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Research Article

Characterization of sewage sludge particles influencing dewaterability

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ABSTRACT

This study presents an investigation into the fundamental characteristics of sludge particles that influence the dewaterability of sewage sludge. Dewatering of sewage sludge is required for the reduction of sludge volume, sludge treatment, and safe disposal of sludges having very high pollution potentials. Particle characteristics important for dewatering, like particle size distribution, particle density, bound water content, surface charge, protein, and polysaccharide content of activated and digested sludges, were determined. Without a suitable method for analyzing the total range of particles in sewage sludge and effective density, new techniques have been developed to determine particle size distribution and particle density with reasonable accuracy. Particles larger than 45 µm were analyzed by wash sieving, while particles smaller than 45 µm were analyzed using a Coulter counter. The results from both methods were combined, maintaining their proportional contribution to the overall particle size distribution. Particle density was computed by determining the dry density and bound water content. Additionally, particle size and velocity were measured using an interference microscope, and these values were inserted into Stokes' Law equation to calculate the effective density of sludge particles.

Introduction

Sewage sludge is an aqueous suspension of particulate solids composed of complex organic and inorganic matter with significant water within the particles. Coackley (1956) indicated that sludge is a mixture of proteins, fats, carbohydrates, polysaccharides, microorganisms, and floes composed of all or some of these materials, grit, and anything else that may get into the sewage system. Treatment and dewatering of sewage sludge have become very important to achieve sustainable sanitation development goals (SDG) (Target 6.2). Most developing countries are lagging behind the target of attaining safely managed sanitation in which on-site and off-site treatment and safe disposal of sludge are major barriers. Sludge contains 99 to around 95% water after proper sedimentation, depending on the type of sludge. Dewatering of sludge is required by drainage on the granular bed, vacuum , or pressure filtration, which tremendously reduces sludge volume for safe handling and treatment. Characteristics of sludge particles greatly influence the dewaterability of sludge.

Determining particle properties of sewage sludges is very difficult due to the complex nature of the particles. Some of the properties of activated and digested sludges have been determined with sufficient accuracy using acceptable methods. These properties include surface charge, bound water content, protein and polysaccharide content, and viscosity of sludges. Without standard procedures

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applicable to sewage sludges, the determination of particle size, particle size distribution, and particle density has always been complex. Still, these sludge particle characteristics are believed to influence sludge dewaterability significantly. Most of the investigators working on particle size and particle density of sewage sludges agree with the complexities of the problem of measuring these characteristics.

In this study, considering the relative importance of various characteristics of sludge particles, efforts have been made to develop new techniques for determining particle size distribution and particle density. Some other properties of activated and digested sludge particles, such as surface charge, bound water content, protein and polysaccharide content, and viscosity of sludges, are also measured with sufficient accuracy using acceptable methods used by most investigators to evaluate mutual interaction and relative influence on sludge dewaterability.

Materials and Methods

Sampling

Sewage sludge is a liquid-solid suspension resulting from the sedimentation phase of wastewater treatment. The high concentration of active microorganisms in sludge causes rapid changes in its characteristics. To reduce the effect of microbial action on sludge particles, fresh activated and digested sludge samples were collected in the morning from the Dalmernock Sewage Treatment Plant and the Philipshill Sewage Works in Scotland, respectively, on pre-scheduled dates for conducting laboratory experiments. Experiments on several batches of samples were conducted over nine months.

Particle Size Analysis

The main objectives of this work were to examine the basic characteristics of the sludge particle, including particle size distribution, surface charge, bound water content, protein and polysaccharide content, and viscosity of sewage sludge. These characteristics of sludge particles greatly influence the dewaterability of sludge. Microscopic examination of sludge particles was made using Vicker's M41 Photoplan microscope. The M41 Photoplan is designed on a modular basis, allowing the use of many accessory components that cover the most widely used microscope techniques. Comprehensive camera facilities cover all the photographic requirements of a routine or research laboratory. The photographs of digested and activated sludges were taken as shown in Figs. 1 and 2, and a few drops of sludges were spread over microscope slides as instructed in the manual. The photographs of sludges show that they are composed of particles of different sizes and shapes, and many of the particles are aggregates of small particles.

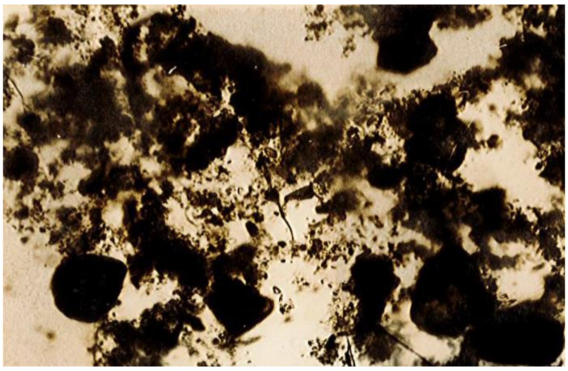

Fig. 1. Digested sludge particles (300X).

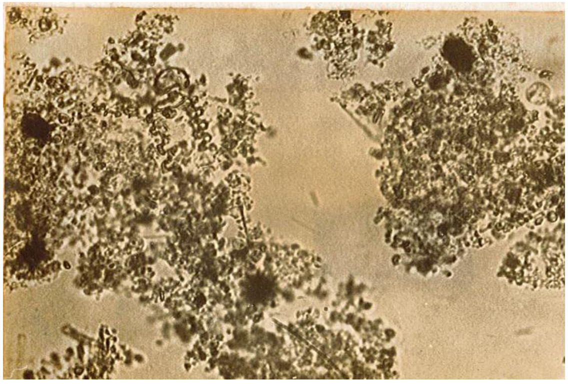

Fig. 2. Activated sludge particles (300X).

