SAND-MANURE SEPARATION FOR ANAEROBIC DIGESTION PRETREATMENT

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BACKGROUND

Cow comfort is a key ingredient to high milk production and ultimately producer profitability. Sand remains the freestall bedding of choice among dairy producers and veterinarians. Mastitis causing organisms require food (carbon source), water, and heat to thrive and survive. Properly selected and/or separated bedding sand contains minimal organic matter. Less organic matter translates to less moisture as organic matter absorbs moisture. Alternative organic beddings such as manure and wood products, although perhaps low in bacteria content at first, experience substantial increases in bacteria counts as soon as a bed is seeded with bacteria. In addition to the biological advantage offered by sand, there are positive physical attributes as well. A cow in the process of lying undergoes what resembles a controlled fall. The cushiony surface offered by sand reduces stresses on knees and joints due to impact with the stall surface. Sand also offers sure footing when rising and moving about freestall alleys. Ultimately, the goal being to increase the number of lactations a cow spends in the milking herd by reducing cull rate due to stress, injury, and disease.

Traditionally, sand bedding has caused substantial manure handling challenges even with relatively straightforward systems such as daily haul and short- or long-term storage. These challenges come to fruition when manure handling equipment and systems are used to process sand-laden manure. Anaerobic digestion (AD) systems are particularly susceptible to sand settling and equipment wear. The implementation of mining equipment and associated system design methodologies to separate sand from manure prior to AD has proven successful over the long-term on dairies. Pretreatment systems to separate sand from manure could potentially increase AD adoption since some producers will elect not to bed with manure—the norm with traditional AD systems.

The specific objectives of this paper are to describe:

1. Physical characteristics of sand-laden manure related to handling, storage, and separation.
2. Sand-Manure Separation (SMS) pre-treatment system operation.
3. Operating characteristics of SMS systems serving as pre-treatment to AD including SMS performance data for use by system designers.

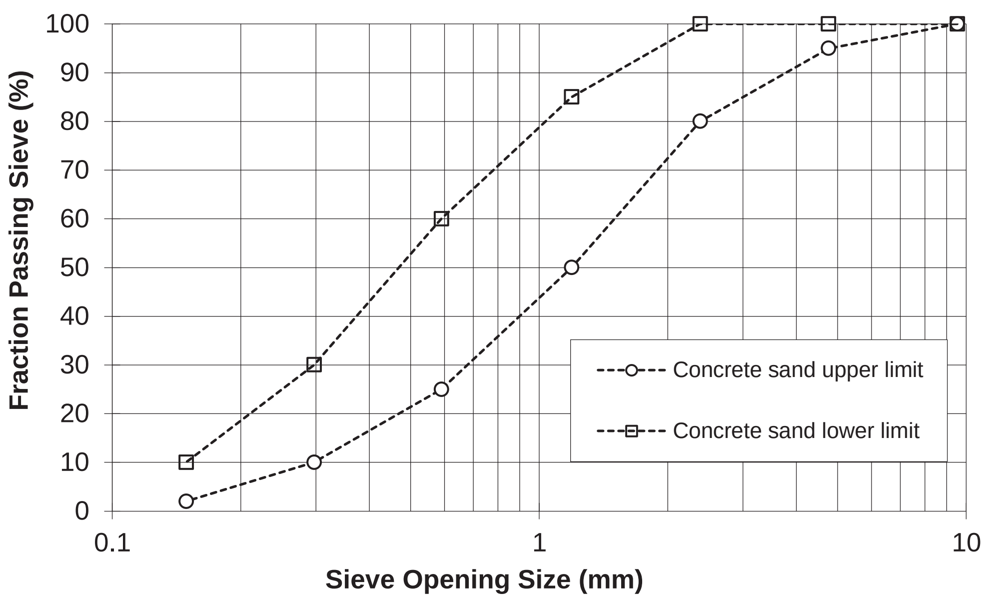
SAND-LADEN MANURE PHYSICAL CHARACTERISTICS

An understanding of the physical characteristics of sand-laden manure (SLM) is essential when designing handling and separation systems pre-AD and advanced treatment. Certain considerations need to be made for SLM as compared to “normal” manure. These considerations must address sand settling and scour. Abrasiveness of sand is another obvious consideration where pumps and other process equipment are concerned. Abrasiveness can be addressed by using materials of construction harder than sand grains and/or materials capable of returning to their “normal” shapes after contact with sand. Low operational speeds also reduce abrasive wear as wear is directly proportional to the speed squared—that is to say, if speed is doubled, wear is increased by a factor of four.

