like substances like raw manure. The test proceeds as follows: i) weigh empty sieves, ii) assemble the sieve series in the order of decreasing size, top to bottom, iii) place a 200 g wet manure sample in the top sieve, iv) using tap water, wash the solids through the sieve series until the sieve effluent is clean, v) dry the sieves and record the mass of each sieve, and vi) plot a cumulative particle size distribution. The US 20, 50, and 140 screens were not used in the wet sieve analysis of manure due to difficulties experienced with screen clogging

3.2.6: Manure Sampling

In section 3.3 a variety of sand separation systems are analyzed. With the exception of the hydrocyclone, which is a working on-farm unit, the separators are laboratory scale. Therefore, for each laboratory trial, manure and sand are collected and then mixed in the appropriate proportions in order to achieve the desired rate of dilution.

3.2.6.1: Materials

The following equipment is required for the collection of raw manure :

20 L bucket
Hand operated alley scraper
Scooping device

3.2.6.2: Methodology

Manure samples were collected from the milking parlor holding pen and return alley at the Michigan State University Dairy Research Unit, East Lansing, MI. This location was selected for sampling since the manure there is free from any bedding (the MSU Dairy uses wood shavings and newspaper bedding).

Sampling proceeded as follows: i) following the A.M. milking (0600 to 0730), the entire holding pen and return area was scraped into a common pile and thoroughly mixed, and ii) the appropriate volume of manure was sampled from the pile by the method of quartering (Van Soest and Robertson, 1985), then transported to the laboratory for immediate use.

A type of sand referred to as 2NS (MDOT, 1990) was used for each trial, and is described in detail in Chapter 4.. This type of sand was selected for two reasons: i) 2NS is a commonly used bedding sand, and ii) it possesses a negligible amount of organic matter, therefore, simplifying laboratory analyses. All sand was donated by Gale Briggs and Son, Charlotte, MI.

3.2.7: Criteria for Acceptable Cleanliness of Bedding Sand

Bishop et al. (1980) reported that coliform counts greater than 10^6 per gram of bedding pose a significant threat to udder health due to mastitis. Currently, there is no literature relating sand bedding VS (db) to coliform bacteria count. Such a relationship would prove useful in establishing a reasonable goal for the acceptable amount of VS (db), or recovery quality, of sand recovered from a separator.

To establish a reasonable goal for recovery quality, samples of sand bedding were removed from the rear (adjacent to drive alley) 61.0 cm of 3 freestalls (11 farms). Mr. George Atkeson, MSU Cooperative Extension, Ionia County, judged each stall either "acceptable" or "unacceptable" from the standpoint of contamination from manure solids. Samples were tested for TS and VS (db). As a result an "acceptable" as well as an "unacceptable" range of VS (db) in bedding sand was established.

3.3: Analysis of Sand Separation Systems

The following section outlines the experimental methodology used to analyze a variety of liquid/solid separation systems. Systems examined include:

i) sedimentation, ii) screening, iii) the hydrocyclone, iv) dissolved air floatation (DAF), and v) the belt filter press.

3.3.1: Sedimentation

The objectives of the settling tests were twofold: i) to analyze the settling characteristics of dilute SLDM and thereby gain an understanding of the interactions between the manure, sand, and water, and ii) based upon the results of the settling analyses, to determine whether or not sedimentation is a feasible method for separating sand from dairy manure.

3.3.1.1: Type-3 Settling Analysis

Type-3 settling analyses are used to monitor type-3 or hindered settling (described in Chapter 2). This is accomplished by measuring the height of the liquid/solid interface as well as the height of sand particles in the solid fraction during twenty four hours of quiescent settling. Twenty four hours was selected as the settling time since this would be the maximum detention time for a batch sedimentation chamber capable of handling one day's worth of SLDM.

3.3.1.1a: Materials

The materials required for the type-3 settling analysis are as follows:

Tap water
Ohaus TS4KS Balance (±0.1 g)
Inversion mixer
(5) Plexiglas settling columns (D=12.7 cm and H=56.8 cm)
(Figure 3.1)
Ruler

3.3.1.1b: Methodology

The methodology for the type-3 settling analysis can be broken down into two distinct categories: i) sample preparation, and ii) the actual settling analysis. Sample preparation includes the mixing of sand and manure. The ratio of sand to manure (S:M) used in samples was determined by taking the average mass of sand used per cow-day over the average mass of manure produced per 636 kg (1400 lb) dairy cow-day. The value used for average manure mass produced was 52.3 kg/cow-day (115 kg/cow-day) (MWPS, 1985). The average amount of sand used was altered during the study due to the fact, as the sand usage survey expanded, the calculated average amount of sand used changed.

TABLE 3.2: Sand:Manure Ratios (S:M).

Date	Manure Produced (kg/cow-day)*	Sand Usage (kg/cow-day)	(S:M)
August 1993	52.3	31	0.59
January 1994	52.3	25	0.48

*(MWPS, 1985)

All tests were performed at S:M equal to 0.59 unless otherwise noted.

Throughout this study SLDM slurries are classified by mass basis dilution ratio (DR). For instance, a 2:1 dilution indicates that the mixture is composed of 2 mass parts of water to 1 mass part SLDM. The relative quantities of sand, manure, and water required were calculated in a manner such that, for different dilution ratios, fluid height in each column would be equal. Table 3.3 summarizes the relative amounts of sand, manure, and water required to attain the specified dilution while maintaining a constant volume.

Sample preparation includes the following steps: i) in Plexiglas columns (Figure 3.1), prepare 0, 0.5, 1, 2, 3, and 5:1 SLDM mixtures using the quantities of sand, manure, and tap water outlined in Table 3.3 and, ii) mix using inversion mixer for 10 minutes. The inversion mixer is capable of simultaneously mixing three settling columns by rotating them about their centroids at a rate of 15 RPM. This mixing technique was chosen over a rotary (propeller) mixer since it reduces turbulence and encourages settling primarily along the y-axis of each column.

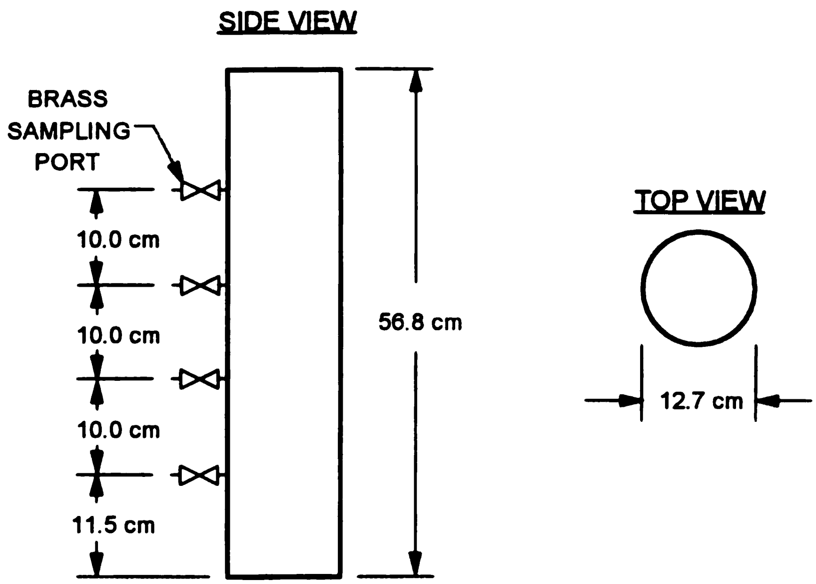

FIGURE 3.1: Plexiglas Settling Column.

The actual settling analysis includes the following steps: i) allow samples to settle under quiescent conditions for twenty four hours, and ii) measure the height of the liquid/solid interface (h_l) and the height of the sand (h_s) in the solid layer at the intervals outlined in Table 3.4.

A sand height ratio (h_{sr}) and solid/liquid interface height ratio (h_{lr}) are calculated to obtain a relative measure of the sand height and the liquid/solid interface height in the settling column. The sand height ratio is a ratio of the highest point at which sand is found (h_s) and the column height (h_i). Similarly, the liquid/solid (h_{lr}) interface ratio is a ratio of the height of the liquid/solid interface (h_l) with respect to column height (h_i). Note that this analysis only pertains to SLDM that is agitated and allowed to settle.

TABLE 3.3: Quantities of Manure, Sand, and Water Required for Type-3 and Batch Settling Analyses.

Dilution Rate	Manure Mass (g)	Sand Mass (g)	Water Volume (ml)
0:1	5074.4	2465.6	0.0
0.5:1	3075.4	1494.3	2284.8
1:1	2206.3	1072.0	3278.3
2:1	1409.6	684.9	4188.9
3:1	1035.6	503.2	4616.3
5:1	676.6	328.7	5026.7

TABLE 3.4: Measurement Times.

Reading Number	Elapsed Time	Reading Number	Elapsed Time
1	30 sec	7	60 min
2	1 min	8	2 hrs
3	3 min	9	4 hrs
4	5 min	10	8 hrs
5	10 min	11	16 hrs
6	30 min	12	24 hrs

3.3.1.2: Batch Settling Analysis

A batch settling analysis is used measure the amount of solids settled over after a specified amount of time. It is also capable of confirming the results found using the type-3 analysis.

3.3.1.2a: Materials

The following equipment are required for the batch settling analysis:

Tap water
Ohaus TS4KS Balance (±0.1 g)
Inversion mixer

(5) Plexiglas settling columns (D=12.7 cm and H=56.8 cm)
equipped with sampling ports and false bottoms (Figure 3.2)

To facilitate sampling of the liquid fractions each Plexiglas column is equipped with brass sampling ports spaced every 10.0 cm. In addition, each column is equipped with a false bottom which enables sampling of the settled solids following the removal of the liquid fraction.

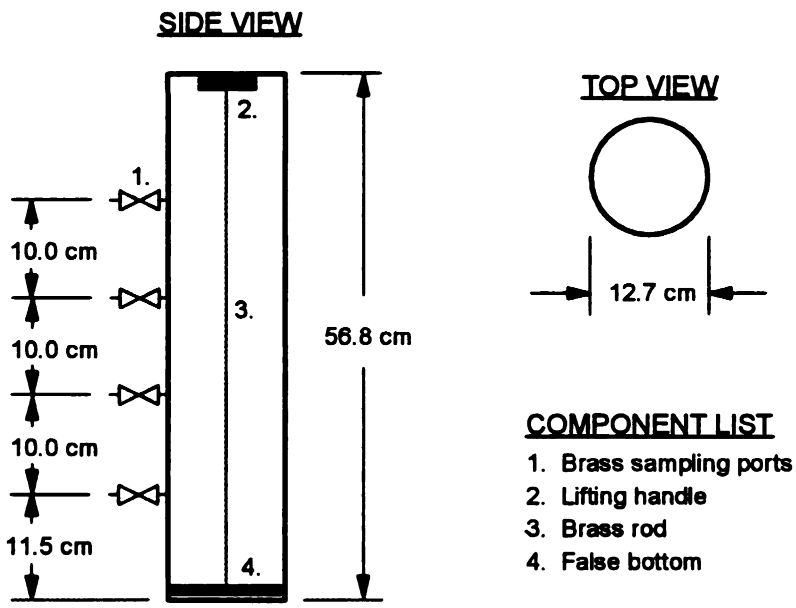

FIGURE 3.2: Plexiglas Batch Settling Column With False Bottom.

