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RESEARCH ARTICLE

SLUDGE DEWATERING SUBJECTED TO CONSTANT VACUUM PRESSURE: A MODELLING APPROACH

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ABSTRACT

Sludge is often generated from the treatment of wastewater and it is essential to reduce its volume before disposal into the environment through dewatering. This helps to reduce the cost of final sludge disposal. This study was therefore aimed at developing a model for the draining time of sludge through the application of vacuum pressure. A vacuum filtration experiment was performed on sewage sludge collected from the wastewater treatment plant situated at the University of Nigeria, Nsukka. The sludge sample was poured into Buchner funnel apparatus and the volume of the filtrate collected was noted at a certain time interval until the end of the experiment. The specific resistance values were obtained using the newly derived-, modified-, and Carman's-equation, respectively. A comparative study was carried out on the three values obtained and the results showed that the newly derived equation gave the best result. Overall, the newly derived equation demonstrated conformity with Carman's equation and can be used for sludge dewatering investigation. This paper covers a relevant subject within the field of waste treatment processes, namely the dewatering of sludge from wastewater treatment system and on a large scale, can aid in producing cost effective mechanism that makes it more possible for developing nations to incorporate adequate and effective sanitation.

INTRODUCTION

In the process of wastewater treatment, sludge due to its waste content forms a significant fraction of waste generated that is complex. Sludge needs to be dewatered before its final disposal (Ademiluyi, 1984; Olukanni and Aremu, 2008; Afangideh *et al*., 2011). Dewatering is a physical process that is used to reduce the moisture content so as to ensure easy handling and processing into semi-solid or prepared as cake (Olukanni *et al*., 2013). Dewatering increases the solid content of sludge between 20 to 35% (Agunwamba, 2001, Olukanni and Aremu, 2008). The sludge consists of solids, oil, fat, protein, phosphates, carbohydrate, nitrogen, water, etc. with a specific gravity of 1.02 to 1.06 for organic fraction and also a specific gravity of 2.5 for inorganic fraction (Ekpobari, 2002). Ghazy *et al.* (2009) stated that sewage sludge poses a serious problem in many countries due to its high treatment costs and risks to environment and human health. A recent study conducted by Randal (2001), revealed that despite the fact that the volume of sludge tends to be less than 1% of the total plant influent, sludge handling costs ranges between 21-50% of total plant operating and maintenance costs. The handling of sewage sludge is one of the most significant challenges in wastewater management. Dewatering of sewage sludge is not only found in removal of the excess moisture but to render the sludge odourless and nonputrescible (Garg, 2009). Ademiluyi and Arimieari (2012) expressed that dewatering of sewage sludge prior to drying or disposal is an important step because the lower the water content of the sludge, the more economical it will be to reduce its volume in order to reduce the transport cost, the less liable to degradation and odour production, and the easier it will be to dry. Sludge filtration theories and derived equations have been based on experimental assumptions and conditions, each researcher making effort to modify already existing theory in order to introduce a completely new concept for evaluating sludge filtration equation (Ademiluyi and Arimieari, 2012).

Over the years, some researchers have come up with different equations to express the resistance of processing fresh sludge into sludge cake. Carman in a study in 1934 postulated a filtration equation whereby an assumption was made that the specific resistance is constant throughout the sludge cake thickness and that the cake is rigid. Ruth (1935) and Shirato (1972) disagreed with Carman's equation in that the specific resistance parameter should be designated as an average value. Therefore, the aim of this study was to develop a model for sludge dewatering through the application of vacuum pressure.

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MATERIALS AND METHODS

Laboratory Setup

The data presented in this work were obtained from filtration experiment conducted using the sewage treatment plant situated at the University of Nigeria, Nsukka. The laboratory experimental set up for determination of specific resistance (R) was done using Buchner funnel apparatus. The sludge sample was poured through the funnel into a graduated measuring cylinder and a vacuum pressure was supplied through a pump connected to a mercury manometer. The applied vacuum pressure was kept constant throughout each experiment in order to determine other varying factors influencing the filterability of the sludge. As the filtration starts, the filtrate is received in the measuring cylinder. The volume of the filtrate collected is noted at a certain time interval until the end of the experiment.