Factors Affecting Settling and Scour

The size, shape, and density (in relation to a bulk medium) of a particle affects the velocity at which it settles and settling velocity is the primary consideration in the design of sand-manure separation systems pre-AD and/or advanced treatment systems. A sand gradation is a description of the particle sizes as well as the quantity of said sizes in a sand sample. Bedding sand can be naturally occurring or manufactured. Manufacturing of sand involves washing processes that remove fine material and organic matter. Sand, free from silts and clay, and organic matter, is an ingredient in concrete. To qualify as concrete sand, sand must meet a size specification prepared by the ASTM (formerly American Society for Testing and Materials), otherwise known as ASTM C-33 (ASTM, 2003). This is a washed sand product. Being washed, C-33 contains a minimal amount of fine material—fine material being described as smaller than 100 mesh or 149 microns. The particle size distribution (gradation) for specification concrete sand is found in Figure 1 and shows the acceptable particle size range.

Figure 1: Concrete sand particle size gradation



Density of sand particles is typically assumed to be 165 lb/ft^3 (SG = 2.65) for analysis of settling (Merritt, 1968). This is not to be confused with the bulk density of stock piled sand, which depending on moisture content and particle size distribution, can range from between 110 to 130 lb/ft^3 (SG = 1.76 to 2.08). The fact sand is approximately more than 2 times more dense than manure (density equal to 62 lb/ft^3, for SG approximately equal to 1.00) (ASABE, 2011) makes settling an ideal mechanism for separating sand from manure.

Settling

Sand-laden manure (SLM) is a mucosal gel where sand grains, along with water, are enveloped between the folds of long chain carbohydrates. Sand is not necessarily in suspension in undiluted SLM mass, but instead held intact due to the viscous nature of the manure. Some sand grains settle from undiluted SLM—those that possess the physical characteristics enabling them to overcome slurry viscosity. These tend to be the largest sand grains. Sand settles primarily in the presence of dilution. Laboratory research has shown, as verified in the field, diluting SLM one to one (one mass part water to one mass part SLM) is enough to disrupt the manure structure (e.g. reduce viscosity) to a point where the sand grains are released and readily able to settle (Wedel and Bickert, 1996). Factors affecting sand settling can be described using Stokes' Law, which states, settling velocity is directly related to: the difference in density between the particle (sand) and the medium (manure); the square of particle diameter (d); and inversely related to viscosity (Merritt, 1968). This is essentially a ratio of inertial forces and viscous forces acting on a particle. In short, large, dense particles in clean water settle fastest compared to small, less dense particles in dirty water. It is conceivable to encounter sand grains and organic matter that settle together at the same velocity when similar Stokes conditions are satisfied, that is to say, a small, dense particle will settle at the same velocity as a large, less-dense particle. This explains why in passive sand settling systems, finer sand grains are laden with organic manure solids.