3.3.1.2b: Methodology

The batch settling analysis is a continuation of the type-3 settling analysis. Upon completing the 24 hour measurement for the type-3 settling analysis, proceed with the following steps: i) sample the liquid fraction through the sampling ports in triplicate 10 ml samples, ii) raise false bottoms to the top of the chamber (see Figure 3.3), iii) measure the thickness of each settled layer then sample in triplicate, iv) perform tests for TS, VS, and S on each sample then calculate the quality of the recovered sand as well as sand content.

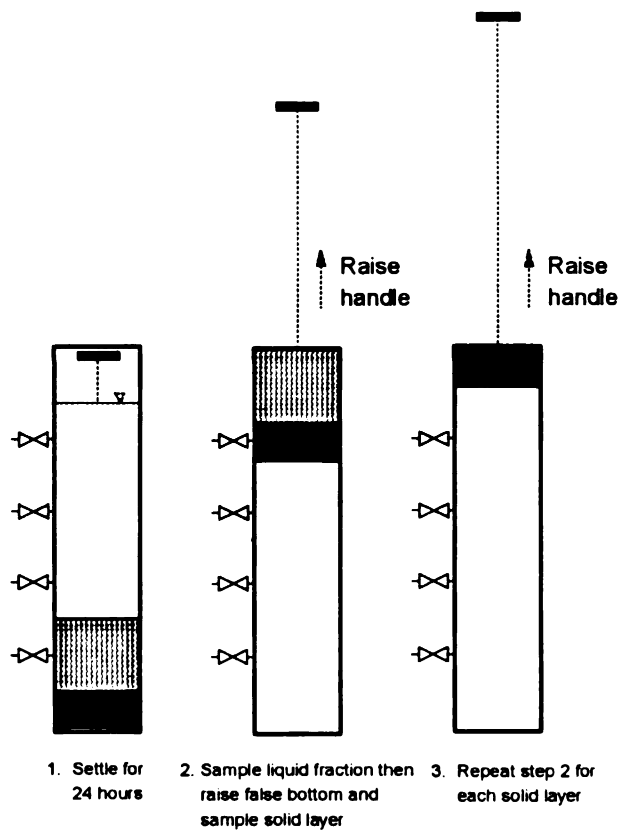

FIGURE 3.3: Batch Settling Analysis Sampling Procedure.

Again, note that this analysis only pertains to SLDM that is agitated and allowed to settle under quiescent conditions.

3.3.2: Screening

3.3.2.1: Materials

The following items are required for the evaluating the efficacy of sand separation by screening (separation on the basis of particle size):

Particle size distributions of bedding sands
Particle size distribution of raw dairy manure

3.3.2.2: Methodology

Particle size distributions of sand and manure are obtained using the sieving method previously outlined. The effectiveness of screening as a method for separating sand from dairy manure is accomplished graphically by comparing the particle size distributions of sand and manure.

3.3.3: Hydrocyclone

3.3.3.1: Materials

On a Michigan dairy farm where manure is irrigated, a 25.4 cm (10 in) Krebs hydrocyclone separator is used to remove sand from manure prior to an earthen irrigation pond. SLDM is scraped into a primary storage pit and is diluted with milking parlor wastewater since it is recommended that the hydrocyclone feed concentration contain less than 30% solids by mass. Agitation begins fifteen minutes prior to pumping and continues throughout the duration of the operation. The hydrocyclone is fed by the same pump used for agitating. Ideally, sand from the underflow is stacked beneath the hydrocyclone and the overflow water and manure solids are directed into the irrigation pond.

3.3.3.2: Methodology

Throughout the hydrocycloning operation, samples were collected four times (triplicate samples) from both the overflow and the underflow. No effort was made to record sampling times with respect to the start of the operation. Samples were tested for TS, VS (db), and S.

3.3.4: Dissolved Air Floatation (DAF)

3.3.4.1: Materials

The following is list of the equipment required to test the DAF:

6 L DAF unit, laboratory scale
Air compressor
Pressure regulator
1000 ml graduated cylinder

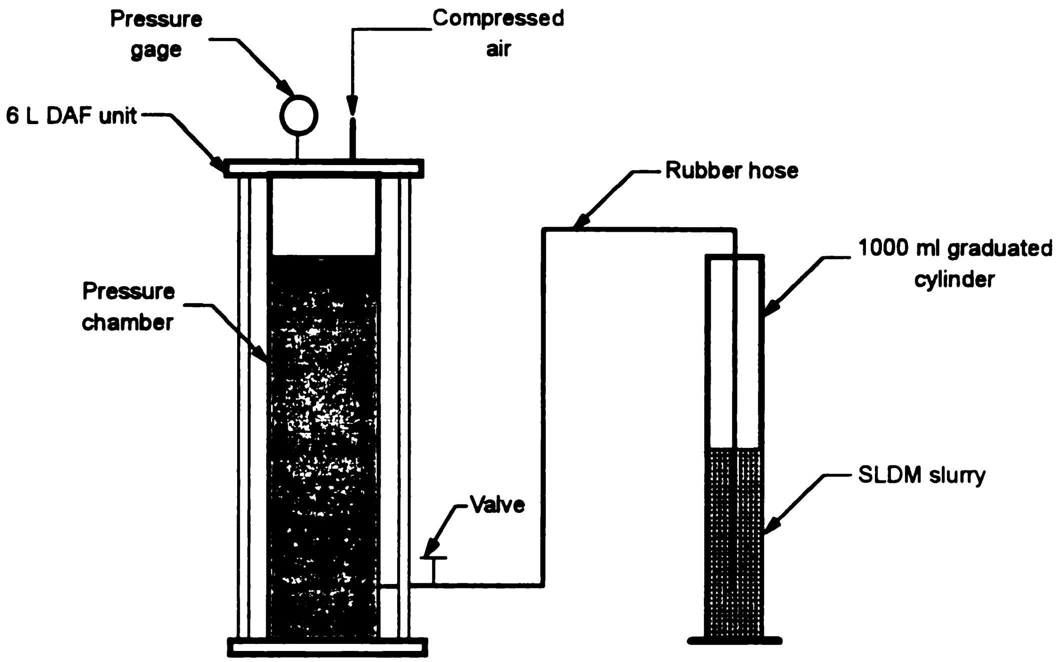

FIGURE 3.4: Experimental Dissolved Air Flotation Unit.

The laboratory-scale DAF (Figure 3.4) unit was donated by the Envirex Inc., Waukesha, WI for the duration of the experiment.

3.3.4.2: Methodology

The following procedure was used to evaluate the effectiveness of the DAF unit: i) prepare 750 ml of a 2:1 SLDM mix in a 1000 ml graduated cylinder and mix by inverting the cylinder by hand, ii) fill DAF with tap water and pressurize to 412 kPa (60 psi), iii) place the DAF outlet hose into the bottom of the 1000 ml graduated cylinder, iv) open the valve which allows the air-saturated water enter the graduated cylinder, and v) monitor the rise rate of the solids.

3.3.5: Analysis of a SLDM Dewatering System--Belt Filter Press With Polymer Conditioning

The goal of each of the previously discussed systems is to separate sand from dairy manure. The goal of the belt filter press with polymer conditioning is to dewater, or extract water from SLDM.

3.3.5.1: Materials

The following is list of the required equipment and materials:

- Polymers:
  - American Cyanamid Magnifloc SD2081 (cationic)
  - American Cyanamid Magnifloc 1885A (cationic)
  - American Cyanamid Excel Plus (cationic)
  - Stockhausen Praestol K295FL (cationic)
  - Stockhausen Praestol PRA3040L (anionic)
- (5) 500 ml plastic containers, disposable
- (5) 5 ml syringes
- (5) 35 ml syringes
- Braun 4172B hand mixer
- 1000 ml beaker
- Glass stirring rod
- Neogen Inc. Crown Press (Belt filter press simulator)

3.3.5.2: Methodology

The following procedure was used to evaluate the effectiveness of SLDM dewatering using a belt filter press with polymer conditioning: i) prepare a 0.4% aqueous polymer solution in a disposable container, ii) mix using the hand mixer and allow to stand for ten minutes, iii) using a 35 ml syringe, add 5 ml of polymer to 190 g of SLDM and stir with a glass rod, iv) continue to add polymer in 5 ml doses until the solids coagulate or until the total amount of polymer used exceeds 150 ml, iv) subject coagulated solids to the belt filter press simulator, and v) analyze final product for TS and VS. This process was repeated for each of the five polymers. A manure sample is considered coagulated when distinct liquid and solid fractions form.

3.3.6: The Batch Aerated Grit Chamber (BAGC)

The BAGC is a sand separation device developed by the author, B.F. Severin (MBI), and W.G. Bickert (MSU Dept. of Agricultural Engineering). The specifics regarding the development and operation of a BAGC are presented in Chapter 4.

3.3.6.1: Materials:

The following is list of the equipment required to test the BAGC:

BAGC unit, laboratory scale (Figure 3.5)
Air compressor
Pressure regulator
Globe valve
Fischer Scientific mercury thermometer (±1 ^{o}C)
20 ml syringes

The laboratory-scale BAGC, which closely resembles a free air-lift pachuca tank (Lamont, 1958), is a Plexiglas column 56.8 cm deep and 12.7 cm in diameter. The column possesses a plastic conical bottom and four Nalgene sampling ports spaced 10 cm apart. The included angle of the conical bottom is 53^{o}. Air is introduced at the apex of the conical bottom through a 1.3 cm orifice. Figure 3.5 is a diagram of the experimental BAGC unit. Figure 3.6 is a diagram of the complete experimental BAGC system.

3.3.6.2: Methodology

Testing of the BAGC proceeds as follows: i) prepare a mixture of SLDM (S:D=0.48) using quantities of sand, manure, and tap water listed in Table 3.5, ii) add the predetermined quantity of dilution water, iii) activate the air system and adjust air flow rate accordingly using the Rotometer, iv) shock load the column with SLDM, v) after ten minutes, measure the temperature of the mixture then remove three 10 ml samples from the dilute manure fraction using the sampling port number 2 (see Figure 3.5), vi) measure the height of the recovered sand

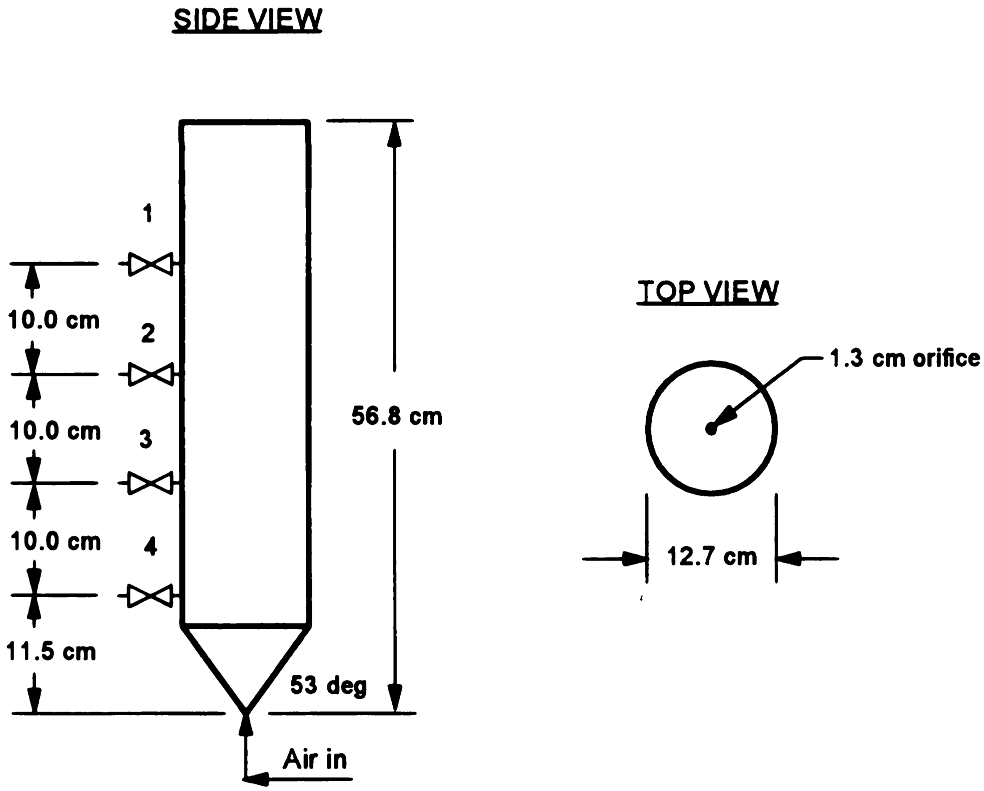

FIGURE 3.5: Experimental BAGC Unit.

