



Investigation into the parameters influencing filter cakes produced by filtration

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Abstract

An experimental study was carried out to investigate the effect of particle size, solids concentration, and applied vacuum on both the apparent specific resistance and final moisture content of filter cakes. The results obtained from filtration test work indicated that the presence of fines particles in the feed suspension leads to a cake containing a large number of small pores which tended to trap water in the cake. Therefore a cake of high moisture content and specific resistance was obtained. As solids concentration in the suspension were increased both the moisture content and specific resistance decreased, however at high solids concentration the moisture content tended to level off and the apparent specific resistance tended to reach a constant minimum value. The dewatering test work was conducted using four samples of wider size range where the effect of ultrafine material was examined.

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Introduction

Filtration is an operation in which solids particles are separated from a suspension in liquid called a “slurry” by contacting the slurry with one side of a porous medium (Tarleton; Wakeman, 2005). In presence of some driving forces, the filter medium allows the liquid to flow through the capillary channel and retain the solids on its surface. There are basically two types of filtration: deep bed filtration and cake filtration. The deep bed filtration is known by various terms like blocking filtration, clarification and ultrafiltration. The deep bed filtration is normally preferred for the separation of fines particles from a dilute suspension (Hermans, 1936; Svarovsky, 2001).

Most of the liquid filtration operations follow the mechanism of cake filtration (Cheremisinoff, 2017). In this method of operation the filtered solids are introduced at the upstream side of the filter medium. Normally the upstream side is at higher pressure (above or at atmospheric) while the downstream side is at lower pressure (atmospheric or sub atmospheric). Particles larger than the pores of the filter medium are retained at its surface, whereas smaller particles enter the pores of the medium, and may block the pores of the medium completely or adhere to the walls of the pores; thus reducing progressively the internal diameter of the pores.

As the filtration proceed the particles retained on the surface of the filter medium form a cake of increasing thickness. This cake forms the “true filtering medium” (Sjenitzer, 1956). In the filtration operation a cake containing filtrate trapped in the void space between the particles is obtained at the end of the operation. In many cases where the recovery of solids is needed, it is necessary that the moisture content of the solids be as low as possible (Gale, 1972).

In many cases where the recovery of solids is desirable it is necessary that the moisture content of the cake is as low as possible, so the cake is subjected to dewatering. Wakeman classified dewatering as one of the filtration post-treatment processes. He defines cake dewatering as a process whereby filtrate trapped

within the voidage of a filter cake is displaced by the application of desaturating forces to the cake. Desaturating forces can be mechanical, as when the cake is compressed to reduce its void volume and at the same time its moisture content or the applied force may be hydrodynamic to effect displacement of the retained filtrate by sucking or blowing air through the cake (Kakwani RM, Gala HB, Chiang SH, Klinzing GE, Tierney JW, 1985). Filtration and dewatering are distinct (Yuping, Xianshu D, Hui L, 2015) 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 effect further moisture content reduction of the cake itself. The fundamental principles underlying the two processes are entirely different.

The objective of this work was twofold. First an experimental study was performed using six initial samples individually at four solids concentration under a constant pressure in order to investigate the various factors which affect cake filterability and porosity. The second objective was an experimental work carried out on the dewatering process by using four size distributions (PSD).

The quantity of fine or coarse particles in the slurry was varied; therefore a sample with a wide size range was obtained. The material used for the filtration and dewatering testwork was crushed particles of irregular shape and spherical glass beads..

Theory

As filtration proceeds a porous cake of solids particles accumulate on a porous filter medium, its filtration rate can be found from (Couper, 2010; Li, 2005; Wakeman and Tarleton, 2005; Sparks and Chase, 2016).

By applying Darcy’s law the (Darcy, 1856; Carman, 1947) flow rate will be

$$Q = \frac{dv}{dt} = \frac{\Delta p}{\mu R} \quad (1)$$

Where Q is the volumetric flow, Δp the pressure drop across the filter, μ the viscosity of the liquid.

