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Comparative Study on Sludge Dewatering Based on Mass Balance Model

Arimieari, L. W.[1*], Ibiang, I. E.[2] and Egop, S. E.[3]

[1]Department of Civil Engineering, Faculty of Engineering, Rivers State University, Port Harcourt, Nigeria
[2]Department of Civil Engineering, Faculty of Engineering, University of Cross River State, Nigeria
[3]Department of Civil Engineering, Faculty of Engineering, Rivers State University, Port Harcourt, Nigeria

* Corresponding author: love.arimieari@ust.edu.ng

Abstract: *The purpose of this work was to use mass balance analysis to develop a model for sludge drying bed filtration. With the use of the new model equation of mass balance analysis, which incorporates the input variable, concentration of sludge (C_O); the state variable, specific resistance (R); and the output variables, solid content (C) and concentration of evaporation (C_{EV}), the filtration experiments with conditioned sludge for agricultural and industrial sludge have demonstrated that specific resistance, R values decreased as the concentration of conditioner ($FeCl_3$) increases. The R values for agricultural sludge created at intervals of 20 minutes with varying conditioner concentrations are 1.63×10^7, 1.51×10^7, 1.42×10^7, 1.20×10^7, 1.03×10^7, 1.02×10^7, 1.01×10^7 and 1.00×10^7 for 10g, 20g, 30g, 40g, 50g, 60g, 70g and 80g respectively. It was discovered that the rate of filtrate increased with the conditioner concentration. It is significant to observe that sludge concentration, solid content, and evaporation concentration all increased as conditioner concentration did, suggesting that conditioners are important for sludge's filterability. The new model equation agreed with the plot of linear relationships for Carman's equation and Ademiluyi and Arimieari's equation for agricultural sludge generated on a 20-minute interval for different conditioner concentrations, according to a comparison using experimental data from agricultural sludge. There is a significant variation in the correlation coefficient, ranging from 0.8857, 0.0491 and 0.0473 respectively. This discrepancy can be explained by the fact that the new model equation includes variables that weren't present in the equations developed by Carman, Ademiluyi, and Arimieari, such as the volume of sludge (m^3), time taken to obtain the filtrate in seconds, and concentration of evaporation (kg/m^3). This study enhanced the previous models by adding more filtering variables based on the sludge drying bed using mass balance analysis.*

Keywords: Sludge Dewatering, Drying Bed, Filtration Resistance, Mass Balance Analysis

1. INTRODUCTION

Wastewater treatment plants are built to process the sewage that is released by nearby companies, industries, and households. Sewage may contain metals, minerals, nutrients like phosphorus and ammonia, and pathogens or organisms that cause disease. The hardest issue to solve is the presence of toxins in sewage sludge from municipal discharges, which could ultimately influence the choice of a usage dewatering method. Sludge can become unsuitable for any useful purpose due to the accumulation of pollutants. The most popular method for dewatering sludge is to use natural sand drying beds. Reviewing and resolving point source pollution practices that ought not to be occurring upstream can be accomplished quite successfully by choosing an environmentally friendly method to sludge dewatering.

Mechanical and non-mechanical methods are employed in dewatering machines to extract moisture from waste water sludge. In mechanical procedures, the sludge is dewatered more quickly by the use of mechanically assisted physical means. The physical methods include vacuum filtration, belt-filter presses, centrifugation, and filter presses. The natural evaporation and percolation processes used in non-mechanic procedures are what dewater the solids. Sludge lagoons and drying beds are these.

Mass balance analysis is a technique used to identify the changes that occur during a reaction in a reactor and to examine the hydraulic flow characteristics of reactors [1].

The parameter used to evaluate the filterability of sludge, sludge filtration resistance, appears to be the problem when determining an appropriate equation for the filtration process. In contrast to other variables that are typically included in filtration expressions, this parameter is difficult to assess directly.

Using a plug-flow bioreactor with a 700 L working volume for sludge, municipal sewage sludge dewaterability through bioleaching has been achieved [2]. The Residence Time Distribution study found that the type of flow was plug flow regime because the wastewater from poultry slaughterhouses was treated using hybrid up flow anaerobic filter (AF) and anaerobic sludge blanket (HUASB) reactors, which produce less biogas and have lower up flow velocities [3].

Sewage sludge poses a significant risk to human health and the environment in many countries because of the high costs associated with treating it and the way wastewater treatment plants operate [4-6]. Conventional methods include treating the sludge in centrifuges, belt presses, or other dewatering units after adding conditioning chemicals to boost the dewatering rate and enhance filtrate quality [7-9].

Fenton technique, which is easy, affordable, and environmentally friendly, is an efficient method for stabilizing sludge from slaughterhouse wastewater treatment plants [10]. Over time, many concepts have been proposed to explain this significant particular resistance equation. The idea of specific resistance and the time velocity plot of sludge filtration at constant pressure served as the foundation for Carman's work. He assumed that the pressure drop across the filter cake, the pressure drop across the initial resistance, and the loss incurred in recovering the filtrate are the three main causes of the overall loss of filtration pressure. He also posited that specific resistance is independent of the concentration of suspended solids.

Since it assumes an ideal scenario in which the cake created during filtration is solid and at constant filtration pressure, Carman's work has come under critique. Ruth conducted an experimental study to confirm the theoretical predictions derived from Carman's equations: the plot of filtrate volume V vs t showed a parabolic relation. Additionally, he proposed designating the particular resistance in Carman's equation as an average constant value.