Derivation of Equation for the Rate of Sludge Dewatering

The rate of sludge dewatering (draining time) is a function of Volume, V; Vacuum pressure, P; Area of the filter medium, A; Solid content, C; Dynamic Viscosity, μ; Specific Resistance, R; and Time, T.

Using Buckingham's π – Theorem, Table 1 shows the fundamental dimensions to express the unit of each variable.

Table 1. M-L-T Dimensions

Variables	Dimension
Volume (V)	L^3
Pressure (P)	$ML^{-1}T^{-2}$
Area of the filter medium (A)	L^2
Solid content (C)	ML^{-3}
Dynamic viscosity (μ)	$ML^{-1}T^{-1}$
Specific Resistance (R)	MLT^{-2}
Time (T)	T

$$V = f(P, A, C, \mu, R, T) \quad (1)$$

Equation can be further expressed as:

$$f_1(V, P, A, C, \mu, R, T) = 0 \quad (2)$$

The total number of variables (n) is seven while the number of fundamental dimensions (m) is three, hence the number of π - terms will be: n – m = 7 – 3 = 4.

Therefore, each π-term can be expressed as:

$$f_1(\pi_1, \pi_2, \pi_3, \pi_4) = 0 \quad (3)$$

Each π-term contains (m + 1) number of variables which can be expressed with the repeating variables: μ, R, A

Repeated variables for each π term are thus expressed as:

$$\pi_1 = \mu^{a}{}_1 \cdot R^{b}{}_1 \cdot A^{c}{}_1 \cdot P \quad (3.1)$$
$$\pi_2 = \mu^{a}{}_2 \cdot R^{b}{}_2 \cdot A^{c}{}_2 \cdot V \quad (3.2)$$
$$\pi_3 = \mu^{a}{}_3 \cdot R^{b}{}_3 \cdot A^{c}{}_3 \cdot C \quad (3.3)$$
$$\pi_4 = \mu^{a}{}_4 \cdot R^{b}{}_4 \cdot A^{c}{}_4 \cdot T \quad (3.4)$$

For π_1

$M^0L^0T^0 = (ML^{-1}T^{-1})^{a1} \cdot (MLT^{-2})^{b1} \cdot (L^2)^{c1} \cdot ML^{-1}T^{-2}$

For M: $0 = a_1 + b_1 + 1$ (4.1)
For L: $0 = - a_1 + b_1 + 2C_1 - 1$ (4.2)
For T: $0 = - a_1 – 2b_1 – 2$ (4.3)
From (4.1), $a_1 = -b_1 – 1$, put in (4.3)
$(-b_1 – 1) – 2b_1 – 2 = 0$
$b_1 + 1 – 2b_1 – 2 = 0$
Hence, $b_1 = -1$, $a_1 = 0$, $c_1 = 1$ (4.4)

$$\pi_1 = \mu^0 . R^{-1} . A^1 . P = \frac{PA}{R}$$

For π_2

$M^0L^0T^0 = (ML^{-1}T^{-1})^{a2} \cdot (MLT^{-2})^{b2} \cdot (L^2)^{c2} \cdot L^3$
For M: $0 = a_2 + b_2$ (4.5)
For L: $0 = - a_2 + b_2 + 2C_2 + 3$ (4.6)
For T: $0 = - a_2 – 2b_2$ (4.7)
From equation (4.7), $a_2 = -2b_2$, put in (4.5)
$-2b_2 + b_2 = 0$
Hence, $b_2 = 0$, $a_2 = 0$, $c_2 = -3/2$

$$\pi_2 = \mu^0 \cdot R^0 \cdot A^{-3/2} \cdot V = \frac{V}{A^{3/2}} \quad (4.8)$$