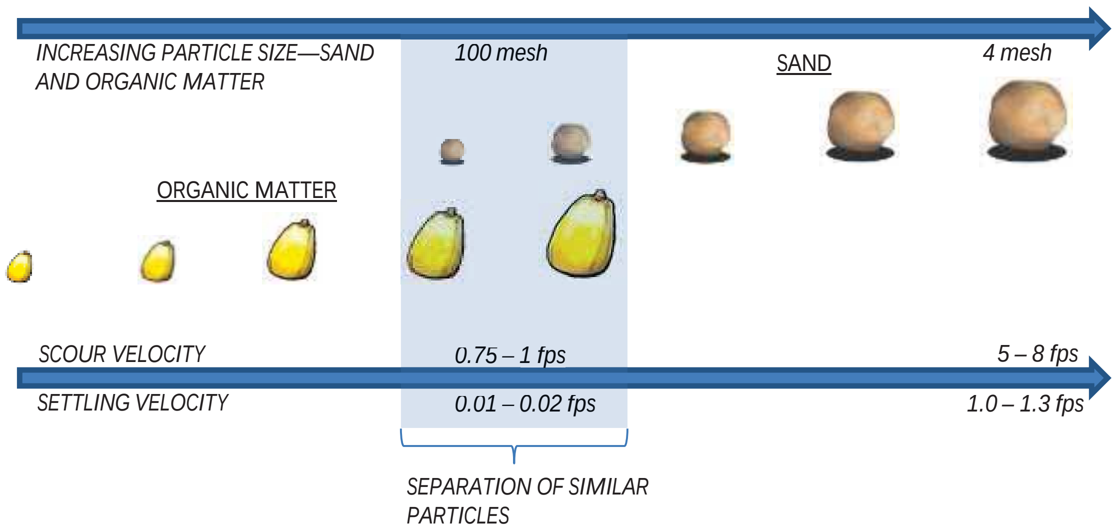
Scour

Scour is the process by which particles are kept in suspension or suspension is initiated by flowing with water. As it relates to dilute SLM, Shields' equation models (validated in practice) scour velocity in pipes and/or channels designed to convey dilute sand and manure for specific particle sizes. Since scour velocity is directly related to particle size (amongst other factors), to maintain scour (in flume pipes), the largest particle in the gradation should be considered. For settling of fines (sand-manure separation), the finest particle to be captured is modeled. Whereas the goal of conveyance is to maintain particles in suspension, the goals of separation are to allow sand grains to settle, yet maintain adequate velocity to scour organic matter. Scour velocities for conveyance and separation typically range between 5 to 8 ft/sec (Wedel, 2000) and 0.75 to 1 ft/sec (Merritt, 1968), respectively. A detailed description of Shields' equation can be found in Camp (1946) and Merritt (1968).

The principles of settling and scour will be shown below to support design considerations related to handling and separation systems. In summary, to properly design handling and/or separation systems pre-AD, knowing the gradation of the bedding sand is essential. Controlling scour and settling is important to successful design and operation of any SLM handling system. Improperly considering settling and scour leads to pipes, channels and tanks full of sand as well as dirty separated sand (e.g. high organic and moisture loading).

Figure 2 pictorially describes, in relative terms, the relationships of settling and scour velocities for sand and organic matter. The shaded region is where similar particle sizes exhibit similar settling and scour characteristics.

Figure 2: Relative Settling and Scour Velocities for Varying Particle Size (not to scale)



SAND-LADEN MANURE HANDLING

Systems designed for manure rather than sand tend to not consider the fact sand settles from diluted manure, which translates to a need to maintain high pipeline velocities and adequate safe access to locations where sand may settle. Furthermore, traditional manure handling equipment relies on materials of construction, component selection, and speeds that are not conducive to long service life in the presence of sand. Mining duty equipment and systems are used to process sand gravel and crushed stone for construction purposes. Sand and gravel plant operators require high recovery of fines so as not to fill ponds and to produce a maximum amount of usable sand product. These goals are in complete alignment with those of a dairy operation.

Challenges with sand bedding extend to anaerobic digestion (AD) systems and other manure treatment systems. With complex networks of influent piping and sealed tanks lacking loader access, ADs are exceptionally sensitive to sand (and debris) settling. Even small amounts of bypass sand, overtime, can be exceptionally problematic.

Consider a 1,000 cow dairy using sand at a rate of 50 lb/cow/day. Assuming, 5% bypass, 2,500 lb sand /day—almost one cubic yard or 200 gal/day would be introduced to the digester daily. In addition to bedding sand, manure contains grit from other sources, such as blow sand, degrading concrete, soil from harvesting, etc. Grit from these sources, often overlooked by designers, alone causes AD failures even on dairies not bedding with sand. It is also reasonable to assume some bypass sand, by virtue of the viscous nature of the AD tank contents, will stay in suspension and discharge from the AD tank. Nevertheless, the goal should be complete sand removal as to relieve all doubt as to the fate of bypass sand. Although, 100% sand recovery pre-AD is not practically achievable without also removing a substantial portion of organic solids where settling processes are concerned, digesters are operating successfully over the long-term where ASTM C-33 concrete sand is used as bedding and 95% sand recovery or greater is achieved.

Conveyance

Conveyance to Sand-Manure Separation (SMS) systems with ADs usually involves some form of scraping without the addition of water. Manure may be augered, alley scraped, vacuum tanked, or scraped directly into a SMS reception pit. Each option has been proven reliable provided, as mentioned previously, steps are taken to mitigate abrasive wear and the tendency for sand to settle in unintended locations. Under no circumstances should gravity be used to convey undiluted SLM. The settling of large sand grains, over time, will lead to clogging. Pipes as short as 12 feet and 2 feet in diameter are susceptible to clogging. Conveying diluted SLM in flush flumes—that is, using water to dilute and provide energy necessary to move manure and sand, can successfully be achieved by selecting the proper combination of pipe slope, diameter, and flow rate to match the required minimum scour velocity (Wedel, 2000). Flume pipes then must be installed by reputable contractors willing to and capable of strictly adhering to design drawings. Flume systems are not particularly common when teamed with ADs as they require substantial quantities of water, thereby, diluting the influent and increasing reactor size and parasitic heat demand (e.g. heating water). Recently, however, ADs have successfully operated in flume systems where pre-AD the manure influent it thickened using conventional liquid-solid separation equipment.

The SMS systems presented here as AD pretreatment rely on scrape systems or any system that does not rely on dilution to convey SLM. These systems include: scraping directly to a reception pit, scraping (manual or automatic) to an auger, or vacuum tanking.