Digested sludge comprises larger particles and activated sludge particles are clusters of biomasses in the liquor. Small primary particles, such as microorganisms visible at higher magnification, are held together by surface polymers to form flocs.

The photograph of digested sludge particles shown in Fig. 1 indicates that digested sludge comprises particles of different sizes and shapes. Activated sludge particles are aggregates of smaller particles. The visual examination (Fig. 2) has good agreement with the observations made by Javaheri and Dick (1969) for activated sludge.

In the study of the dewaterability of sewage sludges, analysis of particle size and its distribution with reasonable accuracy is required, but a lack of proper techniques to measure such a wide range of particles of a complex nature is a barrier to investigating the influence of particle size on dewatering behavior of sewage sludges. Previous investigators have used different techniques for fractionating and particle size analysis, such as sedimentation, elutriation, centrifugation, sieve analysis, coulter counter, and microscopic analysis. In sedimentation and elutriation techniques, the particles are fractionated based on their settling velocity, primarily dependent on particle size and the effective density of the particles. Waring (1961), using a modified, improved version of Jone’s (1954) elutriator, could achieve little success in fractionating sewage sludge. The failure was probably for two reasons:

(1) Many large fibrous particles entrap fines and settle rapidly, but the fines are released under favorable conditions.

(2) During the elutriation process, fragile aggregate formation is observed, probably due to the reduction of surface charges because of washing the sludge’s alkalinity. The fragile aggregates settle with higher velocity than the settling velocity of individual units.

The main difficulty in particle fractionation by sedimentation and elutriation arises from the low effective density of the sludge particles. The larger particles fractionated by sedimentation, as observed under a microscope, are not free from fines. Centrifuging can successfully fractionate sludge particles of smaller size with very low settling velocity, but centrifuging is an accelerating process; the result is the same as elutriation (Coackley, 1965). Moreover, the fractionated particles obtained as a compressed cake at the bottom of the tube could not be dispersed in water to bring back the original properties of the particles. Particle size can be measured very accurately with the help of a microscope, and a particle size distribution can be obtained by counting a large number of particles. The method is tedious, especially for sludges with a wide range of particles, appearing on different levels of focus.

Moreover, difficulty arises in the identification of individual particles. Due to its gelatinous nature, sludge can only be easily sieved by wet sieving B.S. 1377 method (British Standard Institution, 1975) if it is dispersed in enough water. As particles are compressible, there exists a possibility of passing larger particles through smaller sieve sizes, and a layer of sludge deposited on the sieve prevents the passing of particles smaller than the sieve size. The Coulter counter has been used successfully for the analysis of the finer fractions of sludge particles (Abdel-Magid, 1982; Armanazi, 1977; Aziz, 1974; Elhassan, 1973; Faisst, 1980; Smyllie, 1969), but it cannot measure the larger size of particles present in sludge with reasonable accuracy. The error in the analysis of larger particles also arises from the breakup of the particles or floes due to agitation of the stirrer, which is required to keep the larger particles in suspension during analysis by the Coulter counter.

It has been found that larger sewage sludge particles can be easily fractionated by wash sieving under gentle water spray. Considering the advantages and disadvantages of the different methods, it was decided to use both sieves and the Coulter counter to analyze the total range of particles in sewage sludge. The compatibility of the two methods was checked by examining the common size fraction between 45×10^{-6}m and 75×10^{-6} m, which both sieves and the Coulter counter can analyze. The result showed that particle size analysis by wash sieving matched better than wet sieving with Coulter counter analysis (Table 1). In the analysis of the particle size distribution of the original sludge, a $100x10^{-6}m^3$ portion of representative sludge sample was diluted in $200x10^{-6}m^3$ distilled water and sieved through $599x10^{-6}$m, $300x10^{-6}$m, $150x10^{-6}$m, $75x10^{-6}$m and $45x10^{-6}$m sieves in succession by wash sieving. The Coulter counter model ZB analyzed particles passing the $45x10^{-6}$m sieve and added them to the larger sizes obtained by sieve analysis to get the total particle size distribution. Thus, particle size analysis using wash sieving and Coulter counter becomes a new technique for constructing particle size distribution curves of sewage sludge.

Particle Electrophoresis

Electrophoresis refers to the motion of charged particles when an electric field is applied. When the particle's velocity is measured, it is possible to calculate the electrical potential at the surface of the shear between the particle and the surrounding medium and the electrical charge contained within the surface of the shear. A particle's surface potential and charge are reproducible quantities that give information about how the particle can interact with other particles and the nature of the particle surface. The surface charge of sewage sludge particles is considered one of the fundamental properties influencing surface activity and behavior towards settling and filtration (Jorden, 1963, Maulik et al., 1967; Yukawa 1971). The electrophoretic mobility of sludge particles was determined using particle electrophoresis apparatus Mk. II of Rank Brothers.