The total resistance to flow of the cake medium R is defined by this equation; if the flow rate is constant through the depth of the cake and medium, then R is equal to the sum of the resistance of the cake and the medium. Thus:

$$\frac{dv}{dt} = \frac{\Delta p}{\mu(Rc + Rm)} \quad (2)$$

Rc is not a constant since as the filtration proceed the depth of the cake increases and so does its resistance to flow. However, rather than using the increase in depth of the cake as a measure of the increase in resistance it is more convenient to consider in the mass of cake deposited per unit area w, then Rc can be expressed in terms of this.

$$Rc = \alpha w \quad (3)$$

Equation (2) becomes:

$$\frac{dv}{dt} = \frac{\Delta p}{\alpha \mu w + \mu Rm} \quad (4)$$

This equation determines the specific resistance “ α ”. It is the resistance of the cake having unit weight of dry solids per unit area. This shows that, if the resistance of the medium equal zero, then the whole of the pressure occurs in the cake. The equation (3) can be written

$$\alpha = \Delta p \left(\frac{1}{\mu} \frac{1}{w} \frac{1}{dv/dt} \right) \quad (5)$$

Since w is not easily measurable quantity, in order to use equation (3) for practical purposes, w is related to the cumulative volume of filtrate V filtered in time t by

$$w = cV \quad (6)$$

Where c is the mass of dry solids deposited on the cake per unit volume of the filtrate. Hence by substitution from equation (6), equation (3) becomes

$$\frac{dv}{dt} = \frac{\Delta p}{\mu} \frac{1}{(\alpha cV + Rm)} \quad (7)$$

Which if Δp , μ , α , c and Rm are all constant (for incompressible cakes), by integration equation (7) becomes:

$$\frac{t}{v} = V \left(\frac{\mu \alpha c}{2 \Delta p} \right) + \frac{\mu Rm}{\Delta p} \quad (8)$$

The term in brackets is the slope of a plot t/v against v, and is used for the calculation of the specific resistance in the Buchner – funnel test (Christensen and Dick, 1985). The differential equation for filtration for compressible cakes is deducted from equation (7).

$$\frac{dv}{dt} = \frac{\Delta p}{\mu} \frac{1}{\alpha c v} \quad (9)$$

Since Rm is negligible and α , Δp are constant, therefore by integration, equation (9) becomes

$$\frac{t}{v} = \frac{\mu \alpha c}{2 \Delta p} V \quad (10)$$

If V is the volume of filtrate from a filtered area A, then

$$\frac{t}{v} = \frac{\mu \alpha c}{2 A \Delta p A} V = BV \quad (11)$$

Thus a straight line is obtained; t/v is plotted against v, and from the slope B, α may be calculated if μ , Δp , A and c are known.

However, in the subsequent Buchner – funnel test, the solids content of the cake during formation is not measured and thus the value of specific resistance is not the true specific resistance α , but an apparent value; the definition of which depends on the approximation used for “ c_1 ” (Holdich, 2002). The amount of dry suspended solids per unit volume of evaporable material which is water is equal to “c” only under the hypothetical situation where there is no evaporable material in the cake. One outcome of this is that the apparent specific resistance “ α_{ap} ” is not independent of solids content of the suspension as “ α ” should theoretically be. The relation between “c” and “ c_1 ” are:

$$C = \frac{w_c w_s \rho_f}{w_c - w_s} \quad (12)$$

And

$$C_1 = \frac{w_s \cdot \rho_\ell}{(1 - w_s)} \quad (13)$$

Where w_c and w_s are the average mass of dry suspended solids per unit mass of the cake and of the slurry, ρ_f and ρ_ℓ are the density of the filtrate and the density of the liquid in the slurry.

Hence by substitution into equation (11) for c and α , we obtain the apparent specific resistance.

$$\alpha_{ap} = \frac{2 A^2 \Delta p B}{c_1 \mu} \quad (14)$$

Where c_1 is the slurry composition, A is the cross sectional area of the filter, μ is the viscosity of the water, Δp is the pressure derived from the filtration vacuum, and B is the gradient of the plot t/v against v .

Material and methods

The traditional and most commonly used method to determine the filterability of the slurry involves conducting a series of filtration experiments using a Buchner Funnel (Christensen and Dick, 1985). Such tests are divided into two sections, the filtration and dewatering. This work investigated the various factors which affect filtration, namely size distribution, slurry concentration, and the vacuum applied. The material used for the filtration and dewatering test work was spherical glass beads, in order to reduce particle shape effects (Allen; 2003).

Slurry preparation

The filtration tests were carried out for each of the six samples individually (1A to 6A are shown in Table 1 at four solids concentration; 30, 40, 50, and 60% (w./w.). The tests were repeated for each representative sample four times to obtain a set of reproducible data. Therefore from each representative sample four sub-samples were obtained for each solids concentration. To avoid the impurities present in tap water; distilled water was used for preparing the slurry samples for the filtration experiments.

