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Developing cake equation for municipal waste from Kaduna metropolis

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ABSTRACT

Dewatering and drying sludge in order to get the cake is a process that requires some time, depending on the volume and type of the sludge. A dewatering analysis was carried out from a municipal sewage sample collected from Unguwar Sarki area of Kaduna Metropolis, up to the level of obtaining a cake. Although the sludge used in this study was from a municipal waste, it is a bit thick because it is sometimes stagnant in an open drain. The dewatering process was done using dry beds. The t/v verse volume and other relevant graphs were plotted. Using advanced mathematics, an equation was proposed from mass balance equation, to calculate the cake concentration. Also, Matlab was used to plot a graph of the cake concentration; and another cake equation was proposed with Matlab polynomials as the source. The proposed cake equation was given a trial by substituting variables that were obtained in the laboratory works into the equation and a relevant result was obtained.

INTRODUCTION

Wastewater can have a number of definitions. Domestic wastewater is defined as wastewater from household water use, while industrial wastewater is from industrial practices only. Thus, wastewater can be defined generally as “a combination of one or more of: domestic effluent consisting of black water faecal sludge) and greywater (kitchen and bathing wastewater);water from commercial establishments and institutions, including hospitals; and industrial effluent (Corcoran et al., 2010).

Sludge can be described as the accumulated solids produced by a waste water treatment plant and solids left from septage, the liquid pumped from septic tanks. Materials from human waste, residential waste, industrial waste, hospital waste, runoff from streets, farmlands, and in some cases, landfill leachates (Koné et al., 2007). The form of water in sludge determines the effectiveness of sludge treatment operations to separate the water associated with the solids. Before ultimate disposal, the water content of sludge should be decreased both from environmental and economic point of view (Tchobanoglous et al., 2002). Sludge filtration theories and derived equations have been made on experimental assumptions and conditions. According to Ademiluyi and Arimieari (2012), each researcher is making effort to modify already existing theory in order to introduce a completely new concept for evaluating sludge filtration equation. A careful study of researchers works on this topic, have shown that most of them do refer to Carman’s equation as the basis of their research. Carman came up with an equation for sludge filtration based on specific resistance and the time velocity plot of sludge filtration at constant pressure (Carman, 1934).

LITERATURE REVIEW

The year 2014 marks the centenary of the publication of the seminal paper on activated sludge which provided a basis to treat sewage by biological means (Baum et al., 2013). Since then there have been extensive developments in both scientific knowledge and processes to treat wastewaters of all types. There are now many

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aerobic, anaerobic and physico-chemical processes that can treat wastewaters to almost any standard of effluent from the simple removal of gross solids to membrane systems that can produce drinking water quality.

Treatment strategies range along a continuum from high technology, energy-intensive approaches to low-technology, low-energy, biologically and ecologically focused approaches (UN-Wastewater, 2011). Municipal sludge can be obtained from open drains, while in some cases, sludge originates from the process of treatment of wastewater and is separated from the treatment process by sedimentation or flotation. Sludge contains pathogens, heavy metals, many organic pollutants, pesticides, hydrocarbons, etc, if the sewage contains industrial influence (EPA, 2011). Sludge dewatering, commonly achieved through vacuum/pressure filtration or centrifugation, is a paramount process in water and wastewater treatment systems as it reduces the volume of sludge, and consequently, the costs for transporting the sludge to its ultimate disposal site (Ademiluyi, 1986a). In general, efficiency of dewatering depends on the dewaterability of the sludge which is affected by pH, solids concentration, organic content, floc density, and size and content. The characterization of the sludge to be dewatered is the key factor for the design and operation of sludge filters (Koné et al., 2007). The fact remain that a simple technique close to nature and very effective in wastewater treatment is dewatering in drying beds. The principal advantages of drying beds are low costs, infrequent attention required, and high solids content in the dried product, especially in arid climates. The main purpose of a drying bed is to achieve dewatering; that is, a physical separation between liquid and solids (Herwijn, 1996). Koné et al. (2007) carried out experiments with mixtures of septic tank and public toilet sludge, and analyzed the leachate on the first and the last day of filtration for a variety of parameters. Although, the measured concentrations were lower on the last day, the leachate was still far from environmentally safe for disposal with a biochemical oxygen demand (BOD) concentration of 870 mg/L. Hence, according to the final use or standards for receiving water bodies, the leachate should be collected and treated as a concentrated liquid waste stream in ponds.