Thus, Carman later proposed an equation for specific resistance as Equation (1):

$$r = \left(\frac{2A^2P}{\mu c}\right) b \quad (1)$$

Where, r = Specific Resistance (m/kg) A = Area of Filtration (m^2)
μ = Viscosity of Filtrate (poise) C = Mass of Dry Cake per unit Filtrate Vol.
b = Exponent of 'A' in the dimensional Partial Equation

Specific resistance to filtration (SRF or r) was determined using a plot of filtration time /filtrate volume (t/V) versus filtrate volume (V) [11-12].

The specific cake resistance is used to evaluate the effect of different dosages of chemical conditioners and combination of sludge and conditioning agents on the specific resistance and quality of the cake [13]. A plot of specific resistance versus dose can be used to determine the optimal operating condition. They gave the theory as Flow through the sludge cake and filter medium which may be considered as flow through porous media using Darcy's law to model the process.

$$Q = \frac{dV}{dt} = \frac{KA\Delta h}{\Delta L} \quad (3)$$

Where Q = flow rate of filtrate, V = Volume of water, A = Area of flow, k = conductivity

h = head, L = distance and t = time

An equation for sludge filtration was formulated based on the concept of specific resistance using LMT dimensional analysis. The equation was used in determining the performance of sludge drying bed which is a natural means of sludge dewatering. And the result shows that the resistance to filtration for conditioned sludge decreases as the conditioner concentration increases showing that the derived equation is in consonance with Carman's equation and it can be used in evaluating sludge dewatering parameters [14-15]. Thus, they arrived at:

$$R = \left(\frac{\rho g h A^2}{\mu C}\right) b \quad (4)$$

Where R= specific resistance (m/kg), $\rho g h$ = hydrostatic pressure (N/m^2), A = area of filtration (m^2), μ = the dynamic viscosity ($N.s/m^2$), C = the solid content (kg/m^3) and b = the Slope(s/m^6).

A model developed for the dewaterability of conditioned sludge using data from experiments conducted with six sand drying beds. The control experiment was the first bed, which had no conditioner. Ferric Chloride was added to the remaining five beds in the neighborhood of 1%, 2%, 3%, 4%, and 5% respectively, corresponding to 30g, 60g, 90g, 120g and 150g of $FeCl_3$ Seepage (sg) was derived as a linear function of time. The benefit of utilizing coagulants in dewatering sludge is that the more coagulant used, the more dewaterable the sewage sludge becomes, but the drawback is that the effluent cannot be recycled for human consumption due to the toxic ferric chloride used as conditioner [16].

The basic idea that mass cannot be generated or destroyed but that its form may be changed—for example, from a liquid to a gas—is the foundation for mass-balance analysis, according to [1]. They added that the mass-balance analysis provides a practical means of characterizing the processes that take place inside treatment reactors as a function of time.

A simplified word statement provides the general mass-balance analysis for a given reactant as

$$Accumulation = inflow - outflow + \text{generation} \quad (8)$$

By using, a new model filtration equation was developed that includes the input variable, sludge concentration (C_0), the state variable, specific resistance (R), and the output variables, cake concentration (C) and filtrate concentration (C_f) [17].

The desired equation is

$$C_f^1 = \frac{C_0}{1+K_1} + \frac{C_0^2 K_0 \, dR}{7200(1+K_1)} \quad (9)$$

The process of water changing from a liquid to a vapour phase occurs on wet surfaces such as soils and bodies of water. A raindrop, soil moisture, wet surface, water within a plant leaf, or the surface of a stream, lake, or ocean are examples of surfaces that experience evaporation. Evaporation is the result of the exchange of water molecules between air and these surfaces [18-19].

2. MATERIALS AND METHODS

Collection of Samples and Description of Experimental Setup

Agricultural and industrial sludge were collected from the Ikpa Slaughterhouse in Nsukka and Ama Brewery Enugu, Nigeria respectively. The following is a full description of the drying bed design: The drying bed's length is estimated to be 0.9 meters. It is 0.6 meters wide and 1.8 meters deep. The bottom course of gravel surrounding the underdrains extends 0.15 meters above the underdrain top. Clean gritty sand measuring 0.15 meters makes up the top course. A level surface of sand was achieved. The mud is 0.30 meters deep. The metal wall of the drying bed was created with open-jointed under-drain pipe. As a result, the drying bed's estimated area is 0.97 m^2. The experimental setup of a sand drying bed for both industrial and agricultural sludge is shown in Figure 1.

Fig. 1. *Experimental Setup of Sand Drying Bed for Agricultural Sludge and Industrial Sludge*

Determination of Filtration Parameters

The parameters are: Volume of Filtrate (V); Time of Filtrate (T); Height of Sludge on Sand Bed (H); Sludge Temperature; Pressure of Filtration P (ρgh); Area of Filtration (A); Dynamic Viscosity (μ), Solid Content and rate of Evaporation.

Volume of Filtrate (V)

By measuring the meniscus of the measuring cylinder for the filtrate level, the volume of filtrate (change in volume) was determined. Measurements of the filtrate volumes were made at regular intervals.

Time of Filtrate (t)

On the first day, two hours were allotted across a twelve-hour period (7.00 am to 7.00 pm) for filtration. The subsequent ones were then taken throughout the course of twenty-four hours (7 p.m. to 7 p.m.).

Height of Sludge on Sand Bed (h)

By observing the meniscus of the measuring tape that was calibrated at the drying bed's side, the height of the sludge was determined. It was assumed that the starting height was H_0.

Sludge Temperature

Readings were taken after a thermometer was placed inside the sludge drying bed.