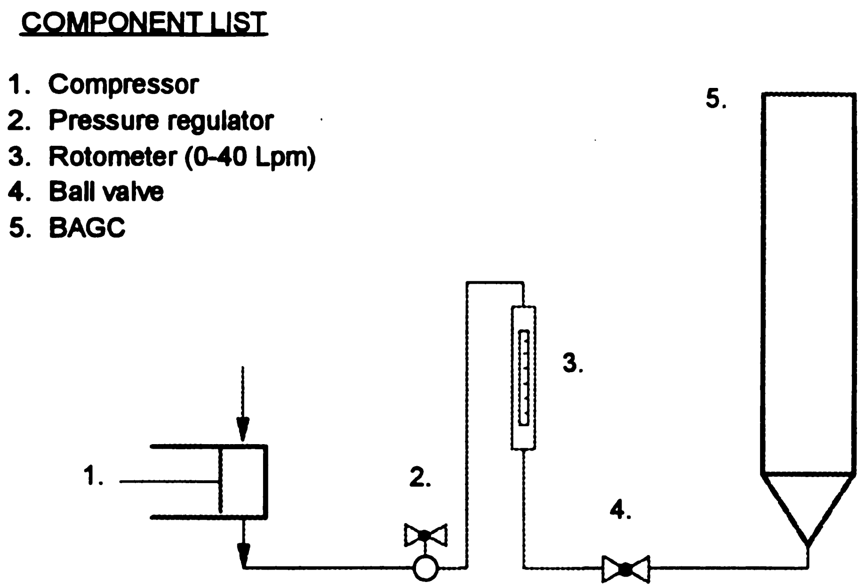

FIGURE 3.6: Experimental BAGC System

fraction, vii) after draining the remaining liquid, pour the settled sand into a aluminum pan and collect three 10 ml samples using the method of quartering (Van Soest and Robertson, 1985), and viii) test all samples for TS, VS , and S then calculate the sand recovery efficiency and the sand recovery quality.

TABLE 3.5: Quantities of Manure, Sand, and Water Required for BAGC Testing

Dilution Rate	Manure Mass (g)	Sand Mass (g)	Water Volume (ml)
0:1	4330.8	2104.2	0
1:1	1882.9	914.9	2797
2:1	1203.0	584.5	3575
3:1	883.8	429.4	3868
5:1	577.4	280.6	4290

To examine the repeatability of these results, for each dilution, this procedure was repeated immediately (a total of 6 replications per data point). The purpose of replicating the test immediately, using manure collected the same day, was to eliminate sample variability due to the day-to-day inconsistencies of the physical properties of manure. A listing of the experimental treatments are presented in Table 3.6.

Note that in the initial exploratory BAGC trials, samples were collected from each of the four sampling ports. However, it was determined that differences in TS, VS, and S from port to port were insignificant, indicating a uniform mix of the liquid fraction..

The following was assumed in the determination of recovery efficiency and sand quality:

- 2NS sand is composed of a negligible amount of organic matter (VS (db)=0.14 %).

- Tap water contains a negligible amount of solids (TS=0.003 %).

TABLE 3.6: Experimental Design for BAGC Testing.

Test Number	Dilution Rate	Air Flow Rate (L/min)	Replications
1	1:1	0	6
2	1:1	5	6
3	1:1	10	6
4	1:1	20	6
5	1:1	30	6
6	2:1	0	6
7	2:1	5	6
8	2:1	10	6
9	2:1	20	6
10	2:1	30	6
11	3:1	0	6
12	3:1	5	6
13	3:1	10	6
14	3:1	20	6
15	3:1	30	6
16	5:1	0	6
17	5:1	5	6
18	5:1	10	6
19	5:1	20	6
20	5:1	30	6

CHAPTER 4
RESULTS AND DISCUSSION

4.1: General Comments

Chapter 4 details the physical characteristics of commonly used bedding sands and SLDM, as well as the results of exploratory tests used to evaluate an assortment of liquid/solid separation systems. The development and testing of the batch aerated grit chamber (BAGC), a new approach to separating sand from manure, is also presented.

4.2.: Bedding Sand Usage Rates and Physical Characteristics

Sand usage data for 55 farms throughout the midwest was compiled as the result of a survey conducted by Wedel and Bickert (1994) as well as an additional survey (unpublished) conducted by R.R. Stowell, Visiting Specialist, MSU Department of Agricultural Engineering . The studies found sand usage in dairy freestall barns to range from 1.6 to 61.8 kg/stall-day (3.6 to 136.0 lb/stall-day), with an average of 24.8 kg/stall-day (54.5 lbs/stall-day). Figure 4.1 is a frequency distribution of the quantities of bedding sand used.

Bedding sand may either be purchased from quarries or removed from the field by bucket loader. These sands range in texture from fine to coarse. For the purpose of this study, sands were classified and subsequently referred to by MDOT (1990) standard sand specifications. Commonly used bedding sands are classified as 2NS, 2MS, and 3FS. Throughout the entirety of this study, bedding sands are referred to by their MDOT classifications in order to avoid confusion due to the slang terms that exist for each. Figure 4.2 presents particle size

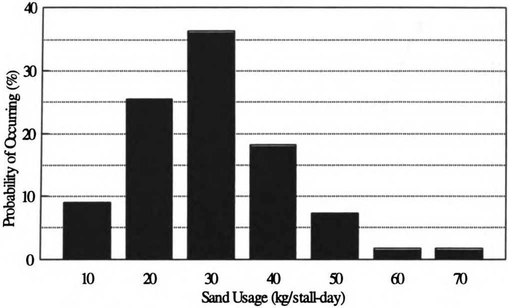

FIGURE 4.1: Sand Usage Probability Distribution (n=55)

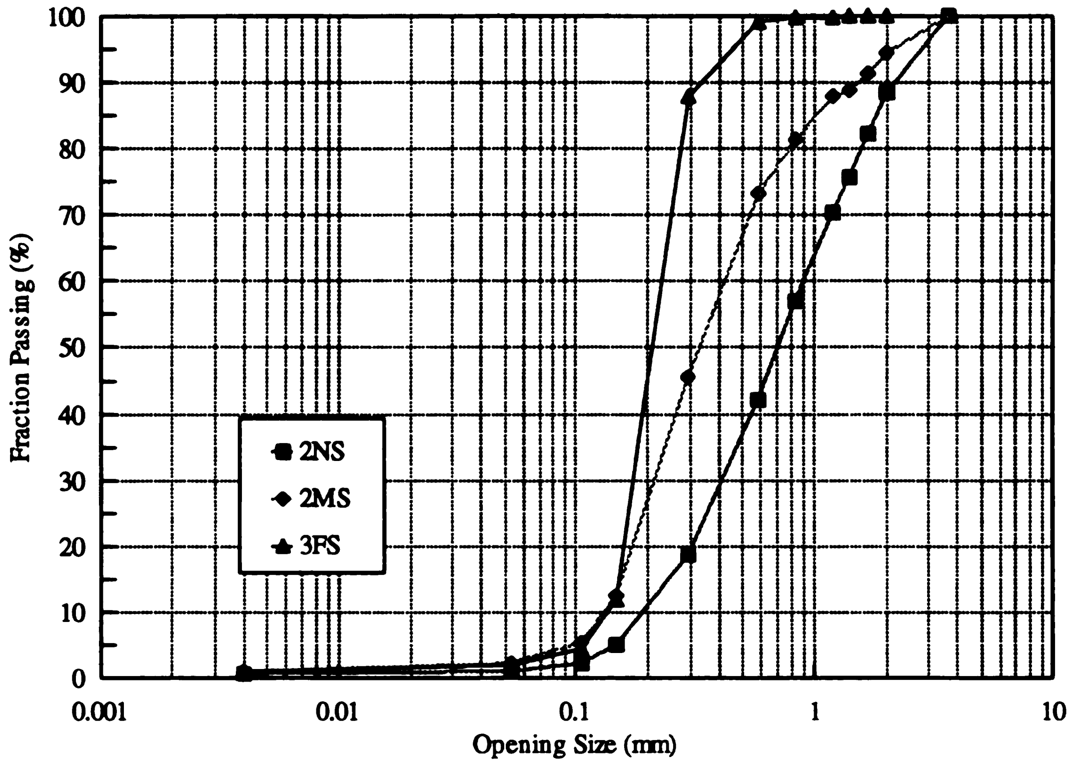

FIGURE 4.2: Bedding Sand Particle Size Distributions

distributions for commonly used bedding sands. 2NS and 2MS are processed (washed and screened) sand. MDOT (1990) states the following for 2NS and 2MS.

> ...these fine aggregates used in concrete mixtures, mortar mixtures and intrusion grout for preplaced aggregate concrete, shall be the fine granular material resulting from the natural disintegration of rock. The material shall consist of clean, hard, durable, uncoated particles of sand, free from clay lumps and soft of flaky material.

The 2MS sand is also referred to as mortar sand, 3 mil, Regular 8, or Number 8. Sand that is used directly from the field is classified as 3FS and referred to as "bank run" by farmers. MDOT (1990) states the following of 3FS.

> ...fine aggregate for bituminous mixtures shall consist of clean, hard, durable, uncoated particles, free from clay lumps, organic materials, soft or flaky materials, and other foreign matter
>
> ...(3FS) shall be natural sand, manufactured sand, or a blend of natural sand and manufactured sand.

Selection of sand type is typically a matter of farmer preference. However, some farmers prefer 2MS and 3FS due to the fact they do not possess large sharp granules that may become imbedded in cow hoofs. As stated in the MDOT standards, sand must be free from organic matter. Table 4.1 presents the dry basis organic matter contents of 2NS, 2MS, and 3FS sands.

TABLE 4.1: VS (db) of Commonly Used Bedding Sands.