For π_3
$M^0L^0T^0 = (ML^{-1}T^{-1})^{a3} \cdot (MLT^{-2})^{b3} \cdot (L^2)^{c3} \cdot ML^{-3}$
For M: $0 = a_3 + b_3 + 1$ (4.9)
For L: $0 = - a_3 + b_3 + 2C_3 - 3$ (4.10)
For T: $0 = - a_3 – 2b_3$ (4.11)
From (4.11), $a_3 = -2b_3$, put in (4.9)
$-2b_3 + b_3 + 1 = 0$
Hence, $b_3 = 1$, $a_3 = -2$, $c_2 = 0$

$$\pi_3 = \mu^{-2} \cdot R^1 \cdot A^0 \cdot C = \frac{RC}{\mu^2} \quad (4.12)$$

For π_4
$M^0L^0T^0 = (ML^{-1}T^{-1})^{a4} . (MLT^{-2})^{b4} \cdot (L^2)^{c4} \cdot T$
For M: $0 = a_4 + b_4$ (4.13)

For L: $0 = - a_4 + b_4 + 2C_4$ (4.14)

For T: $0 = - a_4 – 2b_4 + 1$ (4.15)

From (4.13), $a_4 = -b_4$, put in (4.15)
$- (-b_4) - 2b_4 + b_4 + 1 = 0$
Hence, $b_4 = 1$, $a_4 = -1$, $c_4 = -1$

$$\pi_4 = \mu^{-1} \cdot R^1 \cdot A^{-1} \cdot T = \frac{RT}{\mu A} \quad (4.16)$$

Substituting equations (4.4), (4.8), (4.12), and (4.16) in equation (3)

$$f_1\left(\frac{PA}{R}, \frac{V}{A^{3/2}}, \frac{RC}{\mu^2}, \frac{RT}{\mu A}\right) = 0 \quad (4.17)$$

Since the reciprocal and the squares of π – terms are dimensionless, hence;

$$\frac{V}{A^{3/2}} = \phi\left(\frac{PA}{R}, \frac{RC}{\mu^2}, \frac{RT}{\mu A}\right) \quad (4.18)$$

As the products of two Π terms are dimensionless, the terms Π3 and Π4 can be expressed as

$$\frac{V}{A^{3/2}} = \phi\left(\frac{PA}{R}, \frac{R^2 CT}{\mu^3 A}\right) \quad (4.19)$$

Multiplication of π – terms are dimensionless, hence;

$$\frac{V}{A^{3/2}} = \left(\frac{PRCT}{\mu^3}\right)$$

Experimental analysis shows that R varies inversely with μ and since dimensional analysis provides partial solutions to the problems that are too complex to be dealt with mathematically, hence;

$$\frac{T}{V} = \frac{RC\mu V}{PA^3} \quad (4.20)$$

By plotting T/V against V, we obtained the slope of the fitted line as;

$$\frac{RC\mu}{PA^3} = b = Slope \quad (4.21)$$

This implies that:

$$R = \left(\frac{PA^3}{C\mu}\right)b \quad (4.22)$$

where:
A = Area of Filtration (m^2)
C = Solid Content (kg/m^3)
P = Vacuum Pressure (N/m^2)
R = Specific Resistance (m/kg)
V = Volume of Filtrate (m^3)
μ = Dynamic Viscosity ($N.s/m^2$)
b = Slope (s/m^6)

Comparisons of Specific Resistance Using Newly Derived Equation, Modified Equation and Carman's Equation

Carman developed an expression for the dewatering of sludge by filtration. Specific resistance of sludge was introduced in the equation to compare filterability of different sludge. The equation is expressed by;

$$t/v = \frac{RC\mu V}{2PA^2} + \frac{R_m \mu}{PA} \quad (5.1)$$

By plotting $\frac{t}{v}$ against v, the slope; the fitted straight line is:

$$b = \frac{RC\mu}{2PA^2} \quad (5.2)$$

Hence, $R = \left(\frac{2PA^2}{C\mu}\right)b$ (5.3)

Where all terms retain their usual meaning.

A modified equation was derived using Anazodo's method which is expressed as;

$$t/v = \frac{\mu CRV}{PghA^2} \quad (6.1)$$

With a plot of $\frac{t}{v}$ against v, the slope of the fitted line is;

$$b = \frac{\mu CR}{PghA^2} \quad (6.2)$$

Hence, $R = \left(\frac{2PA^2}{C\mu}\right)b$

RESULTS

The values for filtrate volume, draining time and solid content of sludge were obtained in the experiment. With the aid of regression analysis, specific resistance of the sludge was determined for Carman's equation, modified equation (Ademiluyi and Arimieari, 2012 and the newly derived equation as shown.