However the slurry preparation for the dewatering tests was carried out by mixing the samples together to obtain a sample with a wide size range. Therefore by decreasing or increasing the quantity of fine or coarse particles in the slurry, the influence of particles size on the apparent specific resistance, and the moisture content could be investigated.

A number of samples were mixed together in order to create four samples with a wide size range. A certain amount of particles were taken from the representative samples.

The four mixed samples obtained were then dry screened for 20 minutes at 425, 300, 212, 150, 106, 75, and 63 microns; the - 63 microns fraction was subsequently wet screened at 56, 40, and 20 microns. The four sizes distribution of the mixed sample represented in Table 2 are shown in Fig. 1.

Table 1. Samples Used for Filtration - Dewatering Tests.

Sample Name	Particles Size Range (µm)	Particles Type
1A	450 - 250	Spherical glass beads
2A	250 - 150	"
3A	150 - 75	"
4A	106 - 53	"
5A	90 - 45	"
6A	45 (below)	"
7A	40 - 20	"
8A	50 - 15	"
9A	20 - 6	"
10A	10 - 0	Crushed particles of irregular shape

Table 2. Size distributions of the four samples used for dewatering tests.

Sizes fraction (microns)	Weight (%)			
	Size distributions			
	N° I	N° II	N° III	N° IV
+ 425	1.39	2.82	4.15	8.24
- 425 + 300	8.49	9.40	8.49	12.00
- 300 + 212	4.66	5.97	7.35	7.65
- 212 + 150	11.92	10.93	11.75	15.31
- 150 + 106	9.16	8.13	14.50	19.90
- 106 + 75	9.85	6.75	11.50	4.20
- 75 + 63	7.33	4.65	19.26	16.38
- 63 + 40	9.32	4.86	4.30	5.48
- 40 + 20	25.83	13.89	7.82	9.08
- 20 + 0	12.04	32.56	10.90	1.72
Total	100	100	100	100

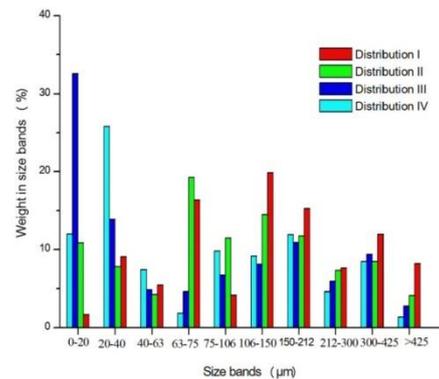


Fig. 1. Sample Size distributions.

From the data of size distribution I four samples were prepared at 20, 40, and 60% solids concentration. Whereas four samples using size distribution II, III, and IV were made up all at 40% solids concentration.

Buchner Funnel apparatus

Many alternative arrangements of apparatus may be used for the determination of the apparent specific resistance of the filter cake. The apparatus consisted of 75mm diameter, 40mm deep Buchner Funnel with a maximum sample volume of 170ml, into which 70mm filter paper were placed. The filter paper used was a Whatman N° 542 hardened ash less filter papers. The Buchner Funnel discharged into a 250ml cylinder marked at 2ml intervals. The vacuum level was controlled by adjustment of the needles valves, the applied vacuum being measured on a dial gauge graduated from 0 to 30 inch of mercury at 2 inch intervals. The vacuum was provided by N.G.N rotary piston vacuum pump.

Filtration Experimental Procedure

The manostat was adjusted to give the required degree of vacuum, (28 inch of mercury), a 70mm filter paper was placed into the Buchner Funnel. The filtration measurements were carried out by transferring the slurry to the funnel and the needle valve gradually opened so that the preset level of vacuum was rapidly achieved, and a digital stopwatch, accurate to 0.01 seconds was started. The filtration time was recorded at 10 ml intervals. At the stage when the last drop of filtrate disappeared from the cake surface a check of the level of the slurry in the funnel was made. There was no need for applied vacuum beyond this stage, and the needle valve was closed. The funnel was disconnected, the filter cake removed and the cylinder emptied. An example of filtration data is represented in table 3.

These tests were conducted using the same procedure for filtration tests. However at this stage the filtration was followed by the dewatering stage. When the last drop of filtrate disappears from the cake surface, a saturated filter cake remained (Kakwani *et al.*, 1985; Yuping *et al.*, 2015).

Table 3. Example of filtration Data.