Pressure of Filtration P (ρgh)

Since a liquid exerts pressure when it is at rest, hydrostatic pressure was considered to be the source of the pressure. The hydrostatic pressure is a direct relationship with the height of a liquid column with homogeneous density. The density of the liquid and the local gravity are the primary determinants of a liquid's hydrostatic pressure, which is not constant. As a result, the following formula may be used to get the hydrostatic pressure in SI units of a liquid column:

$$\text{Pressure of Filtration (P)} = \rho g h$$

Where P = hydrostatic pressure (N/m^2), ρ = density of water (kg/m^3), g = gravity (m/s^2)

h = height (m).

Area of Filtration (A)

The entire area is used as the drying bed's area.It is provided by the expression

The Area (m^2) = Length × Width × Height

Therefore for this research work, the filter bed area = $0.9 \times 0.6 \times 1.8 = 0.97m^2$

Dynamic Viscosity (μ)

Since the filtrate was clear, the viscosity was taken to be the viscosity of water. An equation for estimating water's dynamic viscosity is as follows:

$$\mu = 0.0168 \times \rho \times T^{-0.88}$$

where μ = viscosity ($N.s/m^2$), ρ = density (kg/m^3) and T = temperature (℃)

Rate of Evaporation

The lack of an electronic evaporation meter would make it difficult to measure evaporation directly from the drying bed. Instead, the rate of evaporation would be determined by calculating the difference between the volume of sludge entering the bed, the volume of filtrate, and the volume of water that remained. This method is based on the idea that the nature of the evaporating surface area affects evaporation rate [18].

Determination of the Effect of Conditioner on Specific Resistance and Solid Content

1. Ferric chloride **(**$Fecl_3$**)** at concentrations of 10g, 20g, 30g, 40g, 50g, 60g, 70g and 80g were added each to one bucket of sludge of 10 liters capacity and mixed before filtration. For each filtration circle, the stop watch was started and the volume of filtrate and height of sludge in the bed recorded at 20 minutes interval. The temperature of sludge for each filtration circle was also noted.

2. One bucket of sludge each of 10 liters was diluted with distilled water of 1liter, 2liters, 3liters, 4liters, 5liters, 6liters, 7liters and 8liters volumes and then conditioned with 20g each to produce a filterable sludge of different solid contents. Parts of the conditioned sludge were oven dried at 105^{o}c. These samples were weighed before and after oven drying to enable the determination of solid content.

Developing a model for Sludge Drying Bed

The model used in this study is mass balance analysis using LMT dimensional equation developed by [14] as a governing equation. Sludge drying bed is known as a plug flow reactor. Plug flow reactors are used to model the chemical transformation of compounds as they are transported in systems resembling "pipes". The "pipe" can represent a variety of engineered or natural conduits through which liquids flow.

Sludge Filtration Model

The mass balance equation for sludge filtration process can be expressed as:

$$Inflow - Outflow = Rate\ of\ Accumulation \quad (10)$$

$$Q_oC_o - QC_f = V_f \frac{dC}{dt} \quad (11)$$

$$Q_oC_o - QC_f - Q_{EV}C_{EV} = V_f \frac{dC}{dt} \quad (12)$$

Where Q_o is the rate of sludge inflow (m^3/s); Q is the rate of volumetric increase of the filtrate (m^3/s); Q_{EV} is the rate of sludge evaporation (m^3/s); C_o is the concentration of the sludge (kg/m^3); C_f is the concentration of filtrate (kg/m^3); C_{EV} is the concentration of evaporation (kg/m^3). While V_f is the volume of the filtrate collected at the end of the filtration period (m^3); dC is a small change in the cake concentration (kg/m^3) and t is the time of filtration (s).

Assuming a constant rate of filtration

$$V_f = Qt \quad (13)$$

If losses are neglected, the volume of sludge (V_o) filtered is distributed as the volume of cake (V_c) formed, the volume of filtrate (V_f) and the volume of sludge evaporated (V_{EV}).

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$$V_o = V_f + V_c + V_{EV} \quad (14)$$

also

$$V_o = Q_o t \quad (15)$$

$$V_{EV} = Q_{EV}\, C_{EV} \quad (16)$$

Integrating Equation (12) for a case where Q_o, Q and Q_{EV} are time independent.

$$CV_f = Q_o C_o t - Q C_f t - Q_{EV} C_{EV} t \quad (17)$$

From Equation (13), (15) and (16) and eliminating Q_o,Q and Q_{EV}

$$CV_f = V_o C_o - V_f C_f - C_{EV} V_{EV} \quad (18)$$

$$CV_f = \left(V_f + V_c + V_{EV}\right) C_o - V_f C_f - C_{EV} V_{EV} \quad (19)$$

Because the filtrate is almost pure water, therefore the concentration of the filtrate will be almost zero $\therefore C_f \approx 0$

$$\therefore V_f C_f = 0 \quad (19)$$

Hence Equation (19) becomes

0

$$CV_f = \left(V_f + V_c + V_{EV}\right) C_o - V_f C_f - C_{EV} V_{EV} \quad (20)$$