Table 2. Computed Values of Specific Resistance for Experiment I

Specific Resistant R (m/g Specific Resistant R (m/g × 10^8)			
Solid content C (kg/m^3)	Carman	Modified	Newly Derived
13.85	12.391	6.196	5.576
9.98	17.197	8.598	7.738
8.69	19.749	9.875	98.887
7.86	21.835	10.917	9.826
7.27	23.607	11.803	10.623
6.87	24.981	12.491	11.242

Table 3. Computed Values of Specific Resistance for Experiment II

	Specific Resistant R (m/g × 10^8)		
Solid content C (kg/m^3)	Carman	Modified	Newly Derived
83.50	22.184	11.092	9.983
70.40	26.312	13.156	11.840
64.00	28.943	14.472	13.024
58.60	31.610	15.805	14.225
52.50	35.283	17.642	15.877

Table 4. Computed Values of Specific Resistance for Experiment III

	Specific Resistant R (m/g × 10^7)		
Solid content C (kg/m^3)	Carman	Modified	Newly Derived
27.50	53.610	26.805	24.125
24.00	61.428	30.714	27.643
22.00	67.013	33.506	30.156
20.60	71.567	35.783	32.205
18.50	79.691	39.845	35.861

The specific resistance of the sludge versus solid content was determined for the Carman's equation, modified equation and the newly derived equation as shown in Figures 1-3. The newly derived model fits better than the other models as shown in Figure 1. The figure equally shows an increase in specific resistance as the amount of solid content decreased. The least specific resistance was obtained in experiment II as shown in Fgure 2. This implies that the newly derived model gives the best fit. The less the specific resistance, the more filterable the sludge. In all, the values in experiment II can be used for sludge dewatering studies.