Since electroosmosis occurs in the cell's content when the electric field is applied, the mobility of the particles was observed at the 'stationary levels' of the cell. The 'stationary levels' were computed using the Komagata formula quoted by Show (1969).

$$\frac{s}{d} = 0.500 - \left(0.0833 + \frac{32}{n5}\frac{d}{h}\right)½ \qquad (1)$$

where s is the distance of stationary levels from the faces of the cell, and d and h are the width and height of the cell section, respectively. The flat cell was then filled with the suspension of sludge particles and placed in the bath containing water at 25^0C, where the stationary levels were located. The particles were timed alternatively by reversing the polarity of electrodes to eliminate any effect of drift, and electrophoretic velocities were determined from the equation:

$$U_e = \frac{x/t}{Ve/1} \qquad (2)$$

where U_e is the electrophoretic velocity, t is the time required for a particle to travel a distance x under the applied voltage, Ve. l is the effective interelectrode distance.

Bound Water

Bound water is defined as water in the vicinity of macromolecules whose properties differ from those of bulk water. Bound water of sewage sludges has been measured by the Dilatometer technique and Differential Thermal Analysis (DTA) technique (Heukelekian and Weisberg, 1956; Katsiris, 1977; Peters, 1972). The Differential Thermal Analysis method used in this study has been proven to be reliable, fast, and very useful for studying the bound water content and consequently, the properties of the surface of the sludge particles (Katsiris, 1977). The method of bound water determination by DTA is based on the theory that the bound water does not freeze at temperatures below the freezing point of the free water. The area between the DTA curve and the baseline, i.e. $\int\Delta T dt$, within the limits of the beginning of the effect and its return to the baseline, expresses quantitatively the amount of active substance, i.e., the free water. The difference between total and free water is the bound water of the sludge (Table 2). The apparatus used for this study was a Stanton Redcroft Differential Thermal Analyzer, model 671.

Particle Density

Density is one of the fundamental properties of sludge particles. It has great importance in any solid-liquid separation technique, especially in the study of settleability and filterability. Unfortunately, its determination for sewage sludges is difficult, if not impossible, because of the physio-chemical nature of sludge particles. Despite the importance of particle density, minimal effort has been made to evaluate this characteristic of sewage sludge. Hall (1962) tried density bottles to determine sludge density and achieved little success. Smyllie (1969) used a centrifuge technique to determine particle density, in fact, discovered the density of centrifuged sludge cake. Waring (1961) and Coakley and Kliger (1964) used an interference microscope to measure the particle density of sewage sludge. El Hassan (1973) applied the same interferometric method to measure the density of particles in secondary effluent. In this study, attempts have been made to determine the density of sludge particles from settling velocity and a new technique for computing the density of sludge particles from the densities of different components (fixed residue, volatile solids, and bound water) of sludge particles.

The computation of the density of sludge particles ρ_{SP}, or effective density , $\rho_{sp} - \rho_w$, using the following Stokes law requires the values of settling velocity, V_{SP} and size of the particle, D_{SP} where values of acceleration due to gravity 'g' and dynamic viscosity 'μ' are known.

$$V_{sp} = \frac{1}{18} \left(\frac{\rho_{sp}-\rho_w}{\mu}\right) g \ {D_{sp}}^2 \quad (3)$$

The experimental determination of these two parameters is not simple for sludge particles, which cannot be identified without a microscope. This work uses the particle microelectrophoresis apparatus with a flat cell to determine particles' size and settling velocity.

Sludge solids may be classified broadly into volatile and fixed solids, and water may be classified as free water in which the particles are suspended and bound with water present in and around the particles and moving with the particles. The general equation representing the density of sludge can be written as:

$$\frac{1}{p_s} = \frac{m_v}{p_v} + \frac{m_f}{p_f} + \frac{m_{bw}}{p_w} + \frac{m_{fw}}{p_w} \quad (4)$$

where m_V, m_f, m_{bw}, and m_{fw} are the mass fractions of volatile solids, fixed solids, bound water,and free water, respectively. ρ_V,ρ_f and ρ_W are the densities of volatile solids, fixed solids, and water, respectively.

The density of sludge particles ρ_{SP} is important, which can be written from Eqn. (4) considering the particle phase only, i.e., excluding free water component as:

$$\frac{1}{p_{sp}} = \frac{m_{sd}}{p_{sd}} + \frac{m_{bw}}{p_w} \quad (5)$$

Where

$$\frac{m_{sd}}{p_{sd}} = \frac{m_v}{p_v} + \frac{m_f}{p_f} \quad (6)$$

$m_{Sd}$is the mass fraction of dry sludge, and p_{Sd} is its density. Therefore $m_{Sd}/ \ p_{Sd}$ represents the volume fraction of dry solids in the sludge particles. The effective density of the particles, $\rho_{SP}-\rho_W$, can be written from Eqn. (5) in terms of bound water as:

$$p_{sp} - p_w = \frac{p_{sd}-p_w}{1+\frac{p_{sd}m_{bw}}{p_w \ m_{sd}}} \quad (7)$$

where m_{bw}/m_{Sd} is the bound water of the sludge particles, the value of which largely determines the density of the particles. Hence, as the bound water content of the sludge particles increases, the density of the particles approaches that of water, i.e., the effective density approaches near zero. As a result, the particles at very low effective density tend to remain in suspension.

When the bound water content measured in this study by DTA represents the water associated with the particles, determining dry density,ρ_{Sd} is required to compute particle density, ρ_{SP} using eqn. (5 or 7). The dry density of sludge particles can be measured using a specific gravity bottle. The procedure for determining the specific gravity of solids, as described in BS 1377 (British Standard Institution, 1975), was followed with some modifications.