$$CV_f = \left(V_f + V_c + V_{EV}\right) C_o - C_{EV} V_{EV} \quad (21)$$

From the graph of V_f against V_c

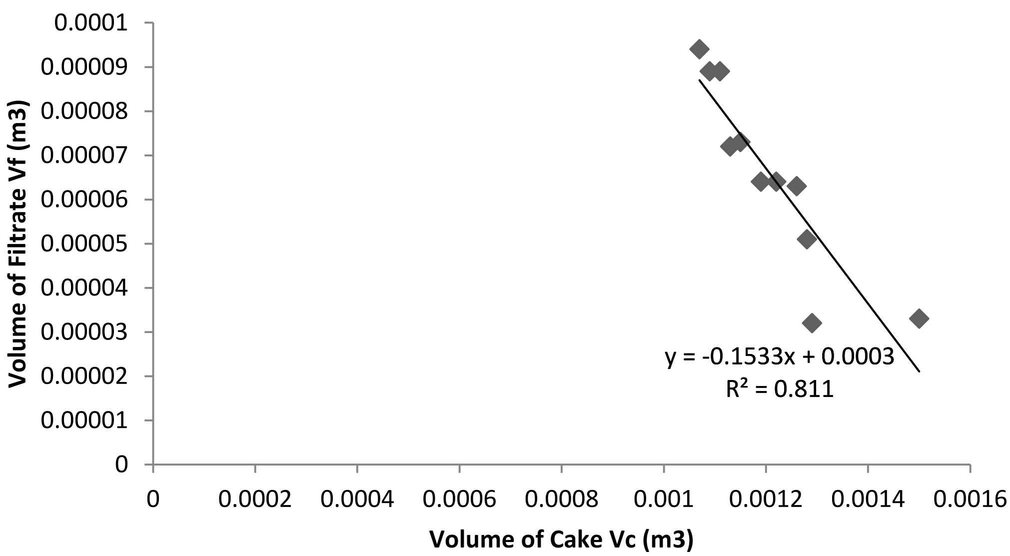

Fig. 2. *Graph of volume of filtrate (V_f) against volume of cake (V_c)*

$$V_f = -0.1533 V_c + 0.0003 \quad (22)$$

$$-0.1533 V_c = V_f - 0.0003 \quad (23)$$

$$V_c = \frac{0.0003 - V_f}{0.1533} = 0.00196 - 6.52 V_f \quad (24)$$

From the graph of V_f against V_{EV}

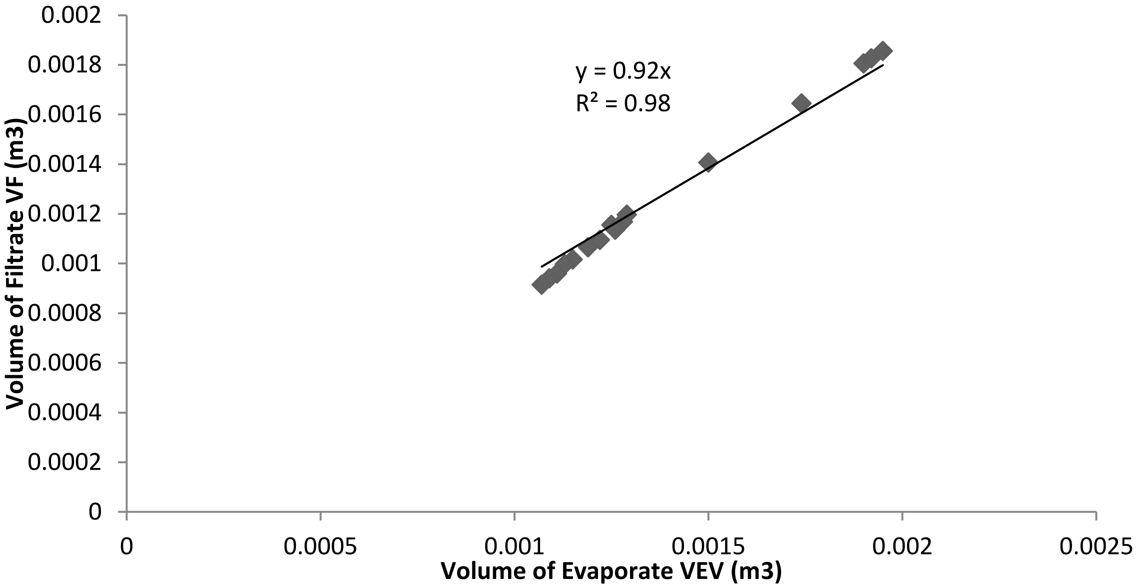

Fig. 3. *Graph of volume of filtrate (V_f) against volume of evaporate (V_{EV})*

$$V_f = 0.92V_{EV} \tag{25}$$

$$V_{EV} = \frac{V_f}{0.92} = 1.087V_f \tag{26}$$

Substituting equation (24) and (26) in equation (21) gives

$$CV_f = \left(V_f + 0.00196 - 6.52V_f + 1.087V_f\right)C_o - C_{EV}\left(1.087V_f\right) \tag{27}$$

$$CV_f = \left(0.00196 - 4.433V_f\right)C_o - 1.087C_{EV}V_f \tag{28}$$

But

$$V_o = V_f + V_c + V_{EV}$$

$$CV_f = \left(V_f + V_c + V_{EV}\right)C_o - C_{EV}V_{EV} \tag{29}$$

$$CV_f = \left(V_f + V_c + V_{EV}\right)C_o - C_{EV}\left(V_o - V_f - V_c\right) \tag{30}$$

$$CV_f = \left(V_f + V_c + V_o - V_f - V_c\right)C_o - C_{EV}\left(V_o - V_f - V_c\right) \tag{31}$$

$$CV_f = V_oC_o - C_{EV}\left(V_o - V_f - V_c\right) \tag{32}$$

$$V_f = -0.1533V_c + 0.0003 \tag{33}$$

The constant 0.0003 is too small to affect the optimization process

Hence

$$V_c = 6.523V_f \tag{34}$$

$$CV_f = V_oC_o - C_{EV}\left(V_o - V_f + 6.523V_f\right) \tag{35}$$

$$CV_f = V_oC_o - C_{EV}\left(V_o + 5.523V_f\right) \tag{36}$$

$$CV_f = V_oC_o - C_{EV}V_o + 5.523V_fC_{EV} \tag{37}$$

$$C_{EV}V_o - V_oC_o = 5.523C_{EV}V_f - CV_f \tag{38}$$

$$\left.\begin{aligned} C_{EV}V_o - V_oC_o &= V_f(5.523C_{EV} - C) \\ V_f &= \frac{C_{EV}V_o - V_oC_o}{5.523C_{EV} - C} \end{aligned}\right\} \quad (39)$$

