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Effect of Pressure, Concentration and Sludge Volume on Two-phase Filtrate Volumes Using Bentonite Clay Sludge

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The effect of pressure, solids concentration and volume of slurry on total and two-phase filtrate volumes was investigated to establish optimum conditions for routine laboratory filtration. Full factorial design with three levels was utilized to obtain 27 unique experiments. The slurry used was prepared by mixing crushed and sieved bentonite clay of 75 microns with distilled water at different concentrations as obtained from the design of experiment. A filter press was utilized and the results were used to calibrate a two-phase exponential equation for sludge filtration to extract the first and second stage filtrate volumes. The total filtrate volume improved with increasing applied pressure and decreasing solids concentration. A slurry volume of 0.22 litres was found to be ideal. Similar effects were noticed on the first and second stage filtrate volume except that an optimum was discovered at 0.18 litres of slurry. The second stage filtration produced an upward curve with a point of inflection at a range of 0.18 to 0.22 litres of slurry. The second stage filtrate volume is also discovered to be directly proportional to the total filtrate volume. This connection may be considered for use to assess the filterability of other slurries.

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1. INTRODUCTION

Accurate determination of the filterability of sludge, as well as translation of experimental results to full scale operation, have been quite difficult. Generally, activated sludge is known to be hard to dewater and many times exhibits filtration behavior that are non-traditional [1]. Large-scale filters are employed in diverse processes treating annually million tons of minerals, chemicals, and liquid wastes [2,3]. The most common laboratory procedures for quantifying sludge dewaterability are capillary suction time (CST) [4] and specific resistance to filtration (SRF). Experimental techniques like the filter leaf test and the Buchner funnel test are only useful for establishing empirical connections. This does not imply that the filter leaf and the Buchner funnel are not practical instruments. Nevertheless, none of them enables the creation of characteristics that may be used to compare sludge or to quantitatively assess the impact of major pressures on a particular sludge [5]. Such a parameter has been suggested by Coackley and Jones [6], who have used the concept of specific resistance of Carman's [7] theory of filtration.

Among the characteristics of sludge which affect filtration are: size, shape, charge of the solid particles, compressibility of solid particles, viscosity of filtrate and of sludge chemical composition, solids concentration dissolved and suspended solid particles. Due to their function in compaction and the need for coagulating chemicals, the size, shape, and density of the solid sludge particles have an impact on filter performance. Little or irregularly shaped particles have a tendency to condense into a mat when exposed to vacuum, leaving few spaces for liquid to go through. On the other hand, regularly sized and shaped particles or huge particles permit a high ratio of voids [8]. It has been shown [9] that the smallest particles of the sludge exercise the greatest coagulating chemical demand per unit weight of solids. Garber [10] found that the particle size of elutriated sludge after thermophilic digestion was greater than after mesophilic digestion. Although many conditioning agents have been used with varying degrees of success, lime and ferric chloride are the most commonly used chemicals [5]. Ademiluyi and Egbuniwe [11] reported that mixing of conditioners at varying percentages has proved effective in lowering the specific resistance of the domestic sludge tested.

The fact that an increase in concentration produces an increase in cake production has long been known. Schepman and Cornell [12] have shown experimentally that the relationship of feed concentration to filter rate is linear and in some cases in direct proportion. This phenomenon is readily understandable when viewed from the standpoint that with more concentrated sludges less filtrate volume has to be removed per pound of filter cake deposited. Torpey and Lang [13] successfully employed elutriation for the sole purpose of thickening digested sludge from a modified activated sludge plant, more than doubling the solids concentration from 2.5 to 5.9 percent. Laboratory experiments are usually carried out before full scale operations are done, to determine the relationship between variables. All of the aforementioned researchers undoubtedly aimed to identify various elements that can influence the filtering process, while also taking optimization into account.