The dry density of the sludge solids was computed using the equation:

$$p_{sd} = \frac{m_{sd}}{V_b - \left(\frac{m_s - m_{sd}}{p_w}\right)} \quad (8)$$

where V_b is the volume of the sp. gr. bottle calibrated by weighing the mass of water at a known temperature required to fill the bottle; m_S is the mass of sludge needed to fill the same bottle. The sludge is deaired under a vacuum before weighing to remove any gas entrapped in the sludge particles; $m_{Sd}$is the mass of dry solids in the sludge mass m_S determined by drying in an oven at 103^0C - 105°C. To obtain a better understanding of the density of volatile and fixed components of sludge solids, the mass fraction of fixed solids and their density were determined for digested and activated sludges. The density of the volatile component of the solids, ρ_v then computed using Eqn. (6) and presented in Table 3.

Protein and Polysaccharide Content

The protein content of sewage sludges was determined by the method used by Coackley (1950-52). The method involves the determination of organic nitrogen which is the difference between total and ammoniacal nitrogen. The protein content is then determined by using the relationship:

Protein content = 6.25 (Total nitrogen - Ammoniacal nitrogen).

Ammoniacal nitrogen was determined by Nesslerization using an optical spectrophotometer as described in standard methods (APHA, AWWA, WPCF, 1980). Total nitrogen was determined by Kjeldahl digestion.

The method followed for the extraction of polysaccharides was like that used by Zang (1966), Pavoni et al. (1972), and Brand (1982). 25 ml of properly settled sludge was diluted to 200 ml. with distilled water and boiled for 20 minutes. The boiled sample was centrifuged at 3000 rpm for 20 minutes. The supernatant liquor was decanted. The precipitates were washed with distilled water, diluted to 200 ml., boiled and centrifuged as before. Each time, the trace of polysaccharides in the decanted liquor was detected by the Anthrone test. The process continued until the diluting water could not extract some polysaccharides from the sediments. The concentration of polysaccharides in the combined supernatant liquor was determined by the Anthrone test.

Viscosity

The resistance to movement of one layer of fluid over an adjacent one is ascribed to the fluid's viscosity, but the presence of sewage particles increases resistance to such movement. Newton postulated that, for the straight and parallel motion of a fluid, the tangential stress, $\tau,$ between two adjacent layers is proportional to the velocity gradient, $\frac{dv}{dy}$in the direction perpendicular to the layer, i.e.

$$\tau = \mu \frac{dv}{dy} \tag{9}$$

where the constant of the proportionality, μ, is termed the liquid's viscosity, which is a characteristic physical property of the liquid at a given temperature. From Eqn. (9), viscosity may be defined as the tangential shear force per unit area that will produce a unit velocity gradient. Hence, viscosity can be determined by measuring either the rate of shear caused by a known shear stress or the shear stress required to induce a known rate of shear.

The apparatus used was a Ferranti viscometer model VM. The viscometer consists of a rotating outer cylinder driven by a small two-phase synchronous motor of high torque and an inner cylinder suspended in jeweled bearings and situated co-axially within the outer cylinder. The resulting rotation of the liquid exerts a viscous drag on the inner cylinder, which is free to rotate against a calibrated spring with a pointer to show the angular deflection. The deflection is proportional to the viscosity of the liquid. To determine the behavior of non-Newtonian fluids, a wide range of shear rates may be produced by the combined effect of a quick-change 3-speed gearbox and a set of three interchangeable inner cylinders. This means the range of the instrument may be extended from low to high viscosity units. The instrument was verified for accuracy at various speeds with different combinations of cylinders, using oils of different viscosities. The viscosity of sludge was then measured at different shear rates using multiple combinations of cylinders and gears.

Results and Discussion

The visual examination of sludge particles revealed their size, distribution, and aggregation modes. The particles present in activated sludge and digested sludge, based on visual examination, may be classified into three major classes:

- Primary particles, include microorganisms, fine cellulose, silt, clay and other fine-grained materials that find their way into the sludge. The size of these particles may vary from 0.5 to 10 µm.
- Flocs or coagulated particles are formed by bio-flocculation and conditions favorable for flocculation during treatment. The size of floes ranges from 5 to 100 µm.
- Fragile aggregates; formed by the loose grouping of flocs or primary particles under favorable conditions. They disperse on agitation or change in the liquid environment.

The particle size distribution of digested sludge from Philips Hill sewage works and activated sludge from Dalmarnock sewage treatment plant have been shown in Fig. 3. It may be observed that activated sludge has 86% particles finer than $45x10^6$ m whereas digested sludge has 50% particles finer than that size, although the concentration of fines smaller than $12x10^{-6}$m is nearly equal in both sludges. This difference in particle size distribution is also visible in microscopic views in Figs. 1 and 2. The higher percentage of large particles in digested sludge was probably because both primary and secondary sludges were being digested together, and the total particle size distribution was influenced by the presence of larger particles in the primary sludge. The digestion process has also promoted particle aggregation to larger sizes. A sample calculation combining the results of two different methods of particle size analysis is shown in Table 1. The availability of the total particle distribution in sludge, for the first time, will now help determine the parameters influencing filterability, such as effective size (d_{10}), median size (d_{50}), uniformity coefficient $(\frac{d_{60}}{d_{10}})$, and the slope of the particle size distribution curve.