Sand-Manure Separation pre-AD

All sand-manure separation (SMS) systems rely on gravity settling, which is largely due to the favorable conditions leading to differential settling. As previously noted, mining-duty sand washing equipment and system design methodologies are used to separate sand from manure. To achieve maximum sand recovery, three Stages of SMS are necessary and shown as Stages 1 through 3, below. Each Stage is designated as either controlled (sand recycle) or non-controlled (sand disposal) separation. The complete SMS process, pictorially, is shown in Figure 3 and material process flow diagram in Figure 4.

Stage 1: Primary SMS

The Stage 1 SMS is a mining duty sand washing system modified for washing manure solids from sand. In mining duty operations, the same class of equipment is used to wash organic contaminants from sand deposits. Using an auger or piston pump, SLM is conveyed into the Stage 1 SMS unit where it is diluted approximately 1:1 (one part water to one part of SLM) using parlor wash water at an approximate rate of 80 gal/min. This is not extra fresh water being added to the system for the purpose of SMS, per se, but instead water that is normally necessary for milking and parlor/holding pen hygiene. Quality of the recycled water is critical and should contain less than 2% TS. Once diluted, settled sand is conveyed out of the SMS using a mining duty auger. Prior to discharging from the SMS, the sand is rinsed with fresh water at an approximate rate of 5 gal/min (1 to 2 gal/cow/day = 0.25 ft^3/cow/day). Even though this is indeed fresh water being introduced into the system for the purpose of reclaiming sand, the amount of sand removed (0.4 ft^3/cow/day) from manure exceeds the amount of fresh water added. Manure, fine sand, along with water flows over a series of overflow weirs.

Figure 3: Sand-Manure Separation System

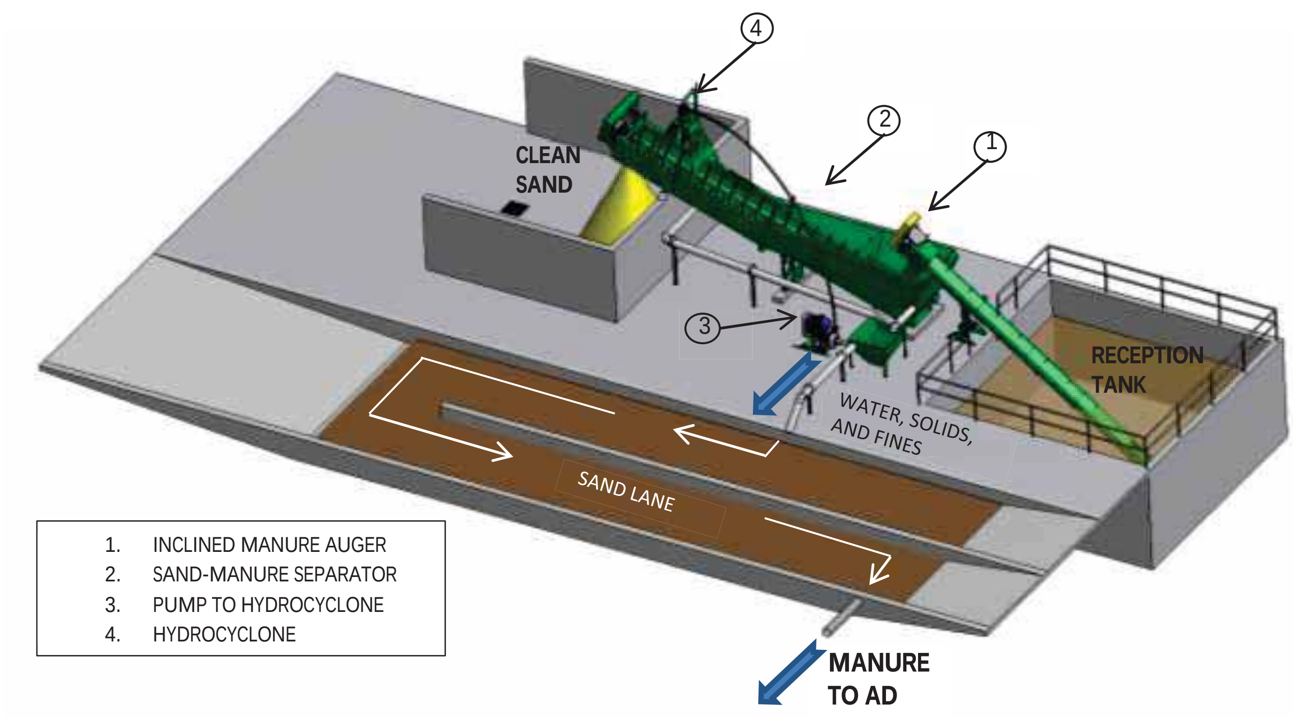
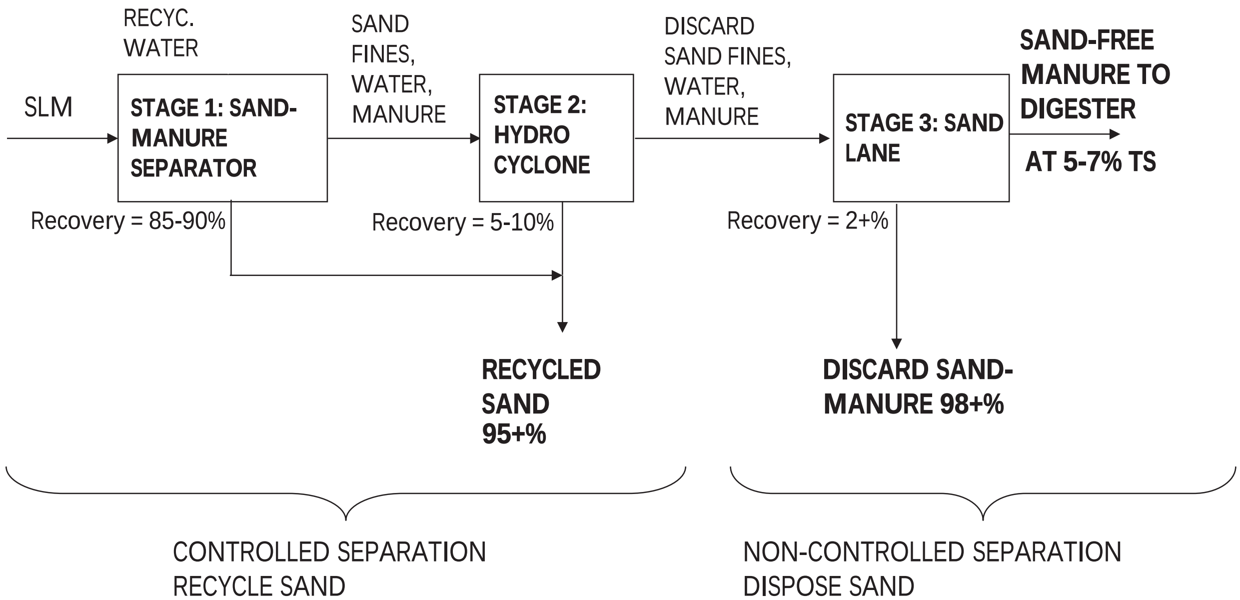