Amah and Ademiluyi [14] developed a two-phase exponential model for sludge filtration. This filtration model gave rise to two major filtration parameters which are first stage flow volume and second stage flow volume. This is shown as Equation (1).

$$V_t = V_0 - \left\{\left[\frac{k_3 V_{(0)1}}{k_2 - k_1} + V_{(0)2}\right] e^{-k_2 t} - \left[\frac{k_3 V_{(0)1}}{k_2 - k_1} + V_{(0)1}\right] e^{-k_1 t}\right\} \quad (1)$$

where V_t is the volume at any time t (mins), V_o is the initial volume to be moisture to be filtered, $V_{(0)1}$ and $V_{(0)2}$ are the moisture contents available for the first phase and second phase filtration and k_1, k_2 and k_3 are rate constants. The two key components identified by the Amah and Ademiluyi [14] model are the result of the interaction of all the elements that can have an impact on the filtering process. Response surface approach is used in this study to examine how the first and second stage filtration volumes derived from Equation (1) are affected by the applied pressure, solids concentration, and volume being filtered.

2. MATERIALS AND METHODS

2.1 Design of Experiment

Three variables were considered during the filtration experiment, namely the pressure (P), solids concentration (S) and volume of slurry (V). Xlstat 2014 was used to determine the Experimental Design using a full factorial design with 3 levels. This is shown in Table 1. A total of 27 different experiments were obtained from the design of experiment to be carried out. Each setup or run order represents varying pressure, concentration of solids and slurry volume. For each run order, 30 min. was used as the sampling time.

2.2 Slurry Formulation

Bentonite clay was first pulverized and sieved using a standard sieve set with a target diameter of 75 microns. The set of sieves were shaken until clay particle could not pass the 75 micron sieve and the retained sample was stored. Sludge was created by following the instructions in Table 1 and utilizing bentonite clay with a particle size of 75 microns that had been dissolved in distilled water. 2 grams of Guar gum was added to each mixture to improve its gel properties. The formulated slurry was left for 16 hours for the bentonite clay to be properly hydrated. The benefit of this is that the physical and chemical characteristics of the sludge may be altered for the purpose of this study, which is one of the reasons why this is advantageous.

2.3 Filtration Procedure

A filter press was used in the filtration process. The filter press maximum carrying capacity was 350 ml and the maximum filter pressure was 100 psi. Specially hardened filter paper, 3.5 inches in diameter was used for the filtration process. For each observation, the experiment was allowed to run for 30 minutes. Meanwhile, every 2 min the filtrate volume was read and recorded.

Table 1. Design of Experiment for Sludge filtration

Observation	Sort order	Run order	Repetition	Pressure (psi)	Conc. (g/l)	Volume (litres)
Obs1	1	1	1	20	30	0.1
Obs2	2	2	1	60	30	0.1
Obs3	3	3	1	100	30	0.1
Obs4	4	4	1	20	65	0.1
Obs5	5	5	1	60	65	0.1
Obs6	6	6	1	100	65	0.1
Obs7	7	7	1	20	100	0.1
Obs8	8	8	1	60	100	0.1
Obs9	9	9	1	100	100	0.1
Obs10	10	10	1	20	30	0.2
Obs11	11	11	1	60	30	0.2
Obs12	12	12	1	100	30	0.2
Obs13	13	13	1	20	65	0.2
Obs14	14	14	1	60	65	0.2
Obs15	15	15	1	100	65	0.2
Obs16	16	16	1	20	100	0.2
Obs17	17	17	1	60	100	0.2
Obs18	18	18	1	100	100	0.2
Obs19	19	19	1	20	30	0.3
Obs20	20	20	1	60	30	0.3
Obs21	21	21	1	100	30	0.3
Obs22	22	22	1	20	65	0.3
Obs23	23	23	1	60	65	0.3
Obs24	24	24	1	100	65	0.3
Obs25	25	25	1	20	100	0.3
Obs26	26	26	1	60	100	0.3
Obs27	27	27	1	100	100	0.3

3. RESULTS AND DISCUSSION

The different concentrations as outlined in Table 1 were used to formulate the sludge and its specific gravity was determined with a mud balance and shown in Table 2.