Filtration Volume (ml)	Filtration Time (sec)		
	T ₁	T ₂	T ₃
20	9	10	8
30	18	19	17
40	28	29	27
50	37	38	37
60	48	49	47
70	61	62	60
80	77	78	77
90	92	93	91
100	104	105	103
110	120	119	118
120	130	138	137
Moisture Content (%)	19.12	19.70	19.20

Dewatering Experimental Procedure

Continuous application of the vacuum beyond this point initiated the dewatering period and air subsequently began penetrating the filter cake. During this dewatering period, the rate of filtrate was recorded. Dewatering was continued for a period of 15 minutes at the end of which the cake was removed from the funnel, the thickness and the diameter of the cake measured. It was then dried in an oven at 105 °C overnight to obtain its final moisture content. Each experiment was repeated in order to obtain an average reading. The applied vacuum was varied for each solids concentration; four levels of vacuum were applied at 20, 40, 60, and 80KPa.

Apparent Specific Resistance Evaluation

The apparent specific resistance is of importance since the yield for vacuum filter is inversely proportional to the square root of the specific resistance. The apparent specific resistance of a filter cake (Irwin, 2007), α_{ap} is represented by equation (14). An example of filtration data is represented in table 3. Also to remove errors associated with manually plotting and calculating the slope of this line, a computer program using linear regression techniques calculated the required slope.

Moisture content evaluation

Once the filtration tests were completed, the cake was weighed wet and dried at 105°C. It was re-weighed and the moisture content determined. The process was repeated for each solids concentration.

Table 3 shows an example of the moisture content data (Catchpole, K.W *et al*, 1970) obtained for a filter cake formed with sample 1A (-425+250 microns glass beads) at a solids concentration of 30%. Filtration and dewatering test work showed that in general particle size, solids concentration and applied vacuum influenced both the apparent specific resistance and the final moisture content of the filter cake.

Results

Filtration Test work on Individual Size Fraction

As stated, the filtration test were carried out using six initial samples (1A - 6A) at 30%, 40%, 50%, and 60% solids concentration with the vacuum applied remained constant at 28” of mercury throughout the filtration process. The full sets of results are plotted in Fig. 2 to Fig. 4. It the moisture content of filter cakes.

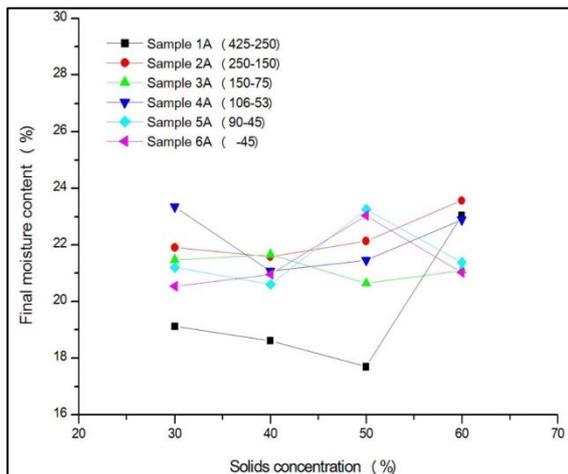


Fig. 2. Effect of solids concentration on the final moisture of the six initial samples

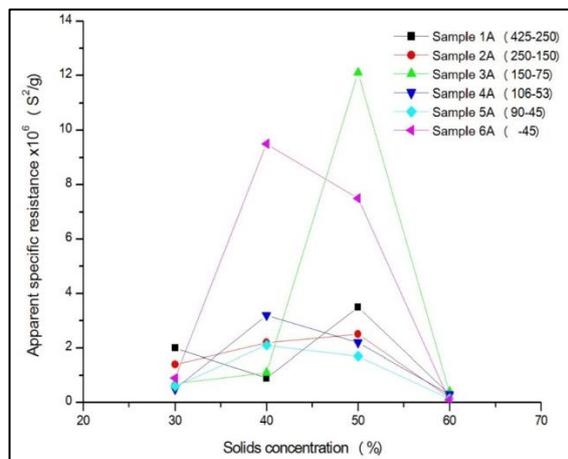


Fig. 3. Effect of solids concentration on the apparent specific resistance of the six samples.

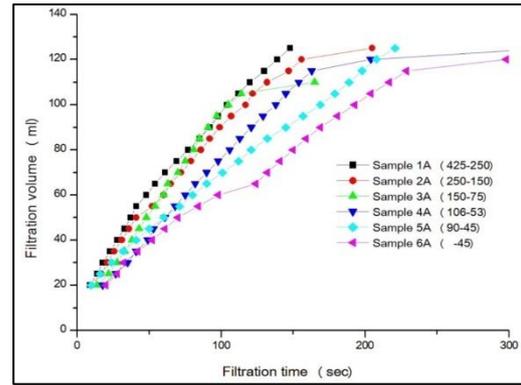


Fig. 4. Filtration volume against time for the six initial samples.