Since the specific resistance is an important parameter in sludge filtration, it is introduced in equation (39). Following modification generated by [14]

$$V_f^2 = \frac{\rho g h A^2 t}{\mu C R} \quad (40)$$

where t is the time measured in seconds

Hence Equation (39) becomes

$$(C_{EV}V_o - V_oC_o) = \left(\frac{\rho g h A^2 t}{\mu C R}\right)^{1/2} (5.523C_{EV} - C) \quad (41)$$

Squaring both sides

$$(C_{EV}V_o - V_oC_o)^2 = \left(\frac{\rho g h A^2 t}{\mu C R}\right) (5.523C_{EV} - C)^2 \quad (42)$$

$$\frac{\rho g h A^2 t}{\mu C R} = \left(\frac{C_{EV}V_o - V_oC_o}{5.523C_{EV} - C}\right)^2 \quad (43)$$

$$R = \left(\frac{5.523C_{EV} - C}{C_{EV}V_o - V_oC_o}\right)^2 \frac{\rho g h A^2 t}{\mu C} \quad (44)$$

$$R = \frac{\rho g h A^2 t}{\mu C} \left(\frac{5.523C_{EV} - C}{C_{EV}V_o - V_oC_o}\right)^2 \quad (45)$$

Introducing concentration of conditioner expressed as C_{CON}

$$C_{CON} \propto R$$

From plot of Concentration of Sludge C_O against Concentration of Conditioner C_{CON}

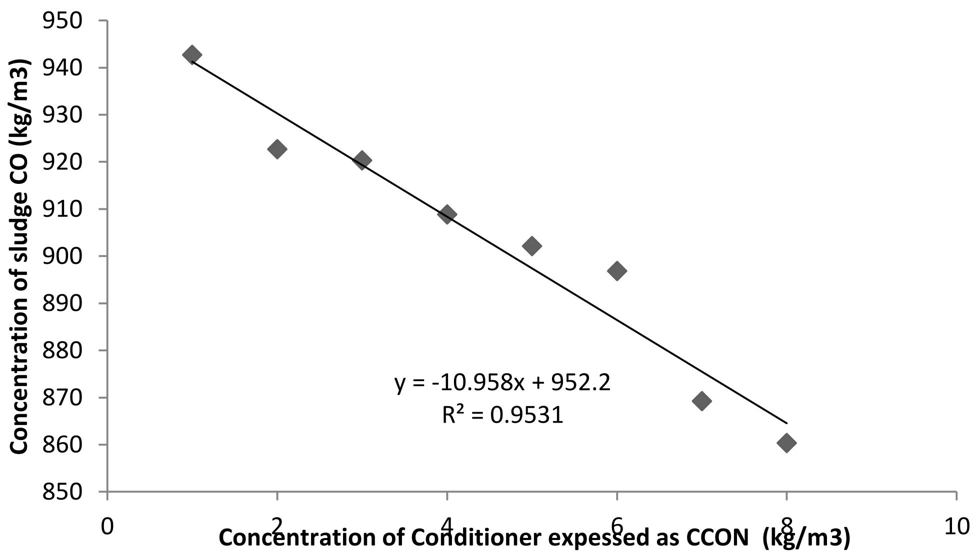

Fig. 4. *Plot of Concentration of Sludge C_O against Concentration of Conditioner C_{CON}*

$$C_O = -10.958C_{CON} + 952.2 \quad (46)$$

$$\therefore R = \frac{\rho g h A^2 t}{\mu C} \left[\frac{5.523C_{EV} - C}{C_{EV}V_o - V_o(-10.958C_{CON} + 952.2)}\right]^2 \quad (47)$$

where, R = Specific Resistance (m/kg), ρgh = Hydrostatic Pressure (N/m^2), A = Area of Filtration (m^2) C_{EV} = Concentration of Evaporation (kg/m^3), C = Solid Content (kg/m^3), μ = Dynamic Viscosity (N.s/m^2), V_o = Volume of Sludge (m^3) and C_{CON} = Concentration of Conditioner (kg/m^3).

3. RESULTS AND DISCUSSION

Filtration of Agricultural Sludge on Sand Drying Bed

The results of the Filtration of Agricultural and Industrial sludge using $FeCl_3$ with different concentrations are shown in Tables 1-12.

Table 1: Filtration of Agricultural sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 20 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure P $=\rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00062	0.0000577	0.0005023	2832.080	0.92085	970.00	917.63	52.37	1.63
2	0.00078	0.0000585	0.0006615	2828.955	0.81454	986.33	920.07	66.26	1.51
3	0.00099	0.0000591	0.0008709	2829.637	0.83859	995.43	925.09	70.34	1.42
4	0.00102	0.0000598	0.0009002	2831.286	0.89159	996.43	920.09	76.34	1.20
5	0.00106	0.0000599	0.0009401	2829.637	0.83859	1010.34	922.29	88.05	1.03
6	0.0014	0.0000599	0.0012801	2831.286	0.89159	1024.24	935.13	89.11	1.02
7	0.00202	0.0000599	0.0019001	2829.637	0.83859	1027.14	934.11	93.03	1.01
8	0.00172	0.0000589	0.0016011	2146.621	0.83859	1015.02	887.00	128.02	1.00