The requirement for further sludge treatment is according to its high organic/nutrient content, pathogenic organisms and high amounts of water. The form of water in sludge determines the effectiveness of sludge treatment operations to separate the water associated with the solids (Guyer, 2011). It should however be understood that, dewatering process is not just for the removal of excess moisture content, but to make the sludge, odourless and less harmful to the environment.

Agunwamba (2001) explained that in order to get the slope b, after dewatering wastewater, the following formula can be used:

$$b = \frac{rC\mu}{2PA^2} \quad (1)$$

Where r= Specific resistance per kg/m^3 of dry cake solids, C= Mass of dry cake deposited per unit volume of filtrate (kg/m^3), μ= viscosity of filtrate, P= Pressure (N/m^2), and A= area of filtrate (m^2)

A well-digested sludge 200-250 mm thick can dry within a week or two, generally without odour under favourable climatic conditions. Drying beds usually consist of graded layers of gravel or crushed stone (150-300 mm) topped with 250-500 mm filter sand. Moisture is lost through percolation and evaporation. The effective size of sand particles ranges from 0.3 to 0.75 mm with a uniform coefficient, not greater than 4. The depth of the sand layer is about 300 mm. Such beds are advantages for dewatering sludges from small treatment plants (Agunwamba, 2001).

Sludge attrition drying process and design of drying beds

Agunwamba (2001) explained attrition drying as an energy efficient process in a compact, robust and low maintenance machine. It can be used to process any mechanically dewatered, digested sludge to a fine humus-like end product of up to 95% solids. There are two approaches employed in the design of drying beds: empirical method and rational method. In the empirical method, the area is computed as the product of the population and the loading rate. As for the rational equation it is dependent on time for sludge to drain (t_1)- that is the time during which draining is the primary drying mechanism (days) and time (t_2) for moisture to evaporate from the drained sludge. Agunwamba (2001) reported that total time can be expressed as:

$$T = t_1 + t_2 \quad (2)$$

Where:

t_1, is the time during which draining is taking place; $t_2 =$, the time for moisture to evaporate from drained sludge.

$$t_2 = \frac{30HS_0}{aE - bR}\left(\frac{1}{S_1} - \frac{1}{S_2}\right) \quad (3)$$

Where: H, initial sludge application rate; R, rainfall in weight month; E, clear water evaporation rate (mm/month); a, correction factor for evaporation from sludge.

Depending on the sludge characteristics, a variable fraction of approximately 50-80% of the sludge volume drains off as a liquid (or leachate), which needs to be collected and treated prior to discharge (Tilley et al., 2014).

In cake filtration, the particles larger than the pores of the filter medium are retained at the surface of the medium, whereas, smaller particles enter the pores of the medium. These smaller particles may either block the pore opening of the medium completely, adhere to the walls of the pores thus progressively reducing the internal diameter of the pore, or pass through the filter medium. As the filtration proceeds, the particles retained on the filter medium will form a porous structure and the smaller particles which are able to pass through the pores initially will get trapped in this porous cake formed by the deposited particles. This is observed practically as the initial filtrate obtained with a new or washed filter medium is often found to be cloudy, but becomes clearer as time progresses. In the filtration operation, a cake containing filtrate trapped in the void spaces between the particles is obtained at the end of the operation. The two characteristics of cake dewatering are the permeability and the final moisture content. Filtration and dewatering are distinct in the sense that filtration leads to the formation of a cake containing a relatively low proportion of residual filtrate, while dewatering is used to affect further liquid content reduction of the cake itself. As applicable to all fluid mechanics problems, equation of continuity and equation of motion are the basic equations describing the overall phenomena (Yükseler et al., 2005).