Dewatering Experiments

As mentioned, ultrafine material was an important factor in this study. In these dewatering experiments four samples with a wider size ranges were employed. The solids concentration and the vacuum applied during these tests were also varied. The dewatering experiments conducted for sizes distribution I, II, III, and IV are plotted from Figs 5 to 16.

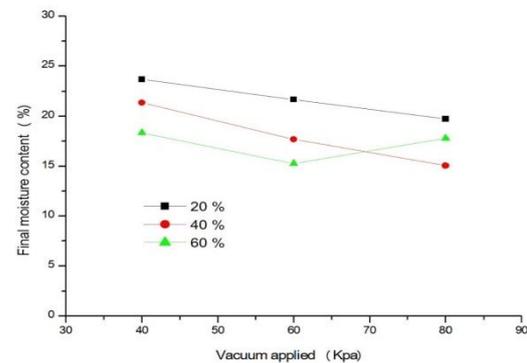


Fig. 5. Size distribution I: Effect of the applied vacuum on the final moisture content of the three solids concentrations.

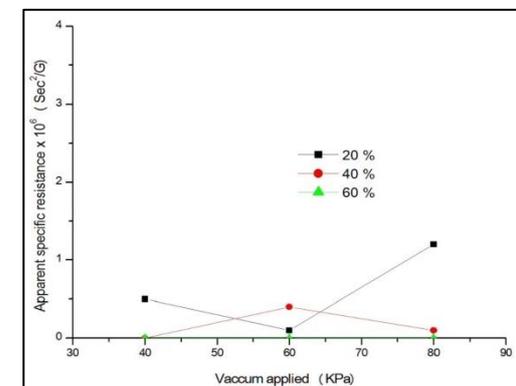


Fig. 6. Size distribution I: Effect of the applied vacuum on the apparent specific resistance of the three solids concentrations.

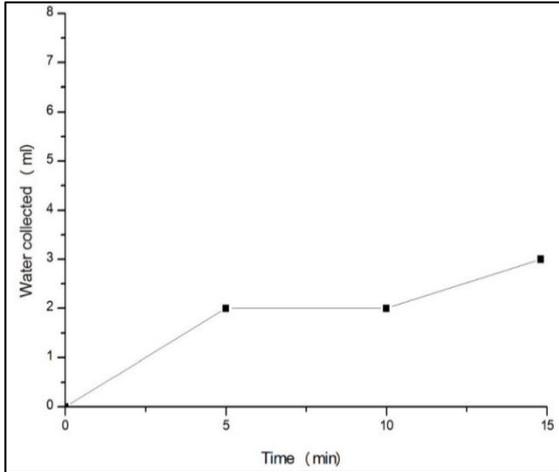


Fig. 7. Size distribution I: Water volume collected during the 15 min dewatering period at 60% Solids and at an applied vacuum of 60 KPa.

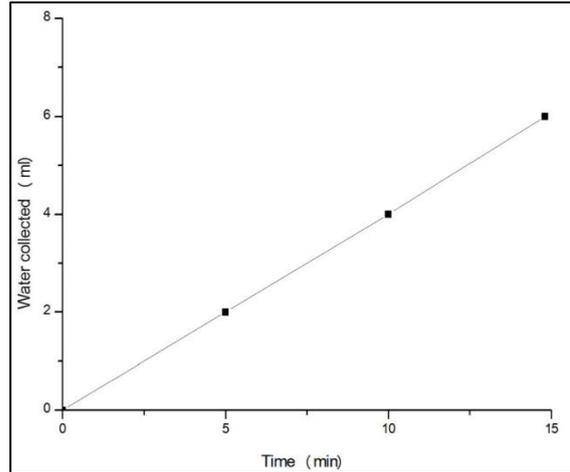


Fig. 10. Size distribution II: Water volume collected during the 15min dewatering period at 60 % Solids and at vacuum of 60 Kpa.