Figure 4: Sand-manure separation (SMS) system process flow.



This primary phase of SMS achieves recovery of approximately 85 to 90%. The total solids content of the Stage 1 SMS effluent is approximately 5 to 7% TS. This corresponds to a dilution ratio of 1:1, or, one mass part of water to one mass part of SLM added to the system

The level of sand recovery and conversely sand bypass achieved in Stage 1 is acceptable for many dairy operations, however, unacceptable for AD systems. The reason for fine sand bypass is fine sand grains cannot overcome the viscosity of the bulk slurry even at a 1:1 dilution.

Stage 2: Hydrocyclone

Recalling Stokes' Law, for particles to settle, inertial forces causing settling must be greater than the viscous forces keeping particles in suspension. Hydrocyclones are mining-duty devices used to separate fine sand from slurry (Figure 5). A hydrocyclone consists simply of a hollow, conical "body". SMS effluent from Stage 1 flows into an above ground steel sump and pumped using a rubber lined pump into a hydrocyclone. In the hydrocyclone particles flow at a high velocity in a circular motion. This imposes centrifugal force on solid particles greater than that which is experienced at 1 "g". The heaviest particles such as sand are forced to the wall of the hydrocyclone and essentially flow and/or settle to the discharge opening at the bottom of the cone (underflow). The underflow material is discharged back to the Stage 1 SMS and combined with the settled sand recovered in Stage 1. The hydrocyclone captures an additional 5 to 15% of the sand entering the system depending on the original sand gradation. Liquids, lighter materials like manure solids, and fine sand grains are forced out through the top of the cone (overflow).