Cake resistivity

The rate of flow may affect the structure of a cake: at low rates a loose structure is formed, at higher ones fine particles are dragged into the previously formed bed. The drag pressure at a point in a cake is the difference between the pressure at the filter medium and the pressure lossdue to friction up to that point. As the drag pressure at a distance from the filter cloth increases, even at constant filtering pressure, the porosity and resistance adjust themselves continuously (Tiller et al., 1979).

METERIALS AND METHODS

Sewage sludge was collected from an open unlined drain along Layin Wanki in Unguwar Sarki area, Kaduna North Local Government of Kaduna State (Figure 1). The sample was collected equally along the length of the open drain in order to get a composite sample. About 15 L of sludge was poured on to a drying bed which was located in the Water Laboratory of the Department of Civil Engineering, Kaduna Polytechnic, Kaduna (Figure 2). The drying bed which was made with a transparent glass was 1.5 m long and 0.5 m wide. The filter medium of the drying consisted of coarse sand and gravel. The sand and gravel had depths of 0.3 m each. The depth above the sand (where the sludge was slowly allowed in) was 0.2 m. A sand layer was placed on top of the gravel. The sand layer enhanced drainage and prevented clogging, as it kept the sludge from lodging in the pore spaces of the gravel. The diameter of the sand layer ranged between 0.1- 0.5 mm. The wastewater was allowed to percolate onto the drying bed for 15 days, and the filtrate was collected after every 24 h, throughout the duration. From the results obtained, the t/v was calculated and graphs of volume V and t/v, V and t were plotted.

In order to develop equations for the volume of filtrate V_f and Cake C, there was need to refer to Ademiluyi et al. (1989), which is:

$$V_f \frac{dC}{dt} = Q_0 C_0 - Q C_f \qquad (4)$$

Where: Q_0, is the rate of sludge flow (m^3/sec); Q, is the rate of volumetric increase of the filtrate (m^3/sec); C_0, is the concentration of the sludge (kg/m^3); C_f, is the concentration of the filtrate (kg/m^3); dC , is the small change in the cake concentration (kg/m^3); V_f, is the volume of filtrate in m^3.

The above equation has it source from mass balance equation for sludge filtration process.

Developing cake concentration equation

Cake concentration equation during dewatering process from mass balance equation (C)

From Agunwamba et al. (1989), an equation can be obtained for, cake concentration C as a function of time.

From Equation 4, if Q, and V_f are considered to be functions of time and Q_o, and C_o, are constants, and C_f remain negligible, therefore:

$$\mathrm{d}C = (Q_0 C_0 - Q C_f / V_f)dt \qquad (5)$$

According to Agunwamba et al. (1989):

$$V_f = Q\,t \qquad (6)$$

And

$$Q = V_f / t \qquad (7)$$

Then, Equation 5 can be integrated, as follows:

$$\int \mathrm{dC} = \int \frac{1}{V_f} (Q_0 C_0 - Q C_f)\ dt \qquad (8)$$

Since $Q = V_f / t$, therefore Equation 8 can be written as:

$$\int \mathrm{dC} = \int \frac{1}{V_f} (Q_0 C_0 - Q C_f)\ dt = \int \frac{1}{V_f} (Q_0 C_0 - V_f / t C_f)\ dt \qquad (9)$$