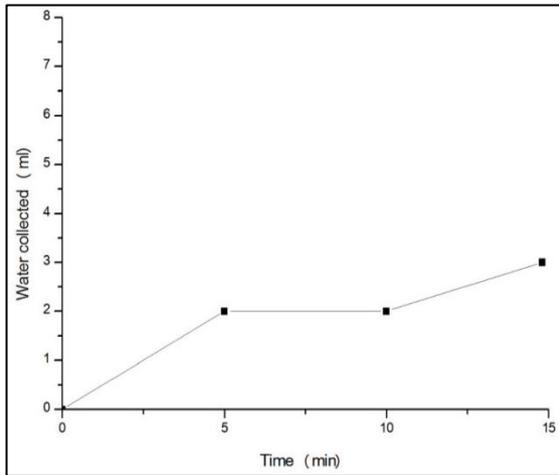


Fig. 8. Size distribution II: Effect of applied vacuum on the final moisture content at 40% solids.

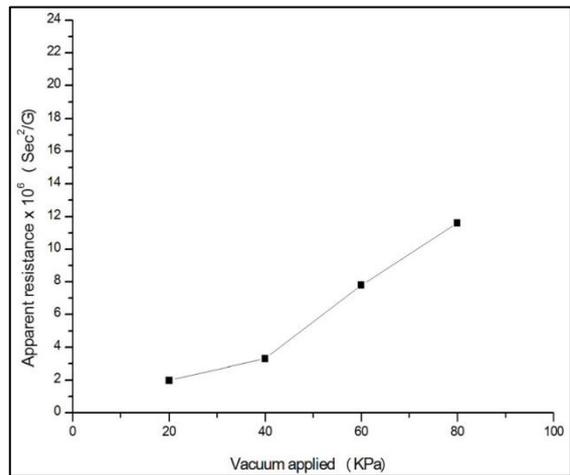


Fig. 11. Size distribution III: Effect of applied vacuum on the final moisture content at 40% solids.

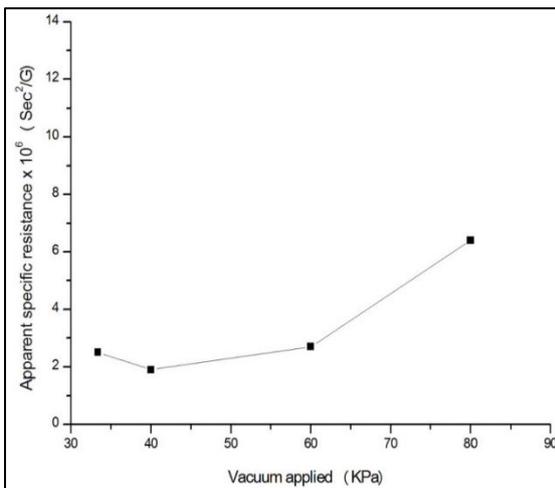


Fig. 9. Size distribution II: Effect of applied vacuum on the apparent specific resistance at 40% solids.

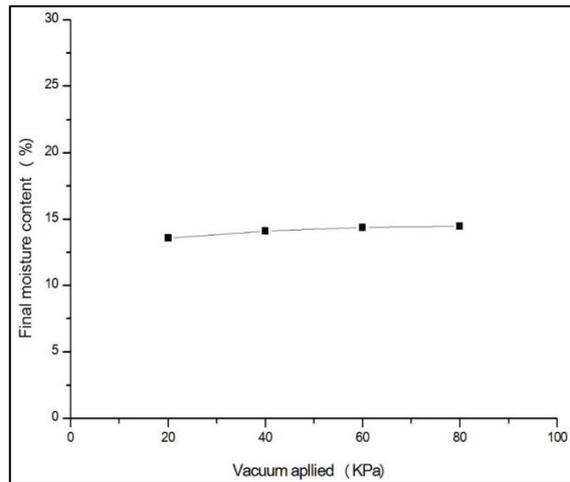


Fig. 12. Size distribution III: Effect of applied vacuum on the apparent specific resistance at 40 % solids.

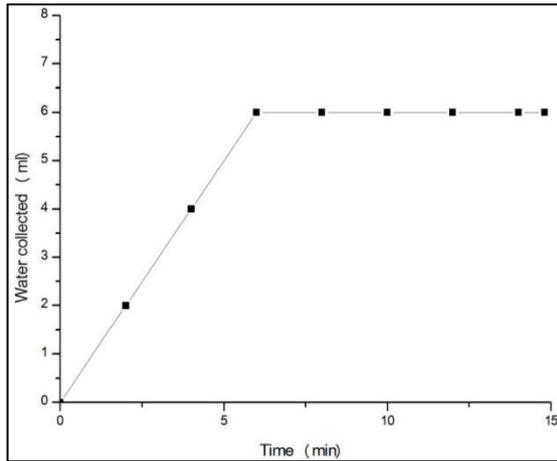


Fig. 13. Size distribution III: Water volume collected in the dewatering period at 60% solids and at an applied vacuum of 60 KPa.