The distribution of electrophoretic velocities of digested and activated sludge particles has been shown in Fig. 4. The mean electrophoretic velocity of activated sludge particles was found to be $1.66x10^{-8}m^2\ sec^{-1}\ volt^{-1}$ (SD 6.99%), and that of

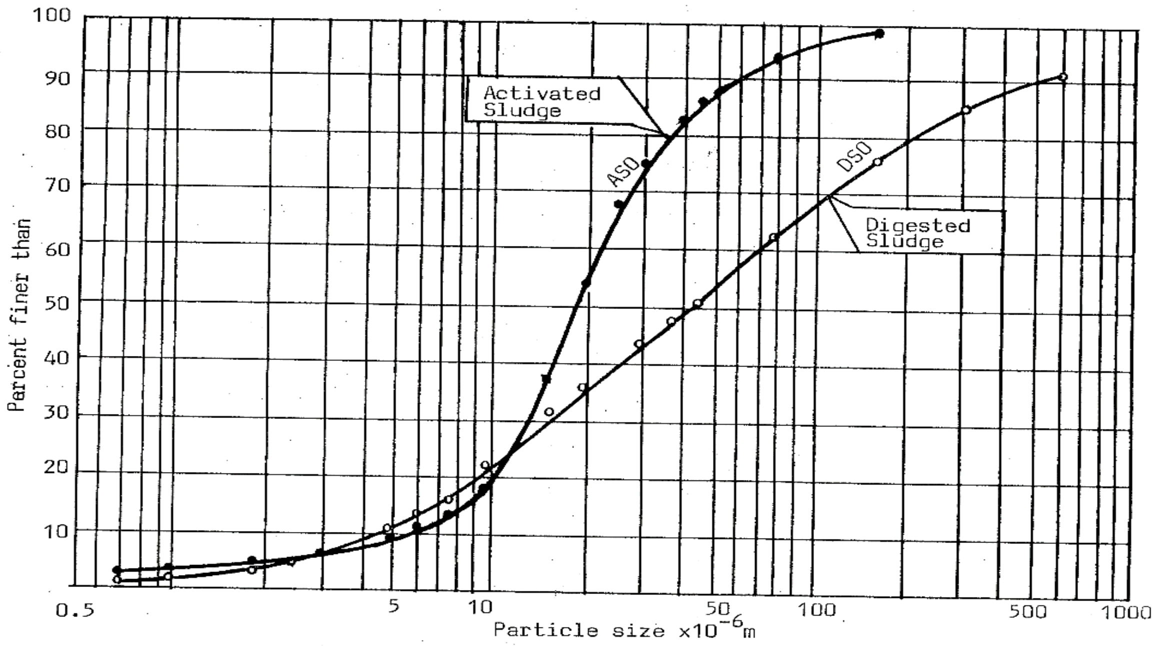

Fig. 3. Particle size distribution of activated and digested sludges

Table 1. Computation of total particle size distribution combining the results of sieve and Coulter counter analysis.

Range of Tools for Analysis	Particle Size $x10^{-6}$m	Materials Passing	% Materials Passing	Multiplier	Percent Finer
	-	5.460	100.00		100.00
	599	4.969	91.01		91.01
Range of Sieve	300	4.619	84.60		84.60
	150	4.157	76.14		76.14
	75	3.458	63.33		63.33
	45	2.723	49.87		49.87
	39.79		96.06		47.91
	31.79		86.84		43.31
	24.75		79.84		39.82
	19.64		71.82		35.82
	15.59		62.51		31.17
	9.89		44.94		22.41
	7.79		32.96		16.44
	6.19		23.81		11.87
Range of Coulter counter	4.91		20.26	X 0.4987 =	10.10
	3.09		13.50		6.73
	2.45		10.09		5.03
	1.94		7.81		3.85
	1.08		4.19		2.09
	0.68		1.64		0.82
	0.43		0.60		0.30
Range Projected	0.00		0.00		0.00

Note: The fraction of particles <45µm is within Coulter Counter's range which is distributed as 100% and then multiplied by fraction <45µm (0.4987) to obtain % finer.

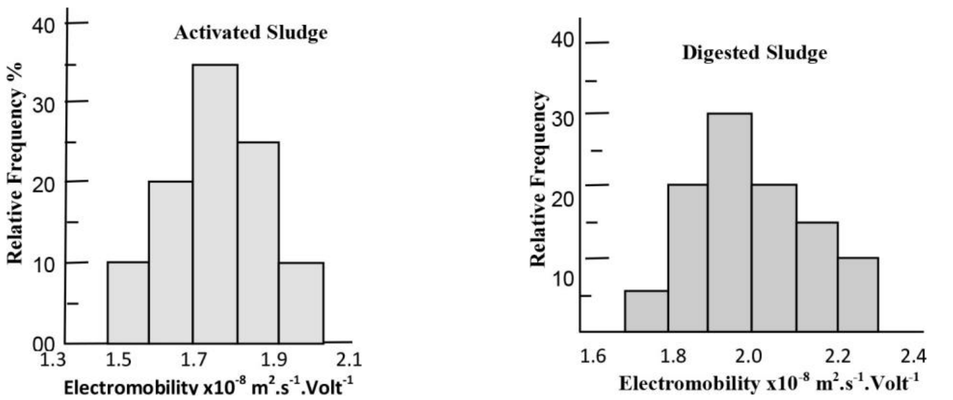

Fig. 4. Distribution of electrophoretic velocities of activated and digested sludge

digested sludge particle was 1.99x$10^{-8}$$m^2$ sec^{-1} $volt^{-1}$ (SD 7.15%). The corresponding electrical potentials at the shear surface between the particles and surrounding medium are 21.33x10^{-3} volts and 25.57x10^{-3} volts for activated and digested sludge respectively.