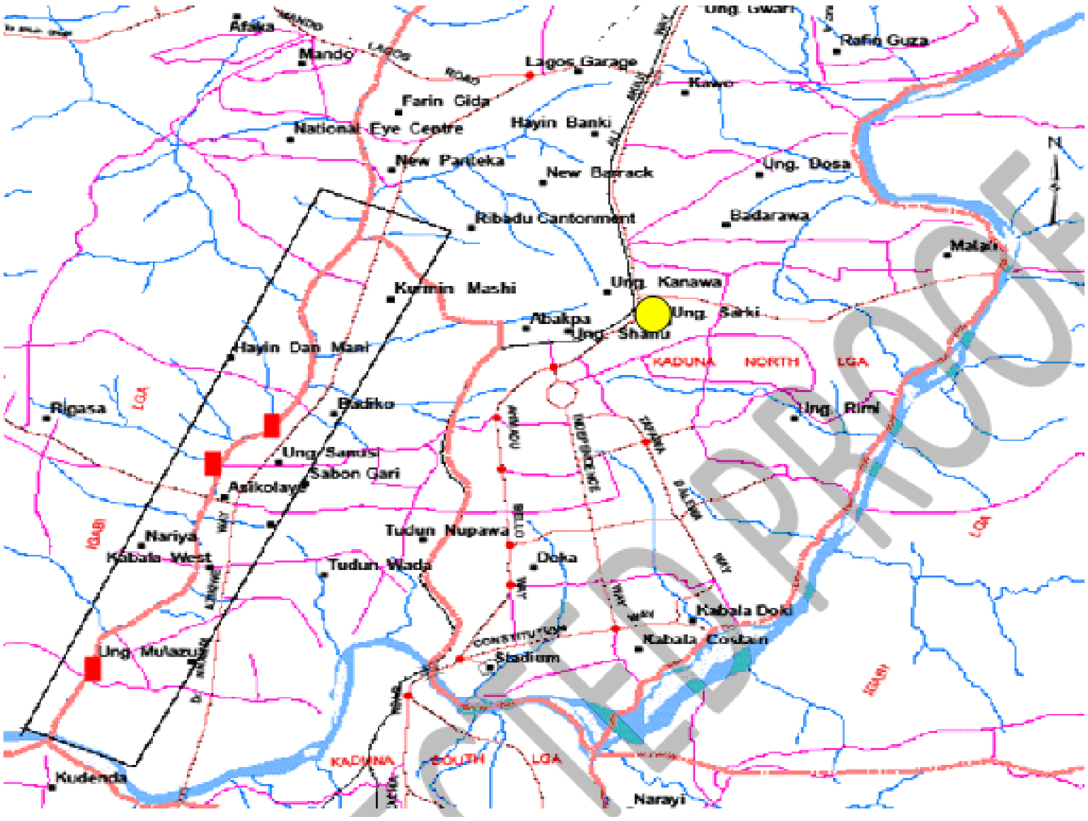

Figure 1. Map of the study area.