For the 27 filtration parameter variations, the filtration process was carried out and filtrate volumes were measured with the results shown as Table 3. The first and second stage filtrate volumes where extracted from Equation (1) after calibration with the experimental data. This is also shown in Table 3. As presented in Table 3 after 30 min. of filtration, the minimum filtrate volume was observed to be 6.2 ml and this occurred at run order 7. This setup had the least pressure value of 20 psi and slurry volume of 0.1 litres as well as the maximum solids concentration of 100 g/l. The minimum occurred at run order 7 because at low applied pressure levels, the fluid flow cannot easily overcome the resistance offered by the cake being deposited as filtration progresses. The slurry volume also influenced the final filtrate level, because at low slurry volume, the moisture content is lower and the solid particle are easily deposited onto the filter media as the slurry height is also small. The concentration of solids significantly influences the formation of filter cake on the filter medium. Filter cake will be formed quickly and grow faster due to more solid particles being deposited on the filter medium because of the high solids concentration in the slurry. This agrees with the work of Ademiluyi and Eze [15] where it was also observed that the specific resistance increases as the solid content increases. Therefore, as more solid particles are deposited, the pressure on them increases and the void ratio decreases which reduces the volume of filtrate that passes through the cake per time. The work of Schepman and Cornell [12] also shows experimentally that a linear relationship exists between the feed concentration to filter rate and in some cases in direct proportion. It is also likely that due to high solids concentration, during filtration, sedimentation may also force more solids particles to be deposited onto the filter medium. On the other hand, the maximum filtrate volume was observed to be 19.8 ml and this occurred at run order 21. This setup had an applied pressure value of 100 psi, solids concentration of 30 g/l and 0.3 litres of slurry volume. This high value of applied pressure means that the filter cake will offer lesser resistance to fluid flow due to an increase in driving pressure. The lower the solids concentration the fewer solids particle available to form filter cake, this will result to a much thinner cake yield. The large slurry volume ensures that there is liquid available in the system to be collected as filtrate, hence the high filtrate volume observed. Analysis of variance was done to determine if there is any significant difference in the results observed. The result showed that at 5 % level of significance, there are significant differences in the observed data ($p<0.05$).

The variations in filtrate volume against pressure, solids concentration and slurry volume are elucidated in Fig. 1. These curves can be used to determine minimum or maximum points of concern. In some cases the relationship is linear.

As observed in Fig. 1(a), the filtrate volume increases with increasing applied pressure. This is so because the more pressure is applied, the greater the ability of the fluid to overcome resistance offered by filter cake being formed. This agrees with the work done by other researchers [16,17]. Fig. 1(b) shows that as concentration of solids increased, the filtrate volume decreases. The higher the solids concentration, the easier it will be to form filter cake and the more resistance to fluid flow through the media. This agrees with the investigation of Coakley and Jones [6] where it was observed that dilution of a thickened sludge results in a drop in specific resistance. Fig. 1(c) reveals that the filtrate volume increases with increase in volume of slurry but is optimum at a slurry volume of 0.22 litres beyond which it declines.

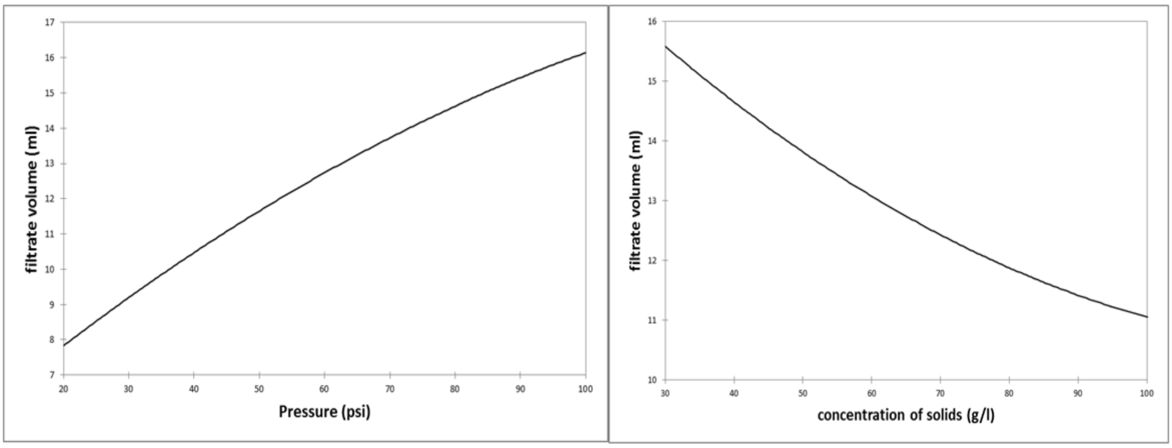
The variations in first stage filtrate volume against pressure, solids concentration and slurry volume as investigated are presented in Fig. 2. They show how the altering factors have an effect on the initial filtrate volume.