The electrophoretic mobilities obtained agree with the values obtained by other investigators (Coackley, 1950-52; Elhassan, 1973; Katsiris, 1977; Langmuir, 1975). As mentioned by Coackley (1959), the reason for the higher velocities in the digested sludge is that there are many more ions in the liquid surrounding the particles; the adsorption of some of these ions may tend to give the particles a higher charge.

The computation of bound water from experimental data has been shown in Table 2. The bound water contents of activated and digested sludge, expressed as a bound water/dry solids ratio, were 9.60 and 4.21, respectively.

Katsiris (1977) used a dilatometer and DTA techniques to determine the bound water content. They found that the activated sludge he examined had a bound water content in the range of 900 to 1100 percent on dry solids, while digested sludge had a bound water content of 300 percent.

Peters (1972) and Forster and Lewin (1972) reported similar values for the bound water of activated sludge, both using a dilatometer. Heukelekian and Weisberg (1956) found a lower value of bound water content in digested sludge. The results clearly indicate that the bound water content is directly related to the sludge's organic matter content.

The distribution of settling velocities of activated and digested sludge particles of nearly the same size (around 20 µm) and shape is shown in Fig. 5. The average settling velocities of activated and digested sludges were found to be 6.860 µm/s (SD 2.152) and

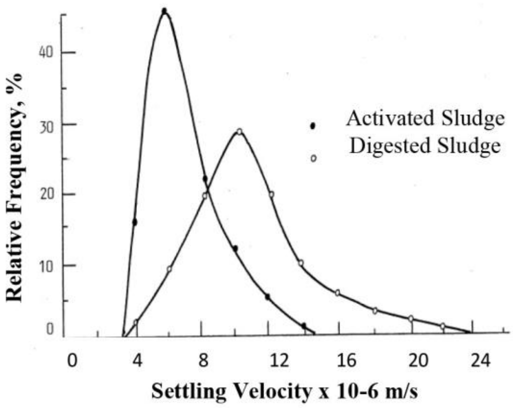

Fig. 5. Distribution of settling velocities of activated and digested sludge particles.

Table 2. Differential thermal analysis of free and bound water.

Cooling rate: 3°C/min Range of Temp: +20°C to -20°C Amplifier: 250 µV				Recorder T(x-axis) : 0.2 mV/cm ΔT (y-axis): 2mV/cm		
Sludge Type	**Mass of Sludge (mg)**	**Dry Sludge (mg)**	**Total Water (mg)**	**Free Water (mg)**	**Bound Water/ Dry Sludge**	**Average Value of Bound Water**
AS	56.5	1.1	55.4	43.8	10.55	$\bar{x} = 9.60$ $SD = \pm 9.38\%$
	45.9	0.9	45.0	36.8	9.11	
	32.2	0.7	31.5	24.4	10.14	
	24.8	0.5	24.3	20.0	8.60	
DS	55.3	2.3	53.0	43.3	4.26	$\bar{x} = 4.21$ SD = ±4.96%
	45.7	1.9	43.8	35.4	4.42	
	29.2	1.3	27.9	22.8	3.92	
	20.3	0.9	19.4	15.6	4.22	

10.537 µm/s (SD 3.516) respectively. A wide distribution, particularly in the case of digested sludge, indicates that all particles are not composed of the same material of equal density.

Moreover, the digested sludge particles are more compact, as shown in Fig.1, due to the partial digestion of organic matter on sludge particles. The values of the effective density of particles, $\rho_{SP} - \rho_W$, computed from the particle size and mean settling velocities using Eqn. (3) are 0.032x10^3 kg/m^3 and 0.048x10^3 kg/m^3 for activated sludge and digested sludge respectively. The density of sludge particles and their different solid components are presented in Table 3. The rate of change of shear stress and apparent viscosity of activated sludge with the change in the rate of shear has been shown in Fig. 6. The rheological behavior of digested sludge at different solids concentrations has been presented in Fig. 7. The results indicate that sewage sludges are non-Newtonian fluid as the shear stress - shear rate relationship does not follow the characteristics linear flow curves of a Newtonian fluid. The study clearly

Table 3. Density of solid components of sludge.

Sludge Solids	Density x10^3 kg/m^3	
	Activated Sludge	Digested Sludge
Sludge Particles (Using Av. Settling Velocity)	1.032	1.048
Sludge Particles (Using Av. Component Density)	1.031	1.093
Fixed Residue	2.487 (SD = ±1.47%)	2.494 (SD = ±1.11%)
Dry Particles	1.504 (SD = ±1.05%)	1.815 (SD = ±1.91%)
Volatile Solids	1.359	1.396