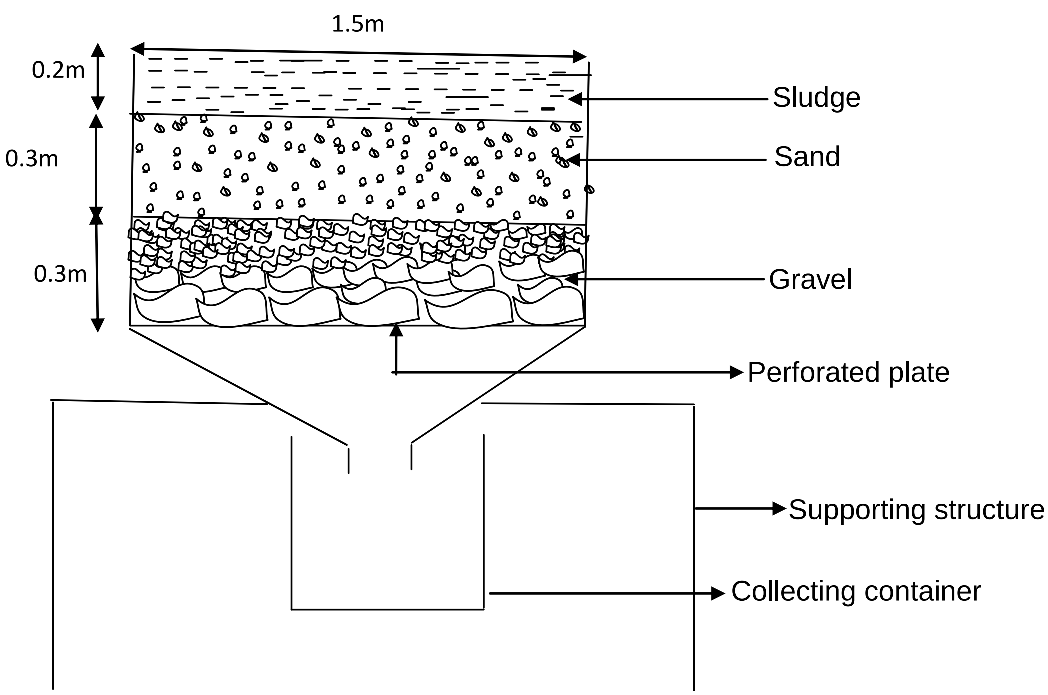

Figure 2. Schematic diagram of the drying bed.

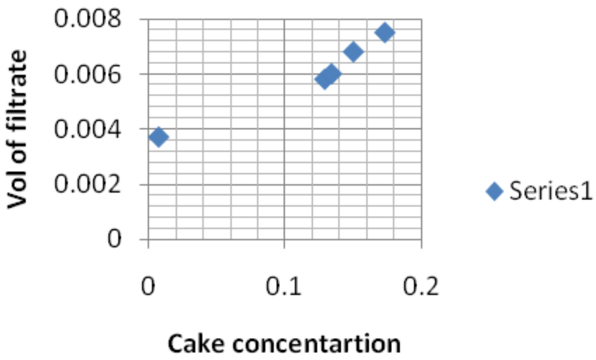

Figure 3. Cake concentration versus volume of filtrate.

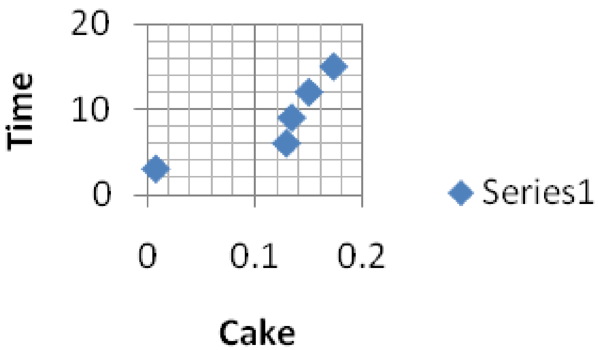

Figure 4. Cake versus concentration.

Re-arranging:

$$\int \mathrm{dC} = Q_0 C_0 \int \frac{1}{V_f} dt - C_f \int \frac{1}{t} dt \quad (10)$$

Integrating further, cake concentration C:

$$C = Q_0 C_0 \frac{1}{V_f} - C_f \log(t) (11)$$

Cake concentration equation during dewatering process from Matlab polynomials

From the data obtained, Matlab was used to obtain the function of V_f as a polynomial. This is what was obtained from Matlab data:

```
clear
clc
x=24:24:264;

p1 = 5.783e-008; p2 = -4.85e-005; p3 = 0.01574;
p4 = -2.487; p5 =203.4; p6 = 701.7;
fori=1:length(x)
f(i) = p1*x(i)^5 + p2*x(i)^4 + p3*x(i)^3 + p4*x(i)^2 + p5*x(i)
+ p6;
y(i)=x(i)/f(i);
end
plot(f,x)
```

$$f(t) = P_1 t^5 + P_2 t^4 + P_3 t^3 + P_4 t^2 + P_5 t + P_6 (12)$$

$f(t)$ was used instead of $f(i)$ used in Matlab in order to take care of time.