Table 2. Specific gravity of slurry with varying solids concentration

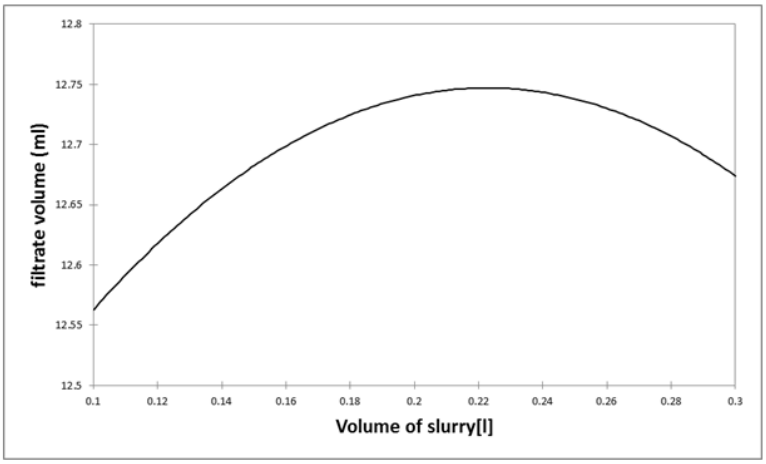
30 g/l				65 g/l				100 g/l			
sp	$\frac{lb}{ft^3}$	**ppg**	$\frac{psi}{1000ft}$	**sp**	$\frac{lb}{ft^3}$	**ppg**	$\frac{psi}{1000ft}$	**sp**	$\frac{lb}{ft^3}$	**ppg**	$\frac{psi}{1000ft}$
0.97	61	8.1	420	0.99	62	8.25	430	1.02	64	8.5	440

Table 3. Filtrate volume at varying filtration parameters

Run Order	Pressure (psi)	Concentration (g/l)	Volume (l)	Filtrate volume (ml) at 30mins	V_1	V_2
Run 1	20	30	0.1	9.8	0.921	8.879
Run 2	60	30	0.1	16.2	0.516	15.684
Run 3	100	30	0.1	17.8	1.316	16.484
Run 4	20	65	0.1	7.4	0.454	6.946
Run 5	60	65	0.1	12.2	0.744	11.456
Run 6	100	65	0.1	17.4	1.018	16.382
Run 7	20	100	0.1	6.2	0.195	6.005
Run 8	60	100	0.1	11	0.600	10.400
Run 9	100	100	0.1	14	0.777	13.223
Run 10	20	30	0.2	11	0.505	10.495
Run 11	60	30	0.2	15.2	0.850	14.350
Run 12	100	30	0.2	19	1.289	17.711
Run 13	20	65	0.2	7.6	0.410	7.190
Run 14	60	65	0.2	13.4	0.702	12.698
Run 15	100	65	0.2	16	0.928	15.072
Run 16	20	100	0.2	6.6	0.371	6.229
Run 17	60	100	0.2	10.8	1.001	9.799
Run 18	100	100	0.2	14	0.987	13.013
Run 19	20	30	0.3	10.4	0.387	10.013
Run 20	60	30	0.3	15.8	0.831	14.969
Run 21	100	30	0.3	19.8	1.196	18.604
Run 22	20	65	0.3	7.6	0.392	7.208
Run 23	60	65	0.3	11.4	0.579	10.821
Run 24	100	65	0.3	16.4	0.667	15.733
Run 25	20	100	0.3	6.6	0.385	6.215
Run 26	60	100	0.3	11.4	0.663	10.737
Run 27	100	100	0.3	13.6	0.800	12.800