Sand Type	VS (db) %
2NS	0.14
2MS	0.35
3FS	0.55

4.3: Determination of Acceptable Recovery Quality Criteria

The results of the bedding sand survey used to establish an acceptable recovery quality range is presented in Table A.1. Table 4.2 presents a summary of these results.

TABLE 4.2: Acceptable and Unacceptable Recovery Quality Ranges.

Sand classification	VS (db) %
Acceptable sand	1.04 to 4.44
Unacceptable sand	4.50 to 23.33

Based on the results presented in Table 4.2, the target recovery quality for recovered sand was set at 2.0 % VS (db).

4.4: Physical Characteristics of SLDM

The average 640 kg (1,400 lb) dairy cow produces approximately 52 kg (115 lb) per day at TS of approximately 12 percent and density equal to 990 kg/m^3 (62 lb/ft^3) (MWPS, 1985). However, manure physical characteristics are dependent upon a number of factors, such as: i) animal age, ii) manure age, iii) ration fed, iv) housing system (i.e. barn floor slope, bedding type, etc.), v) ambient environment, vi) manure handling system (i.e. presence of dilution) (Merkel, 1981, Moore, J.A. et al., 1975, and Sobel, 1968).

Raw manure at a moisture content of 87% can be handled as a semi-solid. Adding bedding sand drastically changes the physical characteristics of manure. For instance, if 25 kg sand/stall-day (55 lb sand/stall-day) at 95% TS and a density equal to 2,500 kg/m^3 is mixed with 52 kg (115 lb) of raw manure, the resulting TS would be 40% at a density of 1,230 kg/m^3 (77 lb/ft^3). After the manure and sand mixture is deposited into a long-term storage pit, precipitation, runoff, and possibly milking center wastewater may be added, significantly reducing TS.

Unlike chopped straw or sawdust, sand particles are incapable of absorbing moisture. This has a significant impact upon the classification of manure flowability. Consider raw manure with chopped straw added to 40% TS and SLDM at 40% TS. By MWPS (1985) standards, at 40% TS, both mixtures would be considered a solid material. The raw manure with chopped straw added could be handled with a fork loader and stacked and is considered solid (MWPS, 1985). The SLDM could be scraped and loaded by bucket loader, but not forks. Therefore, ignoring TS content criteria for flowability, SLDM would be classified as a semi-solid. Although both mixtures possess the same TS content, the methods for handling each one vary immensely. For this reason, established manure flowability standards based on TS do not apply to SLDM (Wedel and Bickert, 1994).

4.4.1: Settling Behavior

The results of settling tests are capable of offering insight into the interactions between settling sand and manure particles. The settling tests are also useful in predicting the performance of sedimentation chambers. In addition, there exists a theory amongst dairy farmers unfamiliar with SLDM that sand will settle out of raw, undiluted SLDM and the resulting liquid fraction may simply be decanted. The results from the following settling tests will be used to either substantiate or dispel this theory.

4.4.1.1: Type-3 Settling Analysis

Figures 4.3 is a graph of h_{lr} and h_{sr} versus dilution ratio. Dilution ratios examined range from 0 to 5:1 This graph indicates that, for undiluted SLDM, it would be impossible to decant the liquid fraction since, a distinct liquid layer does not exist. In the undiluted state, sand and solid manure particles exist throughout the entire profile. When the sample is diluted, agitated, and allowed to settle (Figures 4.4 - 4.8), solid particles begin to settle and a liquid layer forms at the top of the column. The result is a two layered profile that consists of a distinct liquid and a solid layer (type 3 settling). Sand and dilute manure solids exist within the settled solids layer. As the dilution ratio increases, the height of sand particles (h_s) in the solids layer decreases, indicating that the sand is becoming more concentrated, or compacted at the bottom of the column. The effects of dilution are the most noticeable for dilution ratios of 1:1 and greater.

Figures 4.4 - 4.8 indicate that the majority of the sand settles within the first hour of settling. An exception is the 1:1 dilution, in which, a significant amount of sand settling did not occur until t=6 hrs.

Furthermore, neither type 1 or type 2 settling apply to SLDM slurries since, at any degree of dilution (including no dilution), the manure solids interfere with the settling of the sand particles. At 0.5, 1:1, 2:1, 3:1, and 5:1, SLDM displays type 3 settling since there is interference between solid particles and a liquid/solid interface develops. Type 4 settling applies to undiluted SLDM since a distinct interface between the liquid and solid phases does not exist. See Chapter 2 for a review of the four classes of settling.

The results obtained from the 0.5:1 treatment are unique. As previously stated, the 0.5:1 column developed a distinct liquid solid interface. However, sand remained distributed throughout the entire solid portion of the profile, or h_{sl} equals h_{lr}. Wedel and Bickert (1994) reported that at 0.5:1 a liquid/solid interface as well as a sand height interface existed. However, in the present study this was not the case. This is likely due to the variability of manure physical properties.

<u>4.4.1.2: Batch Settling Analysis</u>

The type-3 settling analysis assisted in characterizing the type of settling that occurred at each dilution. It also offers an explanation as to the effects of dilution on a settling sand profile. The batch settling analysis, however, is used to determine the composition of the profiles, with respect to TS, VS and S.

Figure 4.9 is a plot of recovered sand concentration versus dilution ratio. As determined in the type-3 settling analysis, no sand settling occurred in the 0:1 (undiluted) sample. Sand and manure remained uniform throughout the profile. Sand concentration was found to increase as dilution ratio increased. Dilution had little effect upon recovered sand concentration for dilutions less than 1:1. Beyond 1:1, sand concentration increased rapidly until 3:1. For dilutions greater than 3:1 the effects of dilution become less noticeable. Maximum sand concentration was achieved at 5:1.

Samples recovered from the liquid layer were also analyzed. However, after 24 hours of settling, no sand was detected.

Batch sedimentation has the potential to be an effective sand separation system. However, a large amount of dilution water, approximately 5:1 or 420 L/cow day (110 gal/cow-day), are required in order to recover large quantities of sand.

4.5: Existing Liquid/Solid Separation Systems

Several liquid/solid separation devices were tested to determine whether or not they are capable of separating sand from dairy manure. An exception was the belt filter press with polymer conditioning which was tested in order to evaluate its ability to dewater SLDM. The following section details the results of the tests.

4.5.1: Screening

Screening is a separation technique which separates particles on the basis of size. For the most part, screening has been used to dewater manure as opposed to separate sand. Typically, when sand is used in conjunction with a screen separator, the sand is removed by sedimentation prior to the separator. To examine the efficacy of screening, the particle size distribution curves of 2NS, 2MS, and 3FS sand were compared to that of raw manure (Figure 4.10).

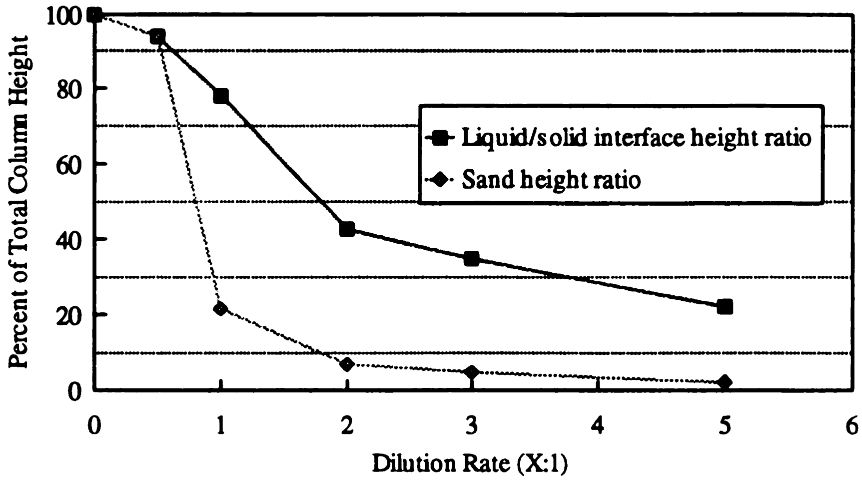

FIGURE 4.3: A Comparison of SLDM Height Ratios at Various Dilutions After 24 hrs of Static Settling.

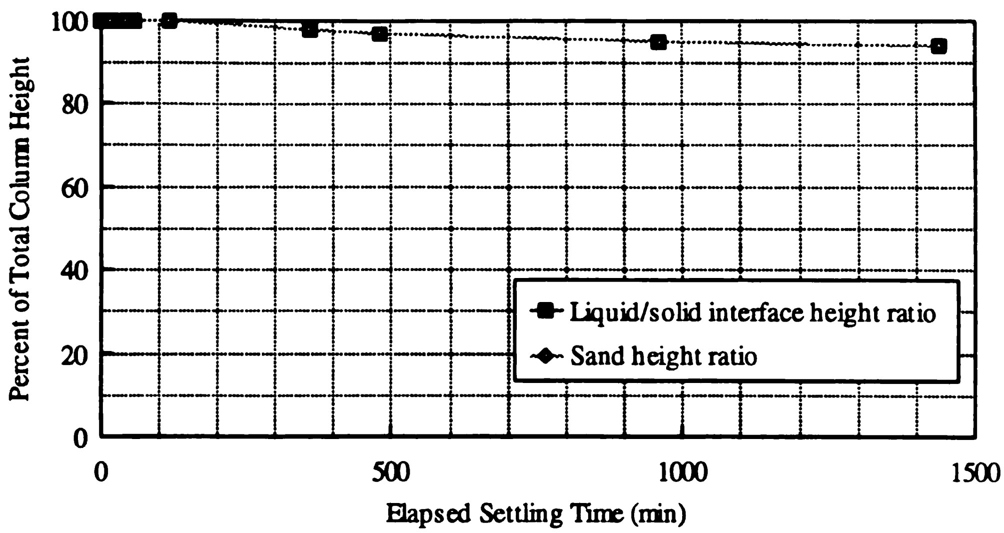

FIGURE 4.4: Type-3 Settling Analysis, DR=0.5:1.

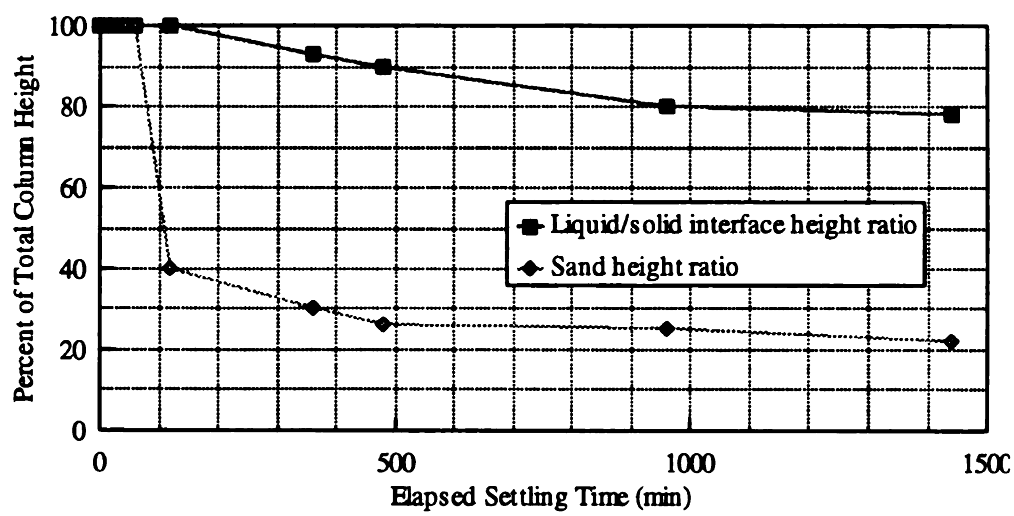

FIGURE 4.5: Type-3 Settling Analysis, DR=1:1.