Table 2: Filtration of Agricultural sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 40 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) (kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure P $=\rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00078	0.0000568	0.0006699	2538.39	0.89159	967.50	912.1667	55.33333	3.02
2	0.00105	0.0000581	0.0009319	2631.262	0.75021	985.50	915.3333	70.1667	2.81
3	0.00114	0.0000585	0.0010215	2633.008	0.79184	990.52	918.4353	72.0847	2.65
4	0.00118	0.0000587	0.0010613	2732.859	0.86424	994.52	916.4353	78.0847	2.29
5	0.00122	0.0000589	0.0011011	2633.855	0.81454	1016.62	918.1053	98.5147	1.50
6	0.00162	0.000059	0.001501	2536.916	0.83858	1014.45	915.0053	99.4447	1.38

7	0.0024	0.0000596	0.0022804	2535.489	0.79184	1024.13	920.1053	104.0247	1.36
8	0.00404	0.0000598	0.0039202	2536.305	0.81454	1032.02	926.1013	105.9187	1.32

Table 3: Filtration of Agricultural sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 60 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity μ ($N.s/m^2$)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00114	0.0000563	0.0010837	2440.05	0.86424	963.67	902.3333	61.3367	3.74
2	0.00165	0.0000579	0.0015321	2437.162	0.77043	982.83	904.3333	78.4967	3.12
3	0.00168	0.0000581	0.0015619	2437.162	0.77043	986.63	904.5633	82.0667	2.96
4	0.00172	0.0000581	0.0016019	2536.916	0.83859	992.63	906.5633	86.0667	2.68
5	0.00176	0.0000588	0.0016412	2534.648	0.77043	1014.2	910.5633	103.6367	1.90
6	0.00184	0.0000589	0.0017211	2437.162	0.77043	1014.40	910.2033	104.1967	1.85
7	0.0026	0.0000591	0.0024809	2437.162	0.77043	1022.3	915.2033	107.0967	1.79
8	0.00562	0.0000593	0.0055007	2437.971	0.79184	1028.1	918.1040	109.996	1.66

Table 4: Filtration of Agricultural sludge using $FeCl_3$ with different concentrations showing the Readings obtained on an 80 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) (kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure P $=\rho gh$ (N/m^2)	Dynamic Viscosity μ ($N.s/m^2$)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.01142	0.0000554	0.0113646	2341.77	0.83859	959.67	889.6667	70.0033	4.07
2	0.00175	0.0000571	0.0016329	2244.195	0.83859	974.00	892.3333	81.6667	3.15
3	0.00186	0.0000577	0.0017423	2338.899	0.75021	984.67	892.3333	92.3367	2.90
4	0.00188	0.0000581	0.0017619	2437.971	0.79184	988.67	892.3333	96.3367	2.64
5	0.00191	0.0000583	0.0017917	2436.354	0.75021	1012.82	898.4333	114.3867	1.63
6	0.00212	0.0000586	0.0020014	2338.899	0.75021	1013.12	896.1143	117.0057	1.43
7	0.00283	0.0000589	0.0027111	2338.899	0.75021	1018.22	898.0173	120.2027	1.39
8	0.00345	0.0000592	0.0033308	2338.899	0.75021	1024.02	902.0103	122.0097	

									1.27

Table 5: Filtration of Agricultural sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 100 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) (kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P = \rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) ×10^7
1	0.00163	0.0000535	0.0015765	2244.19	0.83859	931.00	849.6667	81.33333	3.32
2	0.00175	0.0000571	0.0016329	2244.195	0.83859	974.00	892.3333	81.6667	3.15
3	0.00186	0.0000577	0.0017423	2338.899	0.75021	984.67	892.3333	92.3367	2.90
4	0.00188	0.0000581	0.0017619	2437.971	0.79184	988.67	892.3333	96.3367	2.64
5	0.00191	0.0000583	0.0017917	2436.354	0.75021	1012.82	898.4333	114.3867	1.63
6	0.00212	0.0000586	0.0020014	2338.899	0.75021	1013.12	896.1143	117.0057	1.43
7	0.00283	0.0000589	0.0027111	2338.899	0.75021	1018.22	898.0173	120.2027	1.39
8	0.00345	0.0000592	0.0033308	2338.899	0.75021	1024.02	902.0103	122.0097	1.27

Table 6: Filtration of Agricultural sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 120 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) (m^3)	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) ×10^7
1	0.00102	0.0000533	0.0009667	2145.41	0.79184	897.83	812.5000	85.33333	3.09
2	0.00106	0.0000559	0.0009441	1951.474	0.83859	914.00	818.0000	96.0000	1.97
3	0.00095	0.0000571	0.0008329	1951.474	0.83859	928.00	820.0000	108.0000	1.26
4	0.00114	0.0000576	0.0010224	2146.621	0.83859	936.00	822.00	114.0000	1.07
5	0.0014	0.000058	0.001282	2146.621	0.83859	1007.46	882.3012	125.1551	1.03
6	0.00154	0.0000575	0.0014225	2146.621	0.83859	1009.03	883.0012	126.0251	1.02
7	0.00161	0.0000577	0.0014923	2146.621	0.83859	1012.02	885.0024	127.0218	1.01
8	0.00172	0.0000589	0.0016011	2146.621	0.83859	1015.02	887.0013	128.0199	1.00

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Table 7: Filtration of Industrial sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 20 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity µ ($N.s/m^2$)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00078	0.0000546	0.0006654	2832.081	0.92085	948.50	900.1667	48.33333	1.67
2	0.00082	0.0000594	0.0007006	2734.423	0.89185	969.43	908.0624	61.3676	1.41
3	0.00096	0.0000595	0.0008405	2830.462	0.86424	980.52	910.0712	70.4488	1.32
4	0.00117	0.0000596	0.0010504	2732.859	0.86424	985.12	912.0102	73.1098	1.25
5	0.00145	0.0000597	0.0013303	2830.462	0.86424	990.24	913.0122	77.2278	1.23
6	0.00209	0.0000598	0.0019702	2732.064	0.83859	998.84	919.22	79.6200	1.22
7	0.00245	0.0000599	0.0023301	2830.462	0.86424	1002.98	920.02	82.9600	1.18
8	0.00262	0.0000599	0.0025001	2829.637	0.83859	1015.22	928.14	87.08	1.17