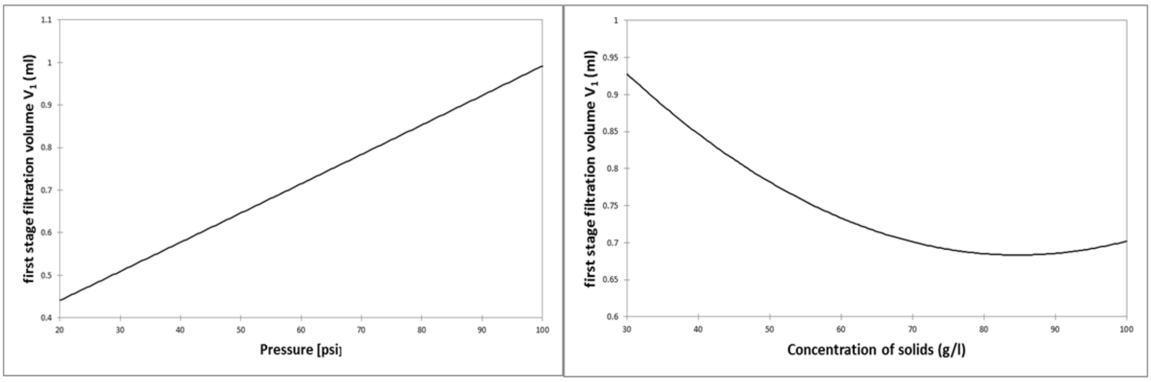


(a) (b)



(c)

Fig. 1. Relationship between filtrate volume (ml) and (a) applied pressure (psi) (b) concentration of solids (g/l) (c) volume of slurry (litres)



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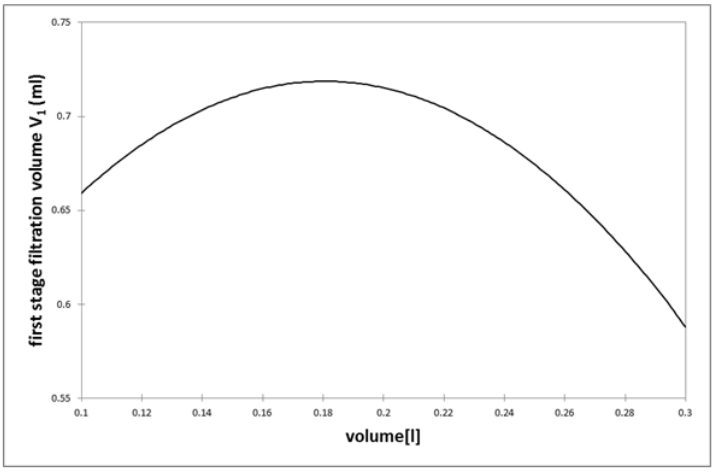

(c)

Fig. 2. First stage filtration volume V_1 against (a) pressure (psi) (b) Concentration of solids (g/l) (c) Volume of slurry (litres)

Fig. 2 illustrate the link that exists between V_1 and the primary variables. As can be seen in Fig. 2(a), the connection between pressure and V_1 is linear. The first step of filtration is improved by increasing the pressure that is being applied. Fig. 2(b) demonstrates that V_1 decreases as the concentration of solids increases up to around 80 g/l, at which point it remains relatively constant. Fig. 2(c) reveals that 0.18 liters of slurry is the optimum volume of slurry to be used for laboratory filtration. This optimum value of 0.18 liters is comparable to the optimal value of 0.22 liters seen earlier on Fig. 1(c). This indicates that raising the pressure that is being applied and using a batch of slurry volume in the filter press within the range of 0.18 to 0.22 liters would provide the optimal volume of filtrate.

The variations in second stage filtrate volume against pressure, solids concentration and slurry volume as studied are presented in Fig. 3 and these illustrate how the factors affect the second stage filtrate volume.