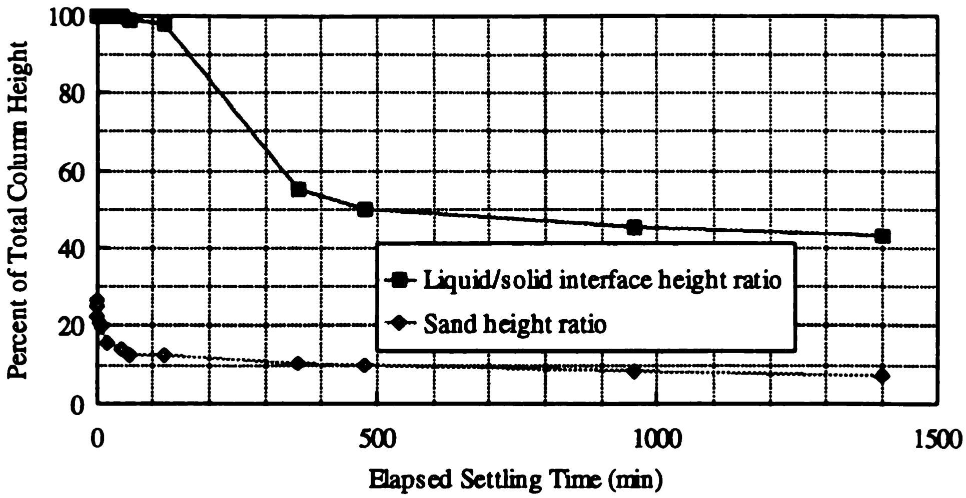

FIGURE 4.6: Type-3 Settling Analysis, DR=2:1.

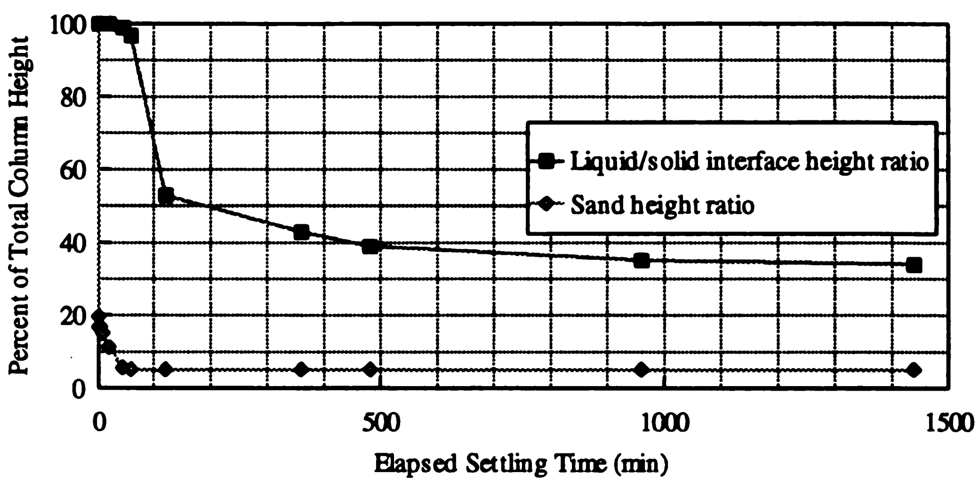

FIGURE 4.7: Type-3 Settling Analysis, DR=3:1.

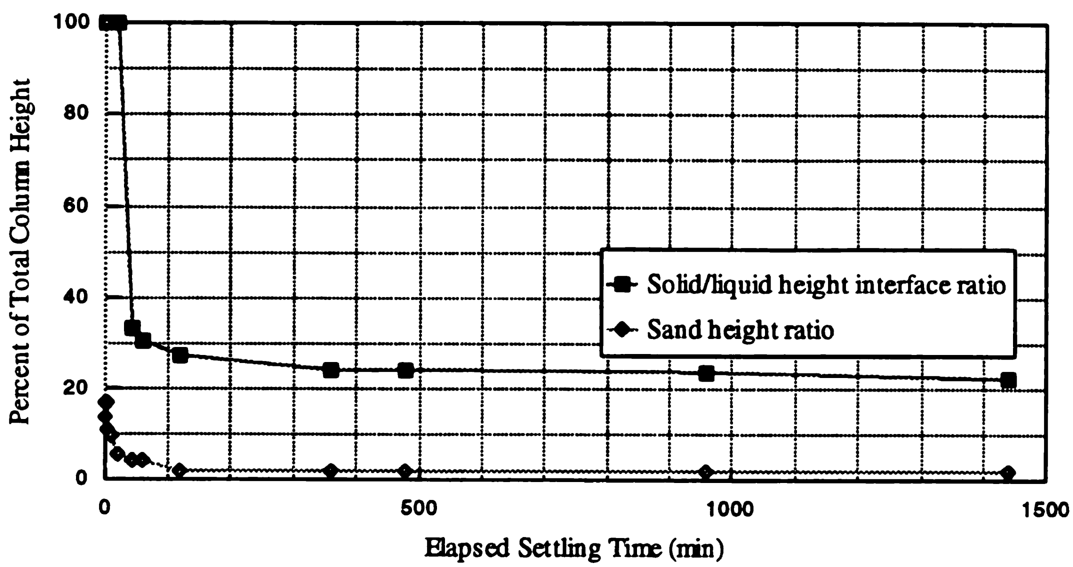

FIGURE 4.8: Type-3 Settling Analysis, DR=5:1.

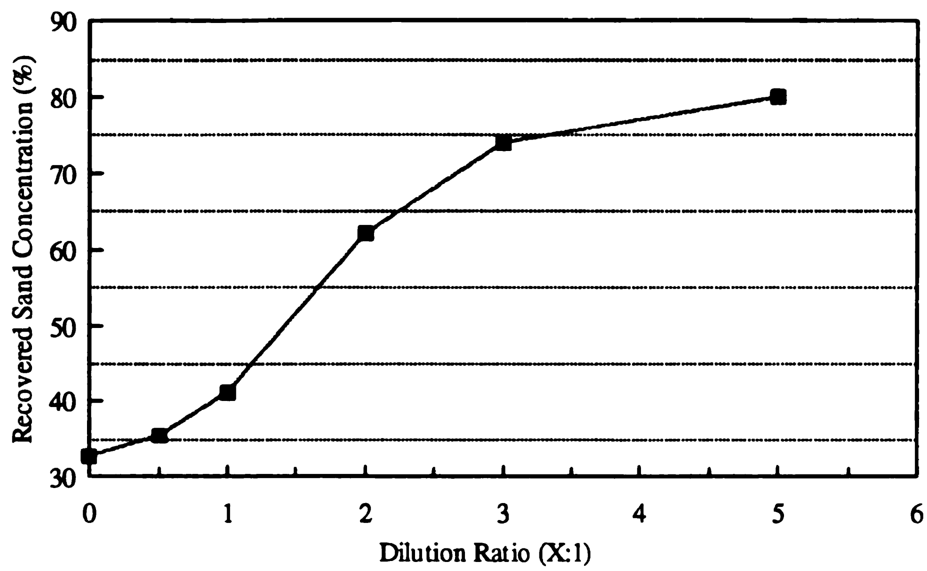

FIGURE 4.9: Recovered Sand Concentration vs. Dilution Ratio

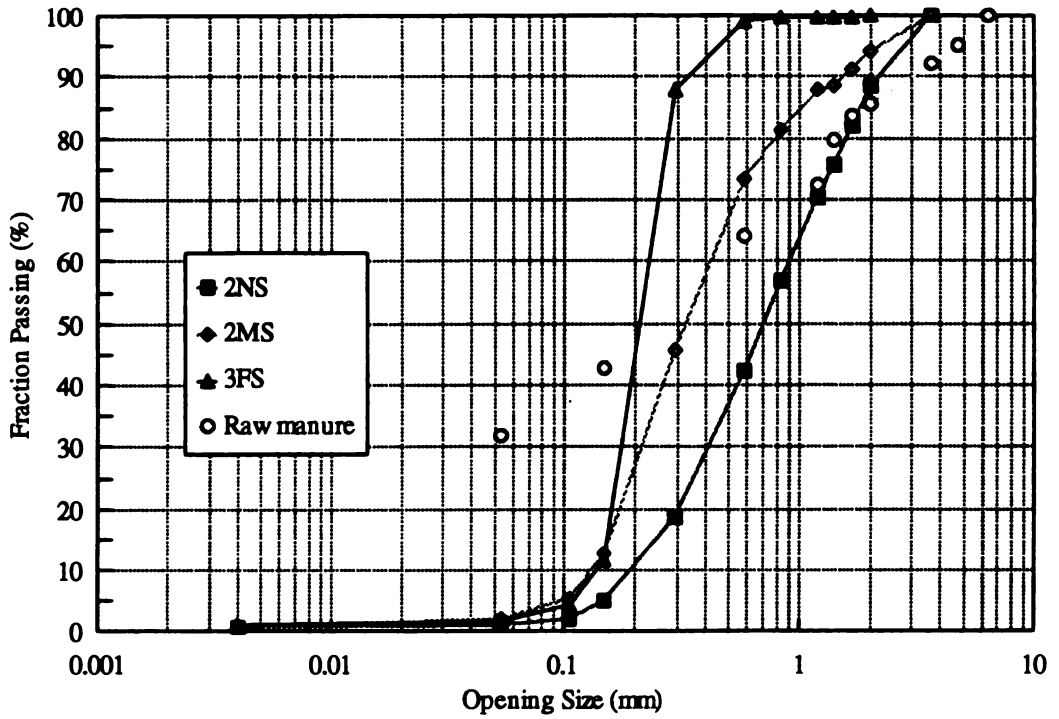

FIGURE 4.10: Bedding Sand and Raw Manure Particle Size Distributions.

A complete listing of the results from the particle size distribution comparisons can be found in Tables A.2, 3, and 4. A summary of the results are presented in Table 4.3.

TABLE 4.3: Sand Recovery Using Screening.

US Sieve Number	Opening Size (mm)	Sand Type	Manure Retained (% of total)	Sand Retained (% of total)
270	0.05	2NS	68.2	94.9
270	0.05	2MS	68.2	97.7
270	0.05	3FS	68.2	98.1

Obviously, the highest percentage of sand was recovered on the smallest screen. However, a high percentage of manure was also retained. Furthermore, a 0.05 mm (US 270) screen is totally impractical due to the fact small screens clog easily. In addition, assuming clogging does not occur, throughput rates are limited with small screens. It is difficult to prevent clogging on the laboratory-scale, let alone on a farm-scale operation. Screen sizes on the farm-scale range from 1.0 to 1.5 mm and 0.12 to 0.39 mm for sloping and vibrating screens, respectively. Based on comparisons of sand and manure particle size distributions, screening can be ruled out as a method for separating bedding sand from dairy manure.