Table 8: Filtration of Industrial sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 40 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity µ ($N.s/m^2$)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00096	0.0000557	0.0008443	2537.655	0.86424	943.83	883.00	60.83	2.49
2	0.00101	0.0000596	0.0008904	2635.257	0.86424	958.42	890.21	68.21	2.36
3	0.00111	0.0000596	0.0009904	2536.916	0.83859	975.05	900.02	75.03	2.16
4	0.00145	0.0000597	0.0013303	2634.489	0.83859	984.02	904.01	80.01	2.10
5	0.00164	0.0000598	0.0015202	2732.064	0.83859	989.42	905.11	84.31	2.04
6	0.00245	0.0000599	0.0023301	2633.008	0.79184	995.14	908.07	87.07	2.03
7	0.00282	0.0000599	0.0027001	2732.064	0.83858	999.62	910.12	89.50	1.95
8	0.00325	0.00006	0.00313	2730.527	0.79184	1013.45	917.22	96.23	1.84

Table 9: Filtration of Industrial sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 60 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity µ ($N.s/m^2$)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00108	0.0000591	0.0009609	2437.971	0.79184	931.17	833.00	98.17	1.28

2	0.00184	0.0000597	0.0017203	2536.916	0.83859	944.20	840.12	100.08	1.26
3	0.00245	0.0000598	0.0023302	2439.343	0.83859	968.42	864.21	104.21	1.23
4	0.00263	0.0000598	0.0025102	2437.971	0.79184	983.36	874.34	109.02	1.19
5	0.00283	0.0000599	0.0027101	2633.008	0.79184	988.14	875.34	112.80	1.15
6	0.00341	0.0000599	0.0032901	2535.489	0.79184	993.25	879.54	113.71	1.13
7	0.00481	0.00006	0.00469	2633.008	0.79184	998.36	882.22	116.14	1.11
8	0.00205	0.000059	0.001931	1950.376	0.79184	996.65	872.15	124.50	1.02

Table 10: Filtration of Industrial sludge using $FeCl_3$ with different concentrations showing the Readings obtained on an 80 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00142	0.0000594	0.0013006	2338.899	0.75021	911.00	810.33	100.67	1.37
2	0.00242	0.0000598	0.0023002	2338.899	0.75021	921.15	815.20	104.95	1.21
3	0.00362	0.0000599	0.0035001	2338.899	0.75021	952.52	842.24	110.28	1.20
4	0.00314	0.0000599	0.0030201	2241.445	0.75021	971.12	858.04	113.08	1.17
5	0.00425	0.00006	0.0041300	2337.253	0.71291	984.34	868.00	117.34	1.16
6	0.00452	0.00006	0.0044	2337.253	0.71290	987.48	869.12	118.36	1.15
7	0.00563	0.00006	0.00551	2435.496	0.73106	992.18	872.16	120.02	1.14
8	0.00631	0.00006	0.00619	2338.076	0.73106	1004.23	882.16	122.07	1.11

Table 11: Filtration of Industrial sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 100 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C (kg/m^3)	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00164	0.0000536	0.0015264	2239.867	0.71291	881.17	778.67	102.50	1.26
2	0.00217	0.0000599	0.0020501	2239.867	0.71291	918.53	809.45	109.08	1.20
3	0.00223	0.0000599	0.0021101	2142.482	0.71291	942.66	830.24	112.42	1.18
4	0.00233	0.0000599	0.0022101	2142.482	0.71290	969.17	852.16	117.01	1.16

5	0.00248	0.00006	0.0023600	2145.414	0.79184	984.23	866.16	118.07	1.15
6	0.00246	0.00006	0.00234	2241.445	0.75020	983.35	863.24	120.11	1.14
7	0.00283	0.0000599	0.0027101	2338.899	0.75021	988.24	866.12	122.12	1.13
8	0.0032	0.0000599	0.0030801	2143.991	0.75021	997.55	874.23	123.32	1.08

Table 12: Filtration of Industrial sludge using $FeCl_3$ with different concentrations showing the Readings obtained on a 120 minutes

Concentration of Conditioner C_{CON} ($FeCl_3$) kg/m^3)	Volume of filtrate (V) m^3	Volume of Cake (V_C) m^3	Volume of Evaporate (V_{EV}) m^3	Hydrostatic Pressure $P=\rho gh$ (N/m^2)	Dynamic Viscosity μ (N.s/m^2)	C_O kg/m^3	Solid Content C kg/m^3	C_{EV} kg/m^3	Specific Resistance R (m/kg) $\times 10^7$
1	0.00082	0.0000519	0.0007081	2146.621	0.83859	871.33	770.33	100.99	1.24
2	0.00107	0.000059	0.000951	2145.414	0.79184	917.62	807.27	110.35	1.14
3	0.00124	0.000059	0.001121	1950.376	0.79184	942.17	829.16	113.01	1.12
4	0.00142	0.000059	0.001301	1951.474	0.83859	967.16	850.10	117.06	1.10
5	0.00152	0.000059	0.0014010	1951.474	0.83859	982.52	863.24	119.28	1.09
6	0.0014	0.000059	0.001281	2145.414	0.79184	982.67	860.16	122.51	1.06
7	0.00176	0.000059	0.001641	1949.729	0.77043	982.00	860.00	122.00	1.05
8	0.00205	0.000059	0.001931	1950.376	0.79184	996.65	872.15	124.50	1.02

Comparison Using Experimental Data from Agricultural Sludge with the New Model Equation, Carman's Equation and Ademiluyi and Arimieari's Equation

The Plots of Linear Relationship for the New Model Equation, Carman's Equation and for Agricultural Sludge on a 20 minutes Interval for Different Concentrations of Conditioner is presented in Figure 5.