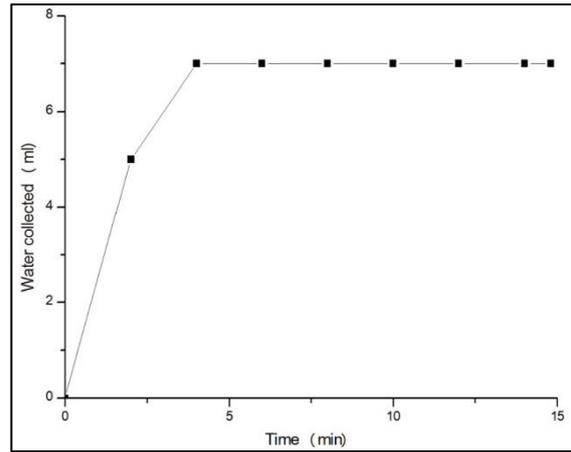


Fig. 16. Size distribution IV: Water volume collected in the dewatering period at 60% solids and at an applied vacuum of 60 KPa.

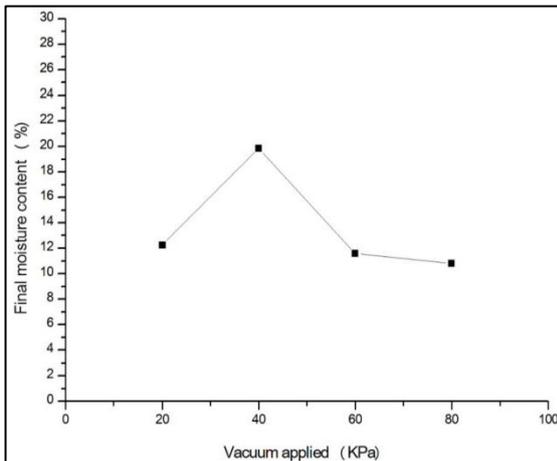


Fig. 14. Size distribution IV: Effect of applied vacuum on the final moisture content at 40% solids.

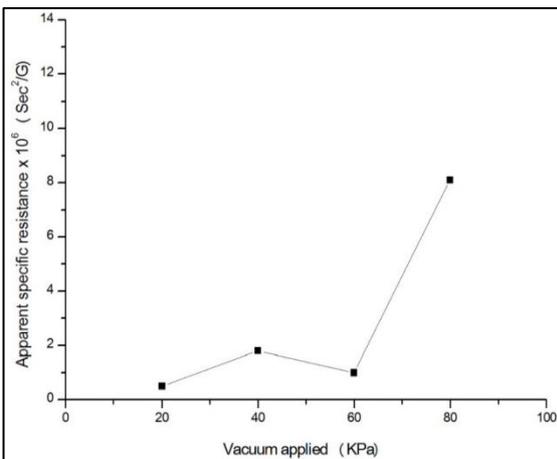


Fig. 15. Size distribution IV: Effect of applied vacuum on the apparent specific resistance at 40% solids.

Discussion

Filtration Results

Initially it was decided to test the six initial samples individually (1A to 6A represented in Table 1), at four solids concentration 30%, 40%, 50%, and 60% under a constant pressure throughout the filtration process. As expected particle size had a strong effect on the final moisture content of the cake (see Fig. 2). The final moisture content was found to increase when the particles size in the slurry decreased. The presence of fine particles in the slurry leads to a cake containing a large number of pores which offer more resistance to the flow of filtrate and also tended to trap water in the cake. As result, the rate of filtrate decreased significantly and a cake of high moisture content is obtained. In general the final moisture content of filter cakes decreased with an increase in solids concentration in the slurry but ended to level off at higher solids concentration.

However, it can be seen from Fig. 2 that there was no correlation between the moisture content and the solids concentration. The results obtained from sample 3A (150 – 75 μm) indicated that the moisture content was found to decrease at 40% (w. /w.) solid but to increase to a high value at 60% (w. /w.) solids.

The apparent specific resistance was found to increase with the increasing solids concentration in the slurry.

In this case as the solids concentration increased in the feed slurry the particles had less time to segregate during the cake formation (because of shorter cake formation period for higher solids concentration) this resulted in a cake of lower porosity which had a high apparent specific resistance. The apparent specific resistance increased to a high value as the particles size in the slurry decreased. This can be seen in Fig. 3 for sample 6A (- 45 μ m) and sample 3A (150 - 75 μ m).