4.5.2: Hydrocyclone

Table 4.4 presents a summary of the results of analyses performed on recovered fractions from a hydrocyclone separator. The abbreviations O and U refer to the hydrocyclone overflow and underflow, respectively. Each entry presented in Table 4.4 is the average of three samples.

TABLE 4.4: Analysis of Recovered Fractions from a Hydrocyclone Separator.

Sample	TS (%)	S (db) %	VS (db) %
1O	9.15	27.46	61.66
1U	57.89	92.38	6.47
2O	7.63	22.59	65.80
2U	55.98	92.38	6.48
3O	7.66	29.14	60.23
3U	65.46	94.22	4.91
4O	6.40	19.18	68.70
4U	69.09	95.28	4.01

Difficulties were experienced due to hydrocyclone clogging. Occasionally, a solid mass of manure and sand would enter the hydrocyclone and, since the local viscosity does not allow the sand particles to be ejected, the mass settles to the bottom of the hydrocyclone and clogs the underflow. As a result, the entire feed stream is diverted to the overflow.

Variations in the hydrocyclone outflow are due to the variations of the solids content of the inflow. It is important to note that all samples were taken while the hydrocyclone appeared to operating optimally (i.e. no clogging). Even for the apparent optimum operating conditions, the VS (db) of the recovered underflow sand was never below 2%

Due to the difficulty in providing a uniform inflow solids concentration with respect to time, hydrocyclone separators are not recommended for use with large manure pits. Increased success may be achieved by pumping from small manure pits since, when confined to a smaller volume, it is easier to obtain a homogeneous mixture of sand, manure, and water.

4.5.3: Dissolved Air Floatation

In wastewater treatment, DAF systems are used to thicken sludge by "floating" colloidal particles. Grit and coarse organic solids have already been removed using grit and primary sedimentation chambers, respectively. For the purpose of separating sand from manure with a DAF, the goal is to float the manure solids and allow the sand to remain at the bottom of the column.

At 2:1 dilution, the air bubbles were incapable of carrying the particles upward due to the high concentration of solids. To combat the problem, the liquid fraction (dilute suspended manure solids) was decanted and fresh tap water was added. Even in what appeared to be an extremely dilute liquid phase, the air bubbles were still incapable of lifting the fibrous solids commonly found in manure. Two additional treatment cycles were performed, resulting in no change in the ability of the air bubbles to float the manure solids.

Due to the inability of the DAF to float the large-coarse manure particles, the system was judged incapable of separating dairy manure from bedding sand and testing ceased.

4.5.4: Belt Filter Press With Polymer Preconditioning (BFP)

Typically, in wastewater treatment BFP systems are used to thicken sludge. Therefore, the grit and coarse organic solids have already been removed using grit and primary sedimentation chambers, respectively. In this test the goal was not to separate the sand from the manure, but instead to dewater SLDM.

Table 4.5 is a list of the quantity of polymer used to achieve coagulation of SLDM. An entry of "N" indicates coagulation was not achieved after adding greater than 150 ml of polymer.

TABLE 4.5: Volume of Polymer Required to Achieve Coagulation.

Polymer	Volume (ml)
American Cyanamid Magnifloc SD2081	N
American Cyanamid Magnifloc 1885A	N
American Cyanamid Excel Plus	150
Stockhausen Praestol K29FL	75
Stockhausen Praestol PRA3040L	N

Only two polymers, American Cyanamid Excel Plus and Stockhausen Praestol, successfully coagulated SLDM. The polymer requiring the smallest dose was selected for further testing. Therefore, the cake conditioned with Stockhausen Praestol K29FL and an non-conditioned SLDM sample were subjected to the belt filter press simulator. Pressed samples were compared to an non-conditioned/non-pressed (control) sample of SLDM (TS=32.70 % and VS (db)=72.47 %). Table 4.6 compares TS before and after pressing. The results are the averages of triplicate samples.

TABLE 4.6: The Effect of the BFP on TS

Sample	Initial TS (%)	Final TS (%)	Difference (%)
nonconditioned/ pressed	32.70	60.88	+86.18
conditioned/ pressed	32.70	61.06	+86.73

By pressing SLDM without conditioning, TS content of the cake was increased by 86.01 %. The SLDM sample that was conditioned with Stockhausen Praestol K29FL and pressed, increased TS by 86.56%. Then, comparing the non-conditioned/pressed cake and the conditioned/pressed sample, the increase in TS is practically insignificant (0.55 %). Therefore, preconditioning has little or no significant effect on increasing SLDM TS on a BFP operation.

Table 4.7 compares VS (db) before and after pressing. Although polymer conditioning has no significant effect upon TS, it does have an effect upon VS. The VS (db) of the nonconditioned/pressed SLDM sample increased by 4.26 %. The VS (db) of the conditioned/pressed SLDM sample decreased by 5.85 %.

TABLE 4.7: The Effect of the BFP on VS (db)

Sample	Initial VS (db) (%)	Final VS (db) (%)	Difference (%)
nonconditioned/ pressed	72.48	75.57	+4.26
conditioned/ pressed	72.48	68.24	-5.85

The fact that VS content of each sample changed while TS of each sample was relatively the same indicates that the polymer conditioning caused a redistribution of FS and VS. For example, again bearing in mind that TS is relatively constant for each sample, as VS of the non-conditioned/pressed increased, FS decreased. Similarly, for the conditioned/pressed sample, as VS decreased, FS increased. This indicates that the polymer induced coagulation enhances the removal of volatile solids from a pressed SLDM cake. This information may prove useful in the event a conditioned and pressed SLDM cake was to be composted and/or if filtrate was to be transferred to an anaerobic digester.

4.5.5: Batch Aerated Grit Chamber (BAGC)

The utility of air induced separation was discovered by bubbling compressed air through a Tygon tube submerged in a dilute (5:1) suspension of SLDM. Two fractions resulted from the fluid flow induced by the rising bubbles: i) a dilute manure fraction and ii) a settled sand fraction. The dilute manure fraction appeared to contain very little sand. Furthermore, the recovered sand was tested and found to contain only 1.7% VS (db). Since the arrangement was a batch process and the phenomena witnessed was similar to that which occurs in a continuous flow aerated grit chamber (Davis, 1992 and Reynolds, 1982), the discovery was called a batch aerated grit chamber (BAGC). The primary difference between continuous flow aerated grit chambers (CAGC) and the BAGC (besides for the fact one is a continuous process and the other is a batch process) is that CAGC's are used to separate grit from wastewater containing approximately 0.25 % TS. The BAGC separates sand from slurries possessing TS contents ranging from 19.1 % (1:1) to 7.1 % (5:1).

In subsequent exploratory tests, separation efficiency and the quality of the recovered sand VS (db) were found to be functions of dilution ratio and air flow rate (Q). Based on the exploratory tests, 90 % was selected as a goal for recovery efficiency.

4.5.5.1: Mixing Intensity (G)

The mixing intensity (G) required to achieve a particular combination of recovery efficiency and quality would be very helpful in future BAGC scale-up. G-value is a function of power input, fluid viscosity, and fluid volume. It was determined that to perform a reological study on dilute SLDM to determine its viscosity would be futile for a variety of reasons. First and foremost, mixer viscometry (Steffe, 1992) would be required in order to keep the sand in suspension. The impeller speeds needed to achieve sand suspension would result in turbulence, vortexing, etc., rendering the test ineffective. Furthermore, air bubbles added to the SLDM have an effect upon viscosity. It would be virtually impossible to perform mixer viscometry on an aerated sample. To circumvent these complications, the viscosity of tap water was used in the calculation of G. The average temperature of the SLDM slurry was 26.4 ^{o}C and ranged from 25 to 29 ^{o}C. Therefore, the viscosity of water at 26 ^{o}C (0.8746 Pa s) is used in all calculations of G. The viscosity of water at 26 ^{o}C was obtained from Perry and Green (1984). Recorded slurry temperatures are listed in Table A.5. Power input (P) and G-value for each air flow rate are presented in Table 4.8.

TABLE 4.8: Power Input and Mixing Intensity

Q (L/min)	P (W)	G (1/s)
0	0	0
5	0.37	9.19
10	0.73	13.00
20	1.47	18.38
30	2.20	22.51

4.5.5.2: Recovery Efficiency and Recovery Quality

Recovery efficiency (Figure 4.11) and quality (Figure 4.12) were plotted versus air flow rate, for dilution ratios of 1, 2, 3, and 5:1. As predicted in the exploratory studies, recovery efficiency and quality both are dependent upon air flow rate and dilution. The highest recovery efficiencies and the cleanest sand were obtained at the 5:1 dilution. As dilution decreased, so did recovery efficiency and quality. For each dilution, recovery efficiency decreased as air flow rate increased. However, increased air flow rates yielded cleaner sand.

As the SLDM mass is shock loaded into the BAGC (dilution water added, air on) it is subjected to the turbulence induced by the air bubbles introduced from the bottom of the column. An exception is the case where air flow rate was equal to zero, in which the entire mass plummets to the bottom of the column. The result is a high recovery efficiency, however, very poor sand recovery quality. The air induced fluid flow serves two purposes: i) to disintegrate the SLDM mass and ii) to suspend manure solids. Increased air flow rates cause the SLDM mass to disintegrate faster. This is confirmed by comparing air flow rate to G-value, or mixing intensity. At higher air flow rates, more power is added to the system, resulting in an intensified degree of mixing (higher G). At higher flow rates, some sand is suspended in addition to the manure solids. This may occur for any or all of the following reasons: i) lack of discrete sand particle behavior due to interference with manure solids and/or air bubbles, ii) increased fluid viscosity at