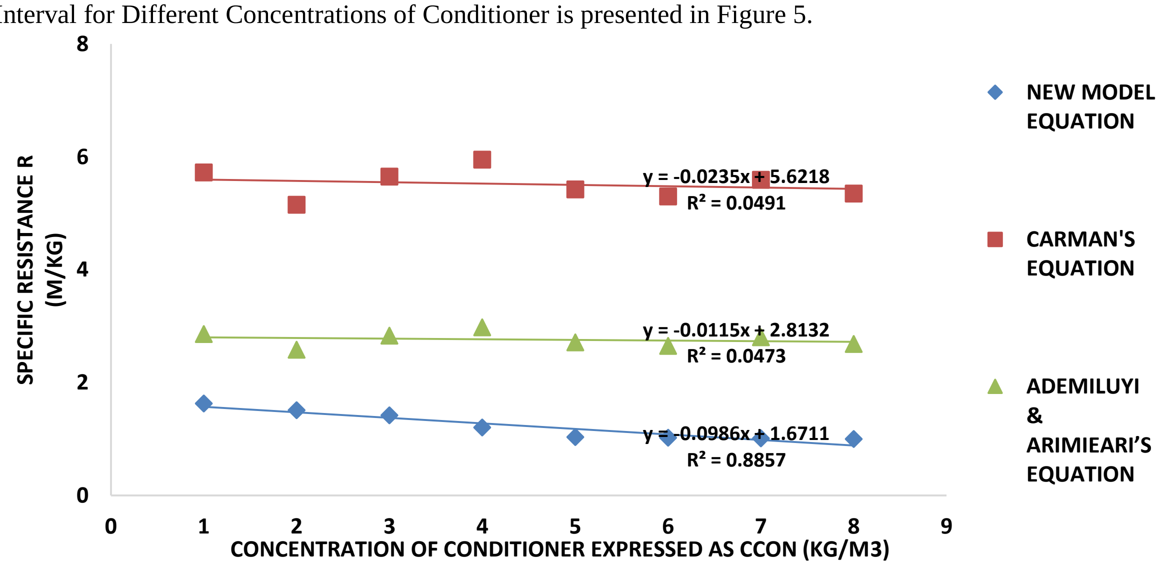

Fig. 5. *The Plots of Linear Relationship for the New Model Equation, Carman's Equation and Ademiluyi and Arimieari's Equation for Agricultural Sludge on a 20 minutes Interval for Different Concentrations of Conditioner*

DISCUSSION

Mass balance analysis was used in this study to develop a model for sludge drying bed filtration. Using the new model equation of mass balance analysis, which incorporates the input variable, concentration of sludge (C_O); the state variable, specific resistance (R); and the output variables, solid content (C) and concentration of evaporation (C_{EV}), the filtration experiments conducted with conditioned sludge for agricultural and industrial sludge have demonstrated that specific resistance, R values decreased as the concentration of conditioner ($FeCl_3$) increases. It was shown that the rate of filtrate increased with conditioner concentration. It is significant to point out that sludge concentration, solid content, and evaporation concentration all increased as conditioner concentration did, suggesting that conditioners are essential to sludge's filterability. The new model equation agreed with the plots of linear relationships for Carman's equation and Ademiluyi and Arimieari's equation for agricultural sludge generated on a 20-minute interval for different conditioner concentrations when compared using experimental data from agricultural and industrial sludge. The correlation coefficients, which range widely, are 0.8857, 0.0491 and 0.0473, respectively. The reason for this discrepancy could be that the new model equation includes variables that Carman, Ademiluyi, and Arimieari's equations did not incorporate, such as the volume of sludge (m^3), time taken to obtain the filtrate in seconds, and concentration of evaporation (kg/m^3). This study enhanced the previous models by adding more filtering variables based on the sludge drying bed using mass balance analysis.

4. CONCLUSION

This study was aimed at developing a model for sludge drying bed filtration using mass balance analysis. The filtration experiments conducted with conditioned sludge for agricultural and industrial sludge have shown that specific resistance, R values decreased as the concentration of conditioner ($FeCl_3$) increases using the new model equation of mass balance analysis which incorporates the input variable, concentration of sludge (C_O); the state variable, specific resistance (R); and the output variables, solid content (C) and concentration of evaporation (C_{EV}). It was observed that the higher the concentration of conditioner, the higher the rate of filtrate. It is important to note that as the concentration of conditioner increases, the concentration of sludge, solid content and concentration of evaporation increased indicating that conditioners play an important role in the filterability of sludge. On comparison using experimental data from agricultural and industrial sludge, the new model equation agreed with the plots of linear relationship for Carman's equation and Ademiluyi and Arimieari's equation for agricultural sludge generated on a 20 minutes interval for different concentrations of conditioner. The coefficient of correlation differs by wide range which includes 0.8857, 0.0491 and 0.0473 respectively. This anomaly may be attributed to the fact that the new model equation incorporates concentration of evaporation (kg/m^3), time taken to obtain the filtrate in seconds, volume of sludge (m^3) and concentration of conditioner (kg/m^3) which were not found in Carman's and Ademiluyi and Arimieari's equations. Using mass balance analysis, this study improved on the existing models by introducing other filtration variables based on sludge drying bed.

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