Stage 3: Gravity Settling

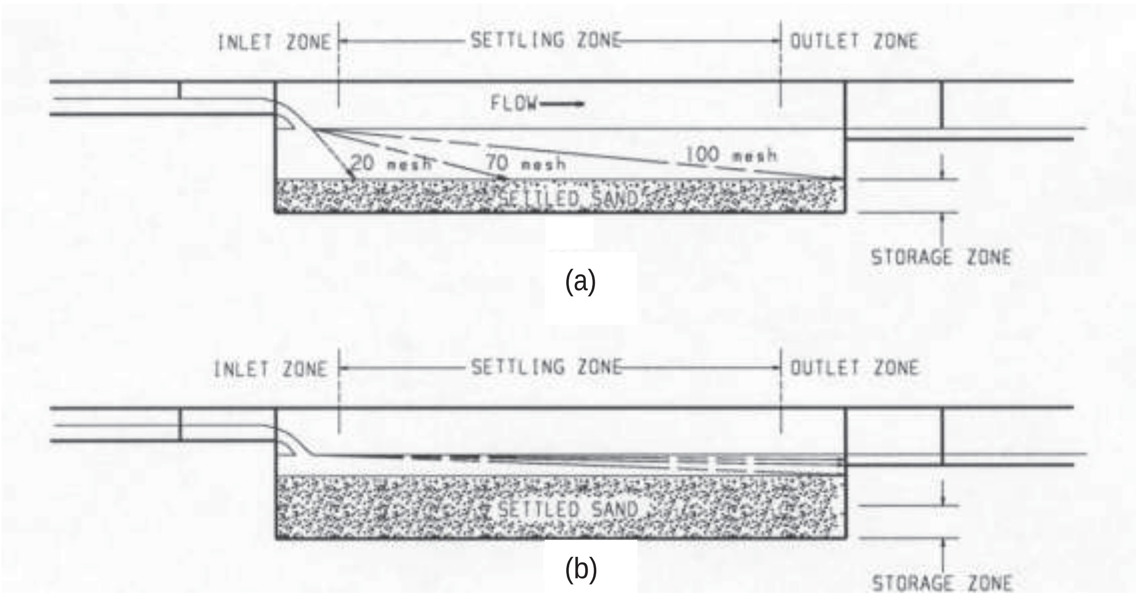
Gravity settling by means of a sand lane follows the hydrocyclone. Sand lanes capture a majority of the fine sand discharged from the hydrocyclone. Sand bypass from the hydrocyclone can occur due to multiple reasons. There are physical limits as to how fine of sand grains a hydrocyclone capture. Fine sand grains may also be embedded or otherwise attached to manure solids. After the turbulence induced by the pumping, the sand grains are physically removed from the organic matter. Finally, the water velocity down the sand lane can be such that fine grains of sand may settle, however, in doing

Figure 5: Hydrocyclone installed above a SMS (l) and hydrocyclone schematic (r)

so a portion of manure solids settle as well (as illustrated in Figure 2). In the interest of preventing sand from filling digesters, this loss of organic matter is considered acceptable in comparison to the alternative, that being, decommissioning and removing solids from AD vessels.

Sand lane dimensions and characteristics (slope, length, width, and surface roughness) are designed based on Mannings' equation (see Merritt, 1968) using hydrocyclone underflow flowrate to optimize horizontal flow velocity at 0.75 to 1 ft/sec. The goal is to have a sand grain enter the lane, settle (particle flow trajectory intersect the basin floor), and not become re-entrained (scoured) into the flow. Proper management of the sand lane is critical to system success. As soon as sand begins to settle on the lane, performance changes. As the "front" of settled sand migrates down the lane, it is imperative to clean the lane before sand discharges from the lane. A sand lane full of sand will discharge sand particles that do not have an opportunity to settle (Figure 6b).

Figure 6: Sand settling lane schematic



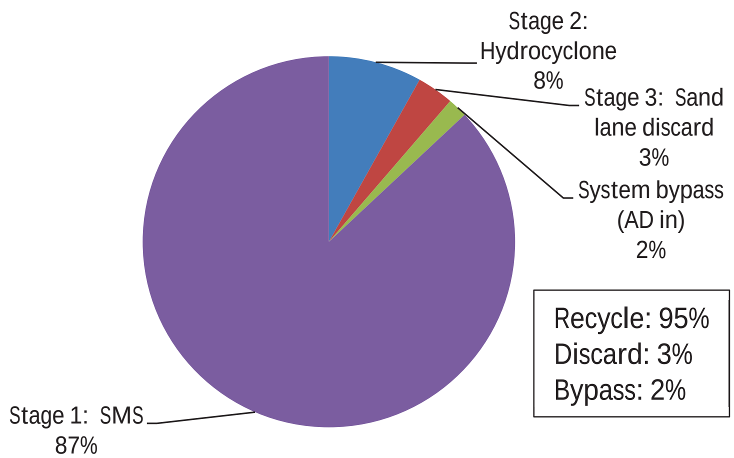
Two lanes facilitate cleaning since flow can be diverted to the lane not being cleaned. This results in a drier recovered product. Sand lanes are a means of non-controlled settling—that is, once constructed, nothing can be done physically to enhance performance (e.g. capture more sand and/or capture fewer manure solids). The only means of control available to the operator is cleaning frequency. Stage 3 sand contains high organic solids loading (VS approximately 5%) compared to Stages 1 and 2 and, therefore, not suitable for recycling. This sand is typically land applied.