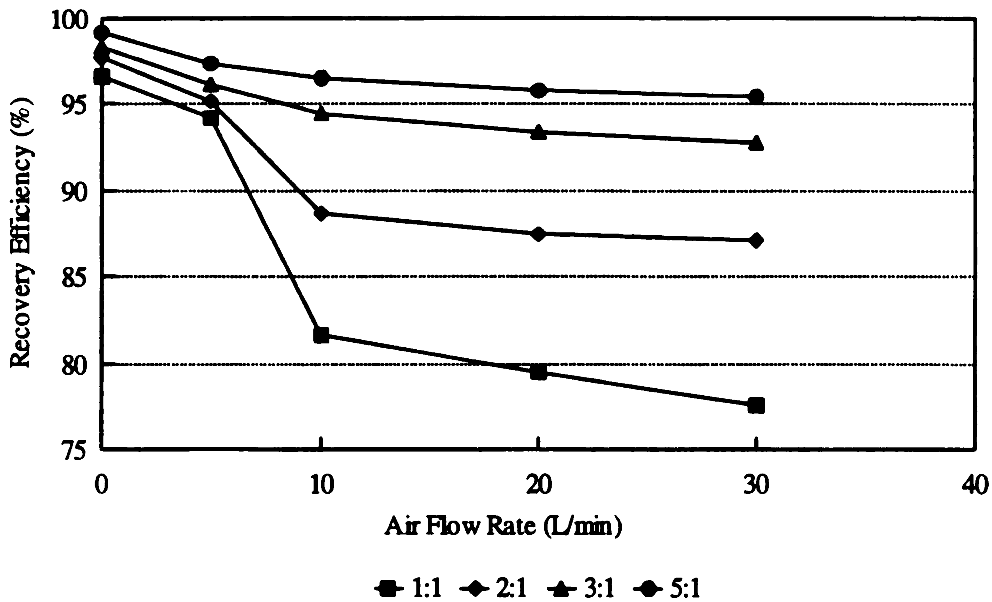

FIGURE 4.11: Recovery Efficiency vs. Air Flow Rate for Various Dilutions

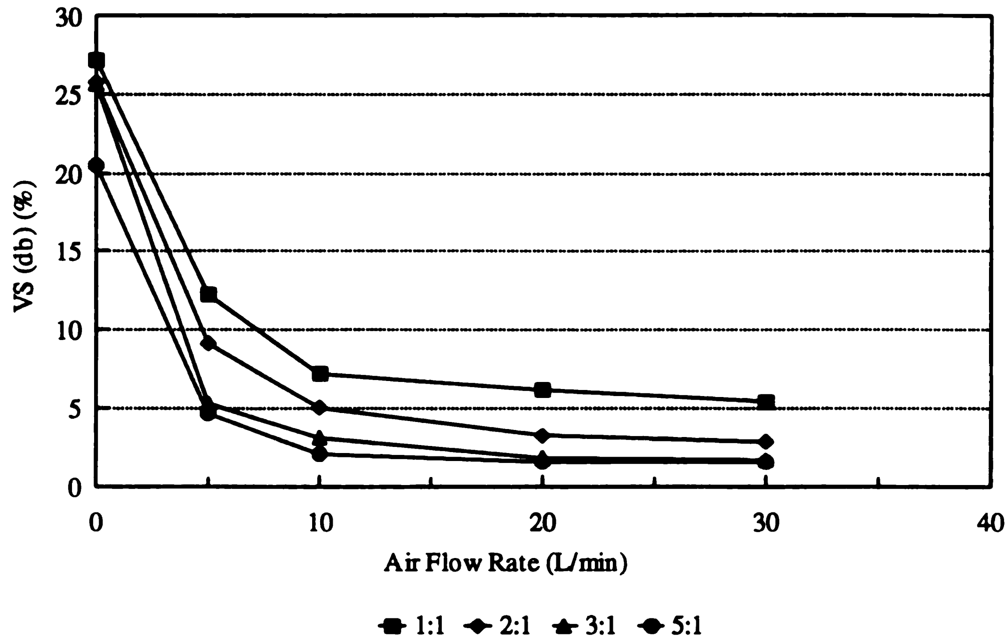

FIGURE 4.12: Recovery Quality vs. Air Flow Rate for Various Dilutions

the lower dilutions, iii) air induced fluid current exceeding the settling velocity of sand. It is impossible to relate air bubble velocity to fluid velocity due to the fact the slip is occurring between fluid components and the fluid is extremely turbulent. Slip occurs when a thin layer of fluid, having a viscosity lower than the bulk of the fluid, forms at the wall of the column (Steffe, 1992).

From Figure 4.11 and Figure 4.12 it is evident that dilution has a greater effect upon recovery efficiency and sand quality at low dilutions compared to higher dilutions. Also, recovery efficiency and sand quality are affected to only a small degree beyond 10 L/min.

Selecting the optimum operation conditions is a matter of selecting a combination of air flow and dilution ratio capable of yielding clean sand while still maintaining a high recovery efficiency. As previously determined, the recovery quality goal for the BAGC is 2 % VS(db). For this study, the optimum operating conditions are those which recover a sand fraction possessing at most 2 % VS (db) and a minimum recovery efficiency of 90 %, at the lowest possible air flow and dilution ratio.

CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1: Summary

Currently, it is estimated that in Michigan sand is used as bedding in over 50% of the dairy freestall barns. Sand possess many favorable characteristics that conventional bedding materials such as chopped straw, wood shavings, and saw dust do not. While using sand, dairy producers report improved udder health, added cow comfort, improved cow traction, and cleaner cows. Furthermore, sand is often cheaper than other bedding materials.

However, the disadvantages of using sand cannot be ignored. When sand is mixed with manure the result is a material which is difficult to handle and store on a long-term basis. Due to the abrasive nature of sand-laden dairy manure (SLDM), machinery components such as pumps and agitators experience premature wear. At the present time, a commercially available device capable of separating bedding sand from dairy manure and applicable to modern dairy facilities is nonexistent.

A variety of liquid/solid separation techniques currently employed in wastewater treatment operations as well as the dairy, mining, and petroleum refinement industries, were applied to SLDM. The following separation techniques were considered: i) screening, ii) sedimentation, iii) the hydrocyclone, iv) dissolved air floatation (DAF), and v) the belt filter press.

A sand separation device named the batch aerated grit chamber (BAGC) was developed. The BAGC is a hybrid of a continuous flow aerated grit chamber and a pachuca tank.

5.2: Conclusions

1a. Sedimentation is an effective sand separation technique. However, dilution water in excess of 1:1 is required in order to recover a significant amount of clean sand. The effects of dilution are reduced for dilution ratios greater than 3:1.

1b. Due to similarities in the particle size distributions of bedding sands (NS, MS, and FS) and raw manure, screening can be ruled out as a method for separating sand from manure.

1c. Hydrocyclones have the potential to be effective sand separators. However, in order to do so, a hydrocyclone must continuously be provided with an inflow composed of a uniform amount of organic solids.

1d. Dissolved air flotation is an ineffective sand separation technique. As the minute bubbles rise, they are incapable of suspending the coarse solids commonly found in manure.

1e. Belt filter pressing (BFP) is a viable technique for dewatering SLDM. Polymer conditioning prior to pressing has little or no effect on assisting in the reduction of TS, when compared to a noncondidtioned/pressed sample. However, polymer conditioning prior to pressing aided in the removal of VS from a SLDM cake.

2a. A BAGC sand separator is capable of yielding: i) a highly dilute manure fraction that can be pumped, stored, and land applied via conventional manure handling techniques and ii) a sand fraction, clean enough that it may be reused as bedding.

2b. Sand recovery efficiency and quality are functions of air flow and dilution ratio. Recovery efficiency of 90 % and sand recovery quality of 2 % VS(db) were obtained at air flow and dilution ratios of 20 Lpm and 3.1, respectively.

LIST OF REFERENCES

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American Society for Testing and Materials (ASTM). 1991. Concrete and aggregates. *Annual Book of ASTM Standards* 4.02: 33-35.

Bishop, J.R., A.B. Bodine, and J.J. Janzen. Effect of ambient environmental on survival of selected bacterial populations in dairy waste solids. *Journal of Dairy Science* 63: 523-525.

Bramley, A.J. and F.K. Neave. 1975. Studies on the control of coliform mastitis in dairy cows. *British Veterinary Journal 131*: 160-168.

Britten. A.M. 1994. Dairy free stall bedding and udder health In *Dairy Systems for the 21st Century*, ed, R. Bucklin, 165-172. St. Joseph, MI: ASAE.

Camp, T.R. 1946. Sedimentation and the design of settling tanks. *Transactions of the ASCE* 53: 895-936.

Camp, T.R. and P.C. Stein. 1943. Velocity gradients and internal work. *Journal of the Boston Society of Civil Engineers* 30: 219-237.

Cox, V.S. and R.S. Marion. 1992. Sand as bedding for a downer cow. *Veterinary Record* 130: 74-75.

Davis, M.L. 1994. Personal communication. Michigan State University. East Lansing, MI.

Davis, M.L. and D.A. Cornwell. 1991. *Introduction to Environmental Engineering*. New York: McGraw Hill Inc.

Fair, G.M., J.C. Maskew, and D.A. Okum. 1971. *Elements of Water Supply and Wastewater Disposal*. New York: Wiley.

Fairbank, W.C., T.A. Schultz, and W.D. Murray. 1984. Planning dairy wastewater systems for mosquito control. University of California Cooperative Extension.

Fischer, J.R., D.M. Sievers, and C.D. Fulhage. 1972. Settling characteristics of swine manure as related to digester loading. In *Managing Livestock Wastes*, 456-462.Columbus, OH: ASAE.

Gilbertson, C.B. and D.D. Schulte. 1987. Hydraulic settling of flushed swine manure-a case study. *Transactions of the ASAE* 3(1): 63-66.

Govier, G.W. and K. Aziz. 1972. *The Flow of Complex Mixtures in Pipes*. New York: Van Nostrand Reinhold.

Hazen, A. 1904. On sedimentation. *Transactions of the ASCE* 53: 45-71.

Hogan, J.S., K.L. Smith, K.H. Hoblet, D.A. Todhunter, P.S. Schoenberger, W.D. Hueston, D.E. Pritchard, G.L. Bowman, L.E. Heider, B.L. Brockett, and H.R. Conrad. 1989. Bacterial counts in bedding materials used on nine commercial dairies. *Journal of Dairy Science* 72: 250-258.

Hurnick, J.F. 1981. Understanding Dairy Cow Behaviour. Notes on Agriculture 17:5-8. University of Guelph, Ontario Agricultural College.

Kappe, S.E. and J.B. Neighbor. 1951. Some new developments in aeration. *Sewage and Industrial Wastes* 23: 833-842.

Kaufman, H.L. 1930. Determining air flow in agitation problems. *Chemical and Metallurgical Engineering* 37: 178-180.

Kivell, W.A. and N.B. Lund. 1940. Grit removal from sewage. *Water Works and Sewerage* 87:176-185.

Lamont, A.G.W. 1958. Air agitation and pachuca tanks. *Canadian Journal of Chemical Engineering* 36: 153-160.

Machina, D.W., and J.K. Bewtra. 1992. Bulk mixing using diffused air in circular and rectangular vessels. *Journal of Environmental Engineering* 118: 1-15.

Machina, D.W., J.A. McCorquodale, and J.K. Bewtra. 1992. Numerical and physical modeling of air diffuser plume. *Journal of Environmental Engineering* 118(2): 253-267.

McFarland, D.F. and M.J. Gamroth. Freestall designs with cow comfort in mind. In *Dairy Systems for the 21st Century*, ed, R. Bucklin, 165-172. St. Joseph, MI: ASAE.

Merkel, J.A. 1981. *Managing Livestock Wastes*. Westport, Connecticut: AVI Publishing.

Metcalf & Eddy, Inc. 1979. *Wastewater Engineering: Treatment Disposal and Reuse*. New York: McGraw-Hill.

Michigan Department of Agriculture. 1993. Michigan Agricultural Statistics 1993. Lansing, MI: Michigan Department of Agriculture.

Michigan Department of Transportation (MDOT). 1990. Standard specifications for construction. Michigan Department of Transportation: 496-497.

Midwest Plan Service. 1985. Livestock Waste Facilities Handbook (MWPS-18). Iowa State University. Ames, Iowa.

Mohsenin, N.N. 1970. *Physical Properties of Plant and Animal Materials, Vol. 1*. New York. Gordon and Breach Science Publishers.

Moore, J.A., R.O. Hegg, D.C. Schultz, and E. Strauman. 1975. Settling solids in animal waste slurries. *Transactions of the ASAE* 18(4): 694-698.

Narayanan, S., V.K. Bhatia, and D.K. Guha. 1969a. Suspension of solids by bubble agitation. *Canadian Journal of Environmental Engineering* 47: 360-364.

Narayanan, S., K. V.K. Bhatia, Guha, D.K., and M.N. Rao. 1969b. Suspension of solids by mechanical agitation. *Chemical Engineering Science* 24: 223-230.