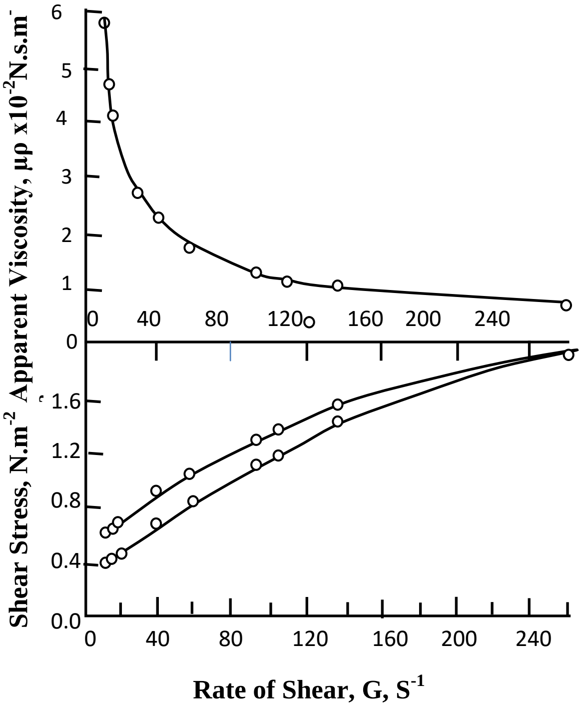

Fig. 6. Effect of solid content on rheology of activated sludge

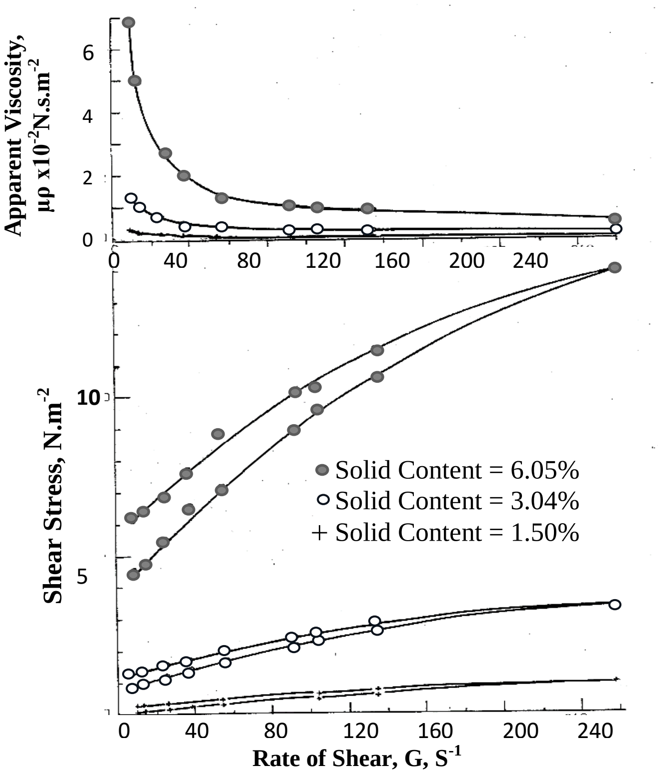

Fig. 7. Effect of solid content on rheology of digested sludge

demonstrates that activated and digested sludges exhibit pseudo and Bingham plastic characteristics with thixotropic behavior. For many liquids, the shear stress-shear rate relationship is not linear; such liquids are broadly classified as non-Newtonian, and this group includes sewage sludge (Buzzel and Sawyer, 1963; Hatfield, 1938; Inkster, 1945; McGeachie, 1970; Somerville, 1971). The viscosity of sewage sludges has mostly been studied regarding its flow through pipelines and transportation (Hatfield, 1938; McGeachie, 1970; Somerville, 1971).

The results in Table 3 show that the dry density of sludge particles increases with the digestion of the organic component of the sludge. The volatile solids and fixed residue of activated and digested sludges have nearly the same densities. So, the dry density depends on the percentage of volatile matter in the sludges. Baskerville et al. (1971) determined the dry density by weighing a sample of dry cake of known volume in air and water and reported a value of $1.360x10^3$ kg/m^3.

The dry density of sludge solids has also been computed to be $1.40x10^3$ kg/m^3, assuming the density of volatile solids is equal to $1x10^3$ kg/m^3 (Metcalf and Eddy Inc., 1972). The density of volatile solids in sludges, as shown in Table 3, is not equal to the density of water. Tylor (1957) found that the specific gravity of combined dry solids of sludge varied from 1.62 to 1.78, where the inorganic and organic components of solids had sp. gr. 2.71 and 1.36, respectively. These values found by Tylor (1957) are in close agreement with those presented in Table 3. The dry density values of different fractions of digested sludge particles indicate that the smallest fraction has the highest dry density. The effective densities of sludge particles presented in Table 3 are a bit higher than values measured by the interferometric method (Coackley, 1964; Elhassan, 1973; Waring, 1961).

The density or effective density of particles is the most important parameter to study the settling of sludge, which depends on the dry density of sludge solids and bound water content, as shown in Eqns. (5) and (7). A graphical presentation of the Eqn. (7) has been shown in Fig. 8, which indicates that the effective density decreases at a higher rate at low bound water content. The difference between the densities of water and sludge particles at high bound water content becomes negligible.

The average protein contents of activated and digested sludge particles, expressed as a percent of total solids, were found to be 38.06% and 15.94%, respectively. The standard deviation of protein contents obtained in several determinations for each sludge type was checked. The coefficients of variation were found to be 5.55% and 4.58%, respectively, for activated and digested sludges. It appears that digestion is quite effective in the digestion or dissolution of protein from the particle phase of the sludge. The protein contents of sewage sludges were well within the range reported by Coackley (1950-52) and Katsiris (1977) but higher than the values found by Waring (1961) and lower than those found by Zang (1966) for activated sludge.