Where: $P_1, P_2, P_3, P_4, P_5, 6$ are the constants of the polynomial.

In order to evaluate $\int \frac{1}{V_f} dt$ in (Equation 10):

Therefore:

$$\frac{1}{V_f} = \int f(t)\, dt \quad (13)$$

$$= \int (P_1 t^5 + P_2 t^4 + P_3 t^3 + P_4 t^2 + P_5 t + P_6)\, dt \quad (14)$$

$$\frac{1}{V_f} = P_1 t^6/6 + P_2 t^5/5 + P_3 t^4/4 + P_4 t^3/3 + P_5 t^2/2 + P_6 t + P_7 \quad (15)$$

Where: P_7 is assumed to be the constant of integration. But Agunwamba et al. (1989) stated,

$$Q_0 = V_f + V_c / t (16)$$

Therefore considering Equation 16, Equation 15 can be put into Equation 11 to become:

$$C = V_f + V_c / tC_0 (P_1 \frac{t^6}{6} + P_2 \frac{t^5}{5} + P_3 \frac{t^4}{4} + P_4 \frac{t^3}{3} + \frac{P_5 t^2}{2} + P_6 t +) - C_f \log(t) \quad (17)$$

Where, $P_1 =$ 5.783e-008
$P_2 =$ -4.85e-005
P_3 = 0.01574
P_4 = -2.487
P_5 = 203.4
P_6 = 701.7
t = 3 h
V_f = 0.0037, V_c = 0.0085, C_f = 0.001, C_o = 0.5.

RESULTS AND DISCUSSION

Figures 3, 4 and 5 and Tables 1, 2 and 3 show the relationship between cake, volume of filtrate and the cake concentration. The trend shows that as the filtrate increased the cake formation increased also. Also, an increase in concentration was obtained as the volume of filtrate increased. It was also clear that, the longer the

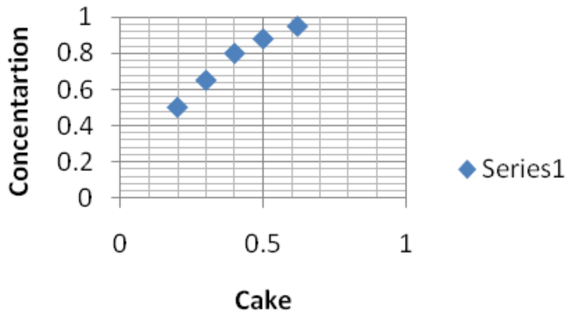

Figure 5. Cake versus concentration.

Table 1. Cake and volume of filtrate.

Cake	V_f
0.0074	0.0037
0.129	0.0058
0.134	0.006
0.15	0.0068
0.173	0.0075

Table 2. Cake versus Time.

Cake	Time
0.0074	3
0.129	6
0.134	9
0.15	12
0.173	15

Table 3. Cake versus concentration.

Cake	Co
0.2	0.5
0.3	0.65
0.4	0.8
0.5	0.88
0.62	0.95

time frame, the thicker the cake. This is an indication that the dewatering process of the sludge using dry sand bed was successful. The sizes of the filter medium and the arrangement of the sand and gravel were appropriately done to obtained better performance of the drying bed.

Conclusion

The results of the analysis showed the trend in the dewatering processes as it affected the volume of filtrate, time and cake. It can then be concluded that, the cake concentration increased with the increase in time and volume of filtration.

Further studies should be conducted to reduce the time duration of taking readings of the volume of filtrate from the 24 h that was used in this research to 12 h so as to determine whether the cake concentration will increase and what quantity of water will be filtered out. Also, using angular particles and coarse sand at the upper layer of the sand may cause the infiltration of the sludge down to the lower layers. Therefore, the type and quality of filter bed should be carefully chosen, in order to obtain an optimum filtration process. Further research should be carried out on an industrial sludge which is thicker than municipal sludge, in order to see whether the filteration will be as efficient as when municipal sludge is used.

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