Overall System Performance

SMS system performance data was collected from an AD system processing SLM manure at a 3,500 cow dairy after three years of operation. Concrete sand is used for bedding. It is assumed the bedding sand particle size gradation and recovery has reached equilibrium—that is, it is assumed a system recovery is lower initially as fines are washed from a large quantity of newly purchased sand. It is further assumed recovery increases and stabilizes once the fines are removed and some sand is purchased to account for the losses. The analysis considers the need to separate all fixed solids (FS) from a manure stream. Some of the fixed solids are attributable to bedding sand and some to grit in manure (not sand bedding)—the result of harvesting, blow sand, concrete degradation, and inorganic minerals in a dairy ration. All sand and grit, regardless of the source, has the potential to settle in tanks. Furthermore, gravimetric analyses of sand-laden manure samples for FS do not differentiate between sand FS and FS found in excreted manure.

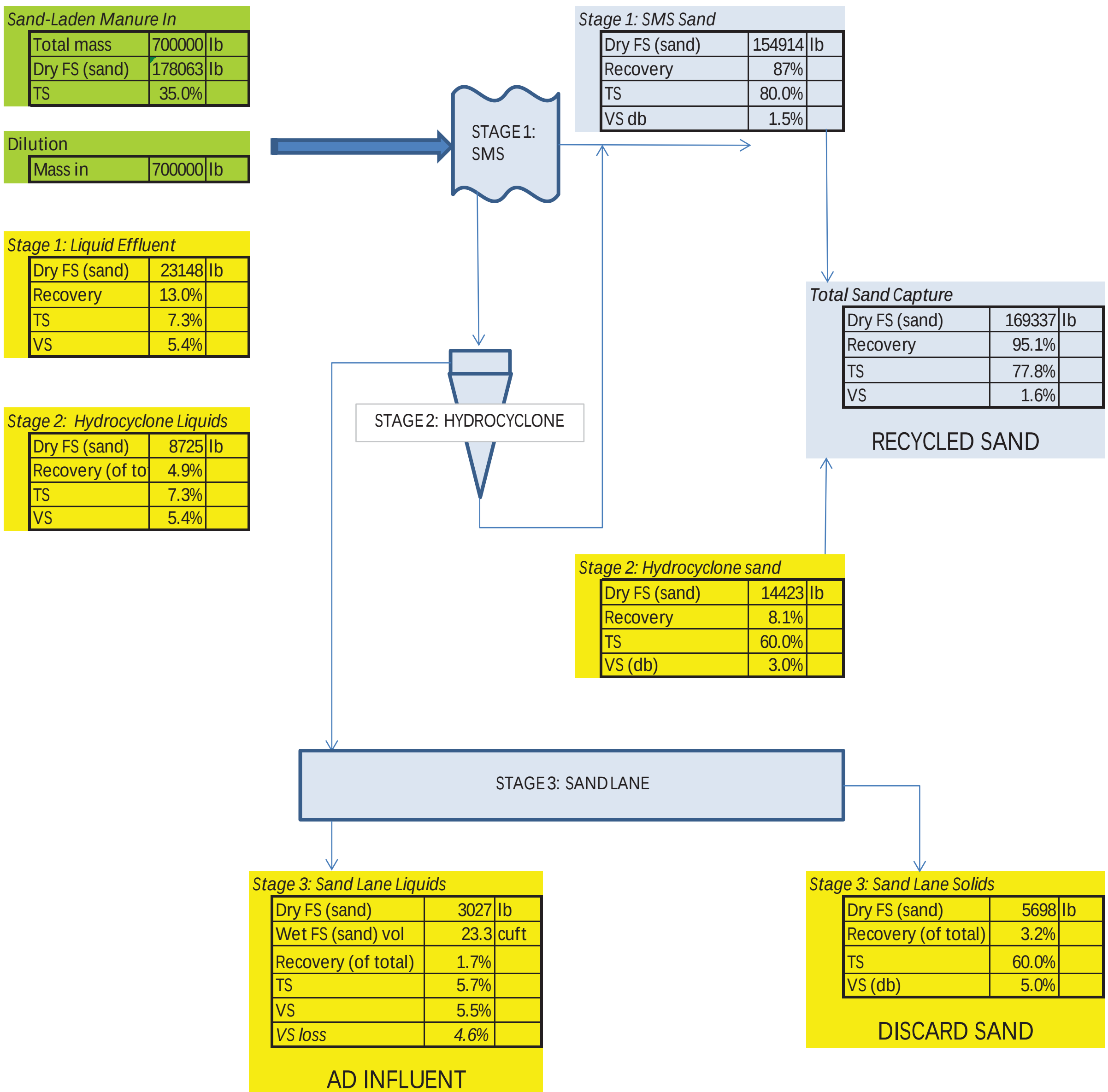
Sand reclaimed from the SMS system was discharged at an average dry basis organic matter content (VS) of 1.6%. Sand is recycled to bed milk cows within one month. By comparing the gradation of the: 1) recycled sand to the, 2) bypassed fines, and 3) input sand using an analysis method described by Svarovsky (1990), average overall recovery of useable sand (SMS Stages 1 and 2) was found to be 95%. This is a sum of the Stage 1 SMS and Stage 2 hydrocyclone recoveries of 87.0 and 8.1%, respectively (see Figure 7). Figure 8 is a complete mass flow analysis for a SMS pre-treatment system. Additionally, 3.2% of sand is captured on the sand lane (Stage 3) and land applied. Settled sand recovered from the sand lane had an organic matter content of 5.0% and is judged too dirty for reuse. Overall sand recovery for the three Stages of separation is 98.3%. The remainder of the sand (1.7%) bypasses the SMS process and is discharged to the digester. For 3,500 cows, 1.7% bypass represents 3,027 pounds of sand per day or approximately one cubic yard. Although some of this sand could eventually settle in an AD vessel, the majority of it is extremely fine (less than 100 mesh) and will remain in suspension due to the viscosity of the manure. Using concrete sand is advantageous since a majority of sand fines are washed out during the manufacturing process. AD designers should have a contingency plan in place to address potential sand accumulation in tanks. Due to the dilute nature of the SMS system discharge (5.7%), any AD receiving this influent will include some kind of mixing. Influents at these low TS concentrations are best suited for mixed plug flow or complete mix systems.