The polysaccharides extracted from activated sludge were found to be 10.65 percent of the total solids content of the sludge. The quantity of polysaccharides extracted from activated sludge agreed with the average value reported by Zang (1966) but was higher than the polysaccharides extracted by El Hassan (1973) from particles in effluent. Brand (1982) found that the number of polysaccharides extracted from activated sludge varied widely depending on the solids content; however, the value reported here is in the lower range of the values he found.

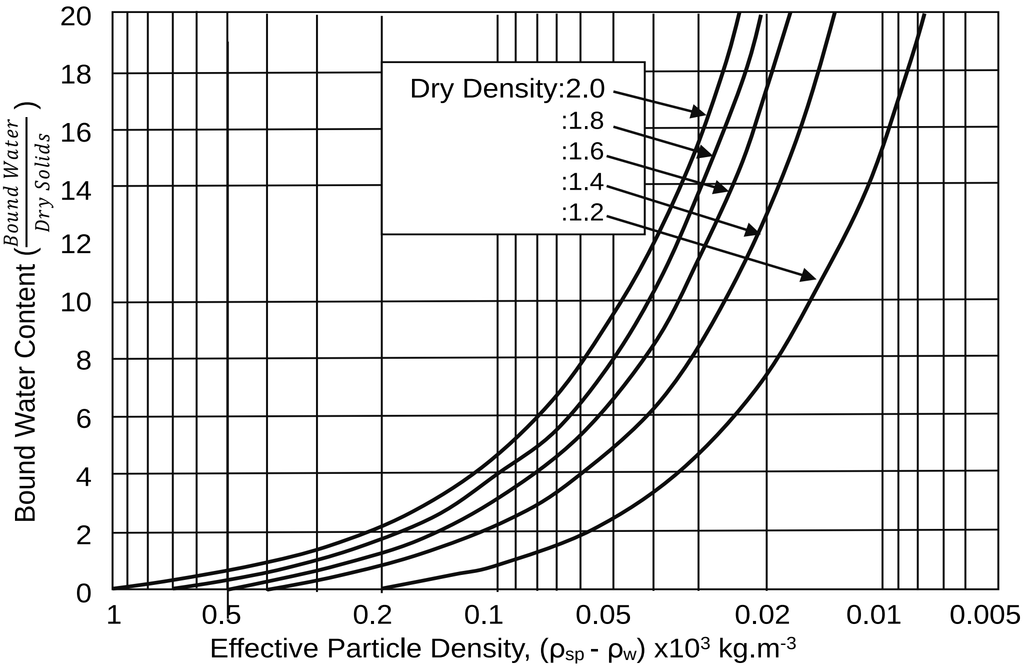

Fig. 8: Correlation among effective density, bound water, and dry density of sludge particles.

The apparent viscosity of digested sludge tremendously increases with the increase in solids concentration. This finding agrees with Buzzel and Sawyer, 1963; Hatfield, 1938; Abdel- Magid, 1982. It may be observed in Fig. 8 that the increase in solids concentration increases the yield stress and the degree of thixotropy. The bigger displacement between the up and down curves of the hysteresis loop has increased the degree of thixotropy. The reason for such behavior may be attributed to the fact that the increase in sludge concentration forms a connected and continuous particle structure, which requires higher initial stress to break down the particle contacts and initiate the particle layers to move relative to the adjacent layers.

The study reveals that for the same solid concentration, activated sludge has a higher viscosity than digested sludge; this is because activated sludge with high bound water content has a higher particle volume producing more flow resistance. The viscosity of sludge decreases rapidly with the decrease in solids content, as shown in Fig. 7, and approaches to a constant viscosity equal to that of water at very low solids.

Conclusions

The particle size distribution of the total range of particles in sewage sludge, determined for the first time using sieves and a Coulter counter, has demonstrated very good reproducibility. This method can be used confidently to study filterability. Additionally, the density of sludge particles, determined for the first time using dry density and bound water measurements, can be correlated mathematically or graphically. This correlation can help obtain sludge particles' density or effective density for any given dry density value and bound water. The density of the dry matter of sludge particles depends on the percentage of organic matter present in the particles. The dry density of the finer fraction of sludge particles is higher than that of the larger fraction. The density of particles in water decreases with water adsorption, and the density of water is approached at higher water content of the particles.

The study reveals that the stability of sludge particles is due to their high surface potential and low effective density. The presence of higher surface charge on digested sludge particles indicates that the protein and polysaccharide contents are not the only factors that determine the intensity of surface charge, the adsorption of ions from the surrounding media also increases the surface charge of the particles. The resident surface charge on particles produces resistance to flow, but it exerts a greater influence on filterability by regulating the stability and aggregation of the particles.

As evident from the experimental results, the proteins and polysaccharide contents of the particles regulate the bound water content and consequently, the density of the particles. Since specific filtration resistance is measured on a dry mass basis, particle density greatly influences the specific resistance. The probable modes through which proteins and polysaccharides influence specific resistance are through lowering particle density by water adsorption and producing a hydrated surface on the particles.

The viscosity of the sludge’s liquid phase is equal to that of water. In cake filtration, as the liquid phase flows through cake’s pore channels as filtrate, it seems logical to use water’s viscosity in computing specific resistance to filtration.

Declaration

The corresponding author declares that he carried out the experimental works in the article in the laboratories of the Civil Engineering Department, Strathclyde University, Glasgow, UK, and certifies that the contents of this paper have not been published before in any journal. The co-author, Tanvir Ahmed, has edited the paper and consented to the article being considered by the Editorial Board for publication in the Journal of Bangladesh Academy of Sciences.

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