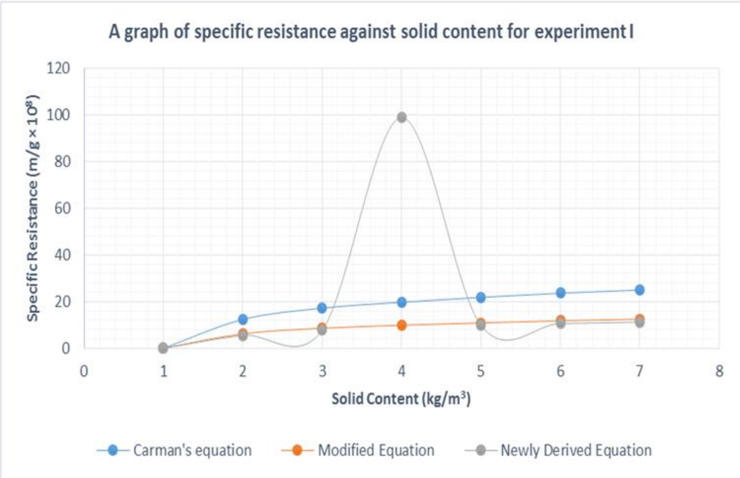

Fig.1. Variation of specific resistance with time for experiment I

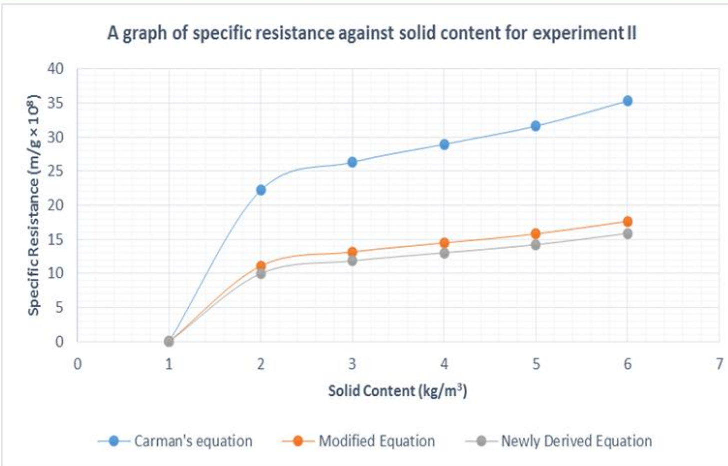

Fig.2. Variation of specific resistance with time experiment II

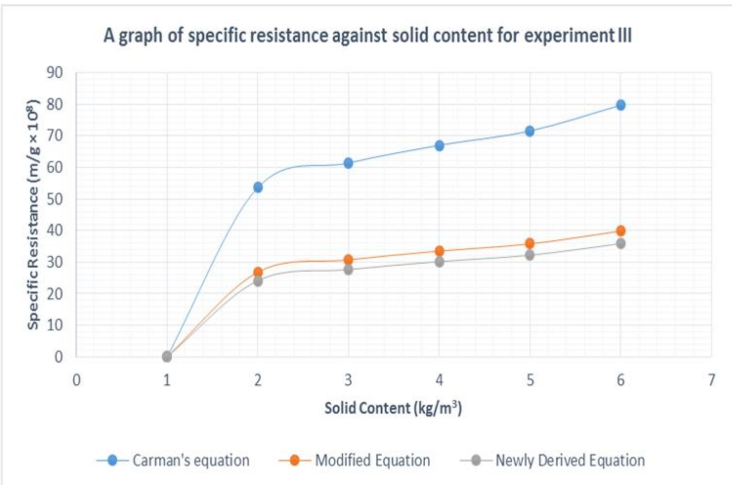

Fig.3.Variation of specific resistance with time fo rexperiment III

The newly derived model fits better in experiment III than in II. Though, the specific resistance is higher than that of experiment II.

DISCUSSION

During the experiment, it was observed that as the volume of filtrate increased, the specific resistance also increased with time. This is due to the thickening of the sludge content. This implies that the concentration of the cake formed, gradually increases bringing about a decrease of the volume of sludge content. As shown in Figures 1-3, the plot of specific resistance (R) against solid content (C) gave more or less a straight line relationship, showing that solid content has great influence on the filterability of the sludge. From the analysis of the data, specific resistance values were obtained using the newly derived equation, modified equation and Carman's equation. From the calculated values, newly derived equation gave overall specific resistance (R) of 8.4992×10^8 m/kg, 9.9827×10^7 m/kg and 24.1245×10^7 m/kg for experiment I, II and III respectively. Modified equation gave 9.4436×10^8 m/kg, 11.0920×10^7 m/kg and 26.8050×10^7 m/kg respectively, while Carman's equation shows that (R) are; 18.8872×10^8 m/kg, 22.1840×10^7 m/kg and 53.6100×10^7 m/kg respectively. The results obtained shows that the resistance to filtration increases with decrease in the amount of solid content of the sludge, so long as the applied vacuum pressure remains constant. These results show a uniform trend, which implies that the experimental data is valid.

Since residues from each wastewater plant are unique, it then implies that no specific treatment process for the dewatering will yield the same results. The specific resistance (R) obtained were compared between the three equations, it was observed that the newly derived equation gave the best result as shown in the graph. It is imperative that the derived equation is more valid since the lower the specific resistance, the more filterable the sludge. There is no better analogy to determine the filterability of sludge than the use of the specific resistance of the sludge. The modified equation gave a closer result and the least is the Carman's equation. In all, the derived equation is in consonance with Carman's equation and it can be used for both sludge drying bed and vacuum filtration or any other sludge dewatering investigation.

Conclusion and Recommendation

Although, vacuum filtration technology is not very economical, it provides a fast means for sludge dewatering and eliminates problems of atmospheric conditions like rainfall, relative humidity, sunshine etc. and clogging of the sand layer when using sludge drying bed technology.
The following options for sludge dewatering equipment are recommended.

1. A pilot mechanical dewatering facility should be established.
2. The mechanical dewatering facility should provide the capacity for simultaneous exploration of various systems such as belt filter press, centrifuge and vacuum filtration.

The performance of these types of equipment could be improved by adding chemicals to the sludge as a conditioner. Overall, effort should be made for specific resistance to be evaluated experimentally in order to ascertain the efficacy of sludge dewatering.

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