As can be observed in Fig. 3(a), the connection between pressure and V_2 is linear. The level of filtration achieved in the second stage is proportional to the amount of pressure that is applied. The decrease in V_2 that can be seen in Fig. 3(b) can be attributed to an increase in the concentration of solids. As can be seen in Fig. 3(c), the volume of the second stage filtrate rises as the volume of the slurry rises. This is to be anticipated due to the fact that an increase in the volume of slurry that needs to be filtered implies that there will be an increase in the amount of water content that is available for the second stage of filtration in the event that the filtration process is allowed to continue indefinitely. On the other hand, the curve seems to have a parabolic shape, with a point of inflection observed around 0.18 to 0.22 litres which may well indicate that as time approaches infinity, the second stage of filtration may become ineffective due to insufficient driving pressure to overcome the resistance offered by the development of consolidated filter cake.

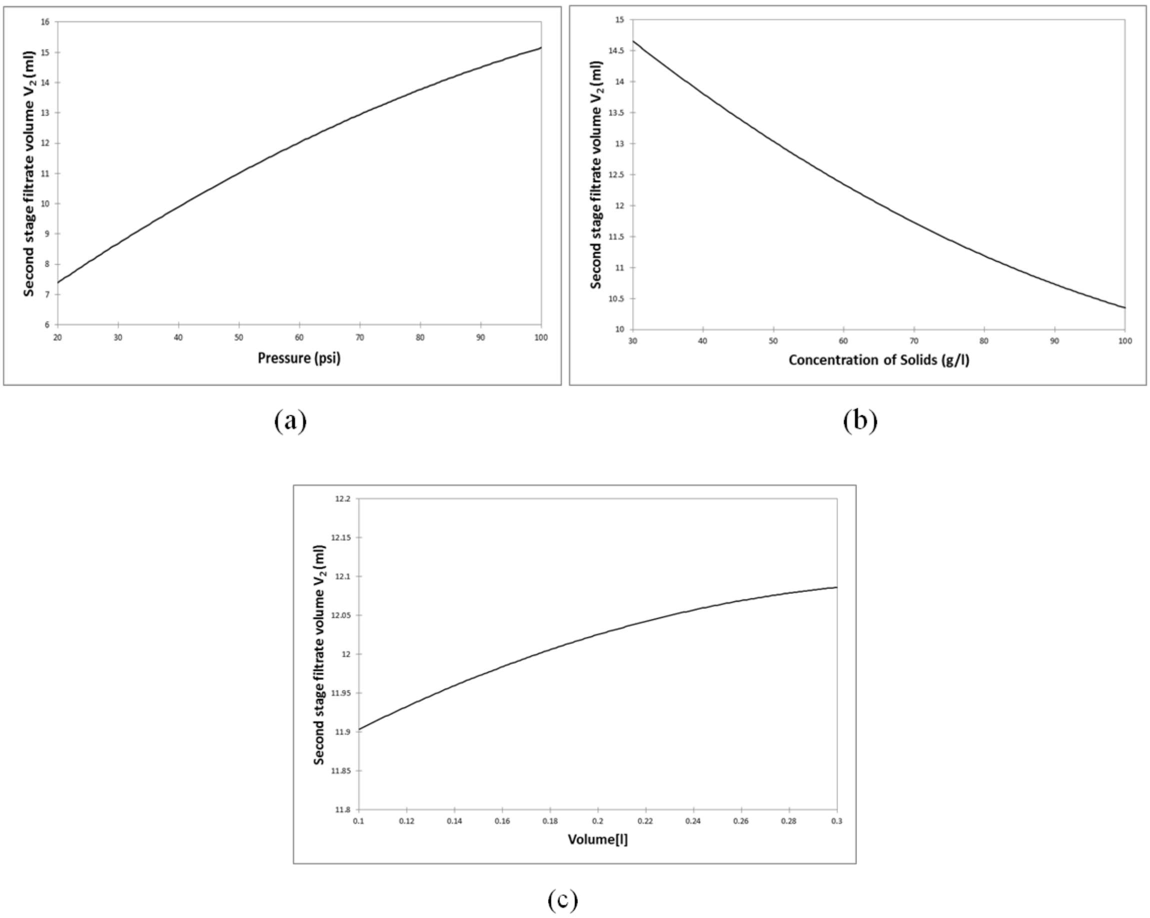

Fig. 3. Second stage filtration volume V_2 against (a) Pressure (psi) (b) Concentration of solids (g/l) (c) Volume of slurry (litres)