Figure 7: Separated sand outcomes



As previously described, due to the dilution necessary to facilitate sand settling, SLM is typically introduced to a SMS system at approximately 30% TS. Sand lane (Stage 3) liquid discharge ranges between 5 and 7% TS. AD designers should be aware of the composition of AD effluent post SMS, particularly TS and VS. Gooch et al. (2006) describes considerations with regard to AD heating requirements when digesting diluted versus undiluted SLM. Lower TS creates a higher parasitic heat load and potentially a system with lower energy output when compared to undiluted AD influents. Some AD operators have observed digesting influent at lower TS concentrations, despite gas output being lower, methane concentration is higher when compared to biogas produced from less dilute manure since contaminants such as carbon dioxide remain in solution. This is a topic for further study. Generally speaking, biogas production is decreased since volatile organic solids (VS) are captured in sand throughout the SMS settling processes. These VS are otherwise fuel for the AD. Approximately, 4.6% of the VS introduced to the SMS system are lost to the recycled sand (Stages 1 and 2) and discard sand (Stage 3).

Figure 8: Sand-manure separation (SMS) system mass balance



CONCLUSIONS

Sand remains the freestall bedding of choice amongst dairy producers due to benefits related to cow comfort, udder health, and milk quality and quantity. Sand-manure separation (SMS) systems operating as anaerobic digester (AD) pretreatment are proven on large dairies over the long-term. Accommodating sand users interested in AD could potentially increase AD adoption since some producers will elect not to bed with manure—the norm with traditional AD systems.

1. Understanding the relationships involving the settling characteristics of sand and manure solids are key to designing successful SMS systems and sand-laden manure handling systems in general.
2. Mining duty design methodologies and equipment are used to separate sand from manure pre-AD. Properly designed SMS systems are capable of 98% sand recovery. This level of sand recovery is achieved via three Stages of SMS: 1) primary SMS, 2) hydrocyclone, and 3) gravity settling.
3. Of the 98% sand recovery, 95% is recycled in Stages 1 and 2 and used to bed milk cows. The remainder captured in Step 3 is land applied. Bypassed sand must be accounted for whether by agitation (preferred) and/or by providing means for tank clean-out. Some organic solids are captured along with the separated sand due to similar settling characteristics for some sand and manure solids. The result is a 4% loss of organic matter (4% not delivered to the AD). The loss of organic matter must be accounted for when estimating biogas production. SMS effluent (AD influent) discharges at approximately 6% TS. AD systems should be selected accordingly with regard to mixing and heating requirements.

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