Nichols, R.D. 1940. Grit-its collection and washing. *Water Works and Sewerage* 87: 190-193.

Perry, R.H. and D. Green. 1984. *Perry's Chemical Engineers' Handbook*. New York. McGraw Hill.

Railsback, S.F. 1992. Aeration at Ohio River basin navigation dams. *Journal of Environmental Engineering* 118: 444-452.

Rendos, J.J., R.J. Eberhart, and E.M. Kelser. 1975. Microbial populations of teat ends of dairy cows and bedding materials. *Journal of Dairy Science* 18: 1492-1500.

Reynolds, T.D. 1982. *Unit Operations and Processes in Environmental Engineering*. Belmont, California. Wadsworth Inc.

Roe, F.C. 1951. Air diffusion-a versatile tool for sewage and industrial waste treatment. *Sewage and Industrial Wastes* 23: 825-831.

Roy, N.K., D.K. Guha, and M.N. Rao. 1964. Suspension of solids in a bubbling liquid. *Chemical Engineering Science* 19: 215-225.

Shutt, J.W., R.K. White, E.P. Taiganides, and C.R. Mote. 1972. Settling characteristics of swine manure as related to digester loading. In *Managing Livestock Wastes*, 463-472. Columbus, OH: ASAE.

Sobel, A.T. 1966. Physical properties of animal manures associated with handling. In *Proc from the Natl. Symp. on Management of Farm Animal Wastes*, 27-32. East Lansing, MI.

Steffe, J.F. 1992. *Rheological Methods in Food Process Engineering*. East Lansing, MI: Freeman Press.

Szabo, E.C. 1970. Mixing by air diffused in water in circular vessel. Masters Thesis. University of Windsor. Windsor, Ontario, Canada.

Taggart, R. 1945. *Handbook of Mineral Dressing*. New York: Wiley.

Tark, M.B. and J.J. Gilbert. 1940. Grit chambers-schemes of yesterday vs. modern mechanical design. *Water Works and Sewarage* 87: 186-189.

Van Soest, P.J. and J.B. Robertson. 1985. Analysis of Forages and Fiberous Foods-A Laboratory Manual for Animal Science 613 (unpublished). Cornell University.

Vargas, K. 1992. Air-lift pump cleans around subsea wellhead. *Oil and Gas Journal* 90: 62-64.

Water Pollution Control Federation. 1959. *Sewage Treatment Plant Design*. Washington, D.C.: American Society of Civil Engineers.

Wedel, A.W. and W.G. Bickert. 1994. Handling and storage systems for sand-laden dairy manure from free stall barns. In *Dairy Systems for the 21st Century*, ed, R. Bucklin, 715-723. Orlando, FL: ASAE.

APPENDIX

TABLE A.1: Sand Bedding Acceptability Survey

Farm	Stall	TS (%)	VS (%)	VS (db) (%)	Acceptability (Y/N)
1	1	90.49	10.68	11.80	N
	2	98.48	3.91	3.97	Y
	3	92.94	4.13	4.44	Y
2	1	90.37	7.52	8.32	N
	2	97.45	3.58	3.67	Y
	3	99.17	3.50	3.53	Y
3	1	97.51	1.59	1.63	Y
	2	87.88	2.07	2.35	Y
	3	91.75	2.33	2.54	Y
4	1	98.46	2.09	2.12	Y
	2	95.95	2.46	2.57	Y
	3	88.60	2.50	2.82	Y
5	1	92.36	4.41	4.77	N
	2	94.69	2.97	3.13	Y
	3	79.78	5.47	6.86	N
6	1	78.67	18.36	23.33	N
	2	86.63	18.74	21.64	N
	3	95.76	5.70	5.95	N
7	1	98.42	1.25	1.27	Y
	2	93.84	2.42	2.58	Y
	3	93.37	2.64	2.83	Y
8	1	95.52	2.70	2.83	Y
	2	97.64	2.53	2.60	Y
	3	87.47	3.93	4.50	N
9	1	95.80	2.38	2.48	Y
	2	94.36	2.54	2.69	Y
	3	92.06	3.33	3.62	Y
10	1	97.55	3.49	3.57	Y
	2	94.00	3.20	3.40	Y
	3	96.78	4.11	4.25	Y
11	1	97.58	2.22	2.28	Y
	2	95.00	0.99	1.04	Y
	3	92.06	1.43	1.55	Y

TABLE A.2: Sieve Analysis Comparison--Raw Manure and 2NS Sand.

US Sieve Number	Opening Size (mm)	Manure Passed (%)	Sand Passed (%)	Manure Retained (%)	Sand Retained (%)
1/4	6.35	100	100	0	0
4	4.76	95.17	100	4.83	0
6	3.66	92.13	100	7.87	0
10	2.00	85.41	88.32	14.59	11.68
12	1.68	83.63	82.05	16.37	17.95
14	1.41	79.55	75.7	20.45	24.3
16	1.19	72.49	70.29	27.51	29.71
30	0.59	63.92	42.19	36.08	57.81
100	0.15	42.81	5.1	57.19	94.9
270	0.05	31.84	1.1	68.16	98.9

TABLE A.3: Sieve Analysis Comparison--Raw Manure and 2MS Sand.

US Sieve Number	Opening Size (mm)	Manure Passed (%)	Sand Passed (%)	Manure Retained (%)	Sand Retained (%)
1/4	6.35	100.0	100.0	0.0	0.0
4	4.76	95.2	100.0	4.8	0.0
6	3.66	92.1	100.0	7.9	0.0
10	2.00	85.4	94.2	14.6	5.8
12	1.68	83.6	91.1	16.4	8.9
14	1.41	79.6	88.6	20.4	11.4
16	1.19	72.5	87.9	27.5	12.1
30	0.59	63.9	73.3	36.1	26.7
100	0.15	42.8	12.6	57.2	87.4
270	0.05	31.8	2.3	68.2	97.7

TABLE A.4: Sieve Analysis Comparison--Raw Manure and 3FS Sand

US Sieve Number	Opening Size (mm)	Manure Passed (%)	Sand Passed (%)	Manure Retained (%)	Sand Retained (%)
1/4	6.35	100.0	100.0	0.0	0.0
4	4.76	95.2	100.0	4.8	0.0
6	3.66	92.1	100.0	7.9	0.0
10	2.00	85.4	100.0	14.6	0.0
12	1.68	83.6	99.8	16.4	0.2
14	1.41	79.6	99.8	20.4	0.2
16	1.19	72.5	99.7	27.5	0.3
30	0.59	63.9	99.1	36.1	0.9
100	0.15	42.8	11.8	57.2	88.2
270	0.05	31.8	1.9	68.2	98.1

TABLE A.5: SLDM Slurry Temperature.

Test Number	Dilution Rate	Air Flow Rate (L/min)	T (^{o}C)
1	1:1	0	27
2	1:1	5	27
3	1:1	10	28
4	1:1	20	28
5	1:1	30	28
6	2:1	0	26
7	2:1	5	26
8	2:1	10	26
9	2:1	20	27
10	2:1	30	27
11	3:1	0	25
12	3:1	5	26
13	3:1	10	26
14	3:1	20	26
15	3:1	30	26
16	5:1	0	25
17	5:1	5	25
18	5:1	10	26
19	5:1	20	26
20	5:1	30	27

TABLE A.6: BAGC Data for Q= 0 L/min.

DR (X:1)		Recovery Efficiency (%)	Sand VS (db) (%)
5		99.6	20.3
		98.7	21.4
		99.0	20.7
		99.2	22.6
		98.8	19.7
		99.9	18.5
	Average=	99.2	20.5
3		99.5	26.0
		98.4	26.0
		98.3	25.4
		97.5	25.0
		98.3	27.3
		97.8	24.2
	Average=	98.3	25.6
2		98.7	26.8
		98.9	25.7
		97.2	26.5
		97.0	25.3
		97.2	24.9
		97.0	25.4
	Average=	97.7	25.8
1		95.0	27.6
		95.3	26.6
		96.6	28.0
		97.2	27.2
		97.6	25.7
		98.1	28.1
	Average=	96.6	27.2

TABLE A.7: BAGC Data for Q=5 L/min.

DR (X:1)		Recovery Efficiency (%)	Sand VS (db) (%)
5		97.0	4.4
		97.4	4.4
		98.9	4.9
		96.6	5.1
		95.3	5.9
		98.6	3.1
	Average=	97.3	4.6
3		96.0	3.2
		96.9	5.7
		96.4	5.9
		96.7	4.8
		95.1	6.7
		95.6	5.8
	Average=	96.1	5.4
2		95.7	9.5
		95.4	9.2
		93.1	8.7
		94.6	8.6
		96.3	8.1
		95.8	10.9
	Average=	95.1	9.1
1		94.2	12.8
		95.6	12.0
		95.3	11.9
		95.2	10.4
		92.6	13.6
		92.2	13.1
	Average=	94.2	12.3

TABLE A.8: BAGC Data for Q=10 L/min.

DR (X:1)		Recovery Efficiency (%)	Sand VS (db) (%)
1		97.0	2.0
		97.4	2.2
		96.3	2.0
		96.1	2.8
		95.3	1.8
		97.1	1.8
	Average=	96.5	2.1
2		94.3	2.9
		94.6	2.5
		95.6	3.8
		93.4	3.7
		93.1	3.4
		95.8	2.0
	Average=	94.5	3.0
3		89.5	5.4
		89.2	5.6
		89.0	4.2
		88.8	5.3
		87.1	5.2
		88.2	4.2
	Average=	88.6	5.0
5		81.4	7.5
		79.1	6.9
		82.3	6.6
		81.4	9.0
		81.9	7.3
		83.6	6.0
	Average=	81.6	7.2

TABLE A.9: BAGC Data for Q=20 L/min.

DR (X:1)		Recovery Efficiency (%)	Sand VS (db) (%)
5		96.1	1.6
		96.6	1.6
		97.1	1.9
		95.3	1.8
		95.2	1.7
		94.2	1.1
	Average=	95.8	1.6
3		92.4	2.0
		93.5	2.0
		93.2	1.8
		93.5	1.4
		94.5	1.6
		93.1	1.8
	Average=	93.3	1.8
2		88.3	3.6
		87.2	3.8
		87.4	3.0
		86.6	2.0
		87.3	3.8
		87.7	3.2
	Average=	87.4	3.2
1		80.8	6.2
		78.2	6.4
		80.2	6.5
		79.5	5.1
		79.3	5.3
		78.5	7.9
	Average=	79.4	6.2

TABLE A.10: BAGC Data for Q=30 L/min.

DR (X:1)	Air Flowrate (LPM)	Recovery Efficiency (%)	Sand VS (db) (%)
5	30	94.2	1.6
		94.3	1.6
		95.2	1.8
		96.2	2.0
		96.1	1.5
		96.0	1.5
	Average=	95.3	1.7
3	30	91.0	1.8
		92.4	1.7
		92.3	1.8
		93.0	1.6
		92.2	1.7
		95.3	1.7
	Average=	92.7	1.7
2	30	87.2	3.0
		88.2	3.0
		88.0	3.2
		87.0	3.0
		86.1	2.6
		86.2	2.5
	Average=	87.1	2.9
1	30	78.2	5.9
		78.3	4.9
		77.3	5.2
		76.1	5.3
		75.1	5.4
		80.1	5.4
	Average=	77.5	5.4