Dewatering Tests

The dewatering test work was conducted using four samples of wider size range. The results are represented graphically in Fig. 5 to 16. It can be seen from these Fig.s that the cake structure, particles size, solids concentration, and increasing vacuum had a significant influence on both the final moisture content and the apparent specific resistance of the filter cakes. It was noticed as the particles size decreased the final moisture content and the apparent specific resistance increased sharply. The presence of fine particles leads to a cake containing a large number of small pores which offered more resistance to the flow of filtrate and also trapped water in the cake. Therefore, the rate of filtrate decreased considerably and a cake of high moisture content and apparent specific resistance was obtained. Using higher desaturating forces would be necessary to obtain a satisfactory dewatering rate from the cake composed by fines particles. However, in the case of size distribution III (6 - 425 μ m) and IV (20 - 425 μ m), the slurry was formed mainly with relatively coarse particles. With size distribution IV the final moisture content was reduced to around 11% and during the dewatering period the flow of filtrate increased with an increasing driving force. However when the applied vacuum was increased beyond 70 KPa the reduction of the moisture content was small and the apparent specific resistance dropped to a very low value. Comparing the results obtained when using size distribution III and IV under a vacuum of 40 and 70 KPa (5.99 10^6 sec²/g) compared to (1.89 10^6 sec²/g) it can be seen that the apparent specific resistance tended to increase sharply with

increasing vacuum beyond 70KPa (21.17 10^6 sec²/g) compared to (8.59 10^6 sec²/g).

Dewatering depended upon the filter cake structure and mainly on the size of particles in the slurry. Most of the dewatering took place within the first five minutes.

Conclusions

From the filtration experiments performed, the following conclusions can be drawn:

1. The size and distribution of particles, solids concentration and operating vacuum had a varied effect on the characteristics of the filtration operation, such as varying both the final moisture content and the apparent specific resistance of the filter cakes.
2. Increasing the particle size in the slurry resulted in decreased final moisture content and reduced apparent specific resistance. The reduction in the final moisture content for the - 425 μ m filter cake compared with - 45 μ m filter cake at 40 % (w. /w.) was around 3 %. However the apparent specific resistance for - 425 μ m filter cake was five times lower than that obtained for - 45 μ m (0.93 10^6 sec²/g compared to 5.11 10^6 sec²/g).
3. Increasing the solids concentration of the slurry reduced the apparent specific resistance, which helped in increasing the filtrate rate.

As far as cake dewatering was concerned, in the second stage of this work, the following parameters were considered to affect such a process;

1. Particles size and shape. Increasing the quantity of fine particles in the slurry resulted in filter cakes of higher moisture content and greater cake resistances which reduced the flow of filtrate. Increasing the quantity of coarse particles in the slurry reduced the cake moisture by 3 to 4 % points and also increased the flow of filtrate.
2. Solids concentration. As this increased the thickness of the cake increased which resulted in a decreased dewatering rate.

3. Applied vacuum. Increases in this resulted in a decreased moisture content but at applied vacuum beyond 70 KPa, the reduction in moisture content was very small.

4. The dewatering period. Most of the dewatering took place within the first five to six minutes of the 15 minutes dewatering period.

It was clear from the work conducted that the presence of small particles had a detrimental effect on both the filtration and dewatering processes.

Nomenclature

A cross sectional area of the filter (it was 38.48 cm² for the 7.0 cm filter paper)

B gradient of the plot t/v against v

C mass of wet cake/mass of dry cake (g c⁻³)

C_i sludge composition (g cm⁻³)

Q volumetric flow rate (ml min⁻¹)

R total resistance to flow of the cake medium

R_c resistance of the cake (cm⁻¹)

R_m resistance of the medium (cm⁻¹)

t time (min)

V filtrate volume collected (ml)

w, average mass of dry suspended solids per unit mass of the cake (% w. /w.)

w_s average mass of dry suspended solids per unit mass of the slurry (% w. /w.)

Greek letters

Δp pressure drop of the cake (KPa)

ρ_f density of the filtrate (g cm⁻³)

ρ_l density of the liquid in the slurry (g cm⁻³)

μ water viscosity at 20^o.4 (1 centipoise = 0.01 g cm⁻¹ sec⁻¹)

α cake specific resistance (sec² g⁻¹)

α_{ap} apparent cake specific resistance (sec² g⁻¹)

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