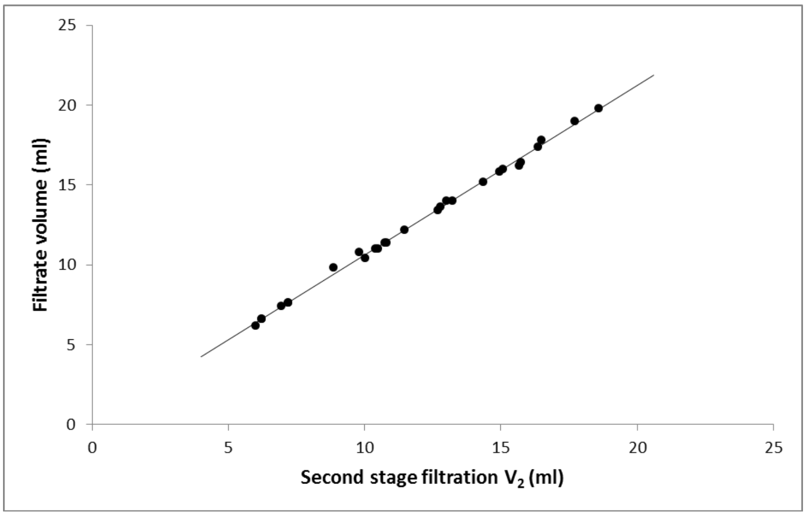

Fig. 4. Relationship between filtrate volume and Second stage filtration V_2

As a potential indicator of the slurry's capacity to be dewatered, the connection between the volume of the second stage of filtration, denoted as V_2, and the volume of the total filtrate produced was explored. Fig. 4 depicts the outcome of this investigation.

CST, SRF, bound water content, and dry solids content are the four metrics that have been described by Peng et al. [18] for assessing the dewaterability of sludge. These parameters may be found in their respective articles. Because it is one of the primary limiting variables in the amount of water that can be removed from sludge effectively, the bound water content has been selected as an indicator for determining the dewaterability of sludge [19]. The two laboratory techniques that are most often used to evaluate the sludge's capacity to be dewatered are the CST and the SRF. However, it is being noticed that the value of V_2 in Fig. 4 varies in a manner that is both linear and positive in relation to the volume of the filtrate. When the variable V_2 is greater, a sludge sample may be filtered more quickly. This means that the volume of the second stage filtrate, denoted by the symbol V_2, can be utilized as a direct indicator of the filterability of sludge.

4. CONCLUSION

The study investigated the optimum total and two-phase filtration parameters for laboratory filtration of sludge using a filter press. The following conclusions are drawn:

1) Synthetic sludge made from bentonite clay proved to be especially useful because the sludge characteristics can easily be varied as intended.
2) Increasing applied pressure from 20 psi to 100 psi and decreasing the solids concentration from 100 g/l to 30 g/l greatly improved the filtrate recovered from the filtration process of sludge. However, unlike applied pressure and solids concentration, slurry volume was discovered to be optimum at 0.22 litres beyond which filtrate volume decreases.
3) The first phase filtrate volume improves with increasing applied pressure and decreasing solids concentration. However, at 0.18 litres, the first phase filtrate volume was discovered to be at optimum. It is therefore concluded that an optimum range of 0.18 to 0.22 litres is required for both rapid and complete filtration.
4) The effects of applied pressure and solids concentration on the second stage filtrate volume were similar to the first stage filtrate volume. However, as volume of slurry increases the second stage filtrate volume increases as more liquid is available to participate in this stage if filtration is allowed to run indefinitely. The second stage filtrate volume is directly proportional to the total filtrate volume. This offers the opportunity to utilize V_2 as an indicator of filtration potential of various slurries in the laboratory.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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