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Thickening of Clay Slurries by Periodic Pressure Flow through a Porous Polyethylene Tube

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ABSTRACT

A periodic pressure filtration process is evaluated to determine if the process can be used to thicken clay slurries. Current environmental cleanup operations, such as soil washing, result in large volumes of dilute slurries that must be filtered to remove the particles. The soil particles collected during the filtration, if clean, can be returned to the ground. One step in the dewatering and filtering process is thickening the slurry before filtering. The periodic pressure filtration process is one possible process for thickening clay slurries, but no performance data are available for evaluating the process. In this work a one-tube periodic pressure filter process is evaluated by measuring the thickened slurry discharge and filtrate rate while varying the design and operating parameters. The experimental results show that the process can thicken slurries of 1 to 3% inlet mass concentration to about 30 to 40% mass concentration.

INTRODUCTION

Problem Statement

Increasingly, water treatment systems are being called upon to produce effluents of substantially higher quality. One of the major objectives of water treatment is the removal of fine particles. The purpose of this work is to evaluate the concept of using a porous tubular filter in periodic pressure-driven flow to thicken dilute clay slurries.

Technological Significance

Micron and submicron particles frequently occur by accident or by design in many fluid process streams. When these particles are hazardous materials, it becomes especially important to remove them to prevent contamination of the environment. For example, the washing of soils to remove contaminants also produces waste streams that contain wide ranges of particle sizes. Multiple stages of filters, thickeners, and/or settlers (1) are required to produce a washwater that can be reused or returned to the environment and to reconstitute the soil so that it may be returned to the ground (2).

The costs of separating particles from liquids vary widely depending on the materials and the type of equipment. As a generalization, two of the most significant factors are the total volume of slurry to be filtered and the manpower or labor required to operate the process. Filter presses, centrifuges, and other filtering devices can be automated to reduce labor costs (3, 4) but at a significantly increased capital cost. Settling ponds may be the least labor-intensive to operate, but the trade-off is the size required for the ponds and the periodic dredging that is required. In each of these cases, the processes can benefit by a reduced volume of slurry.

Slurries can be thickened by a continuous gravity thickener (3, 4), by continuous crossflow filtration through a porous membrane tube (4), or by periodic pressurized filtration flow through a porous tube as applied in this work (5). The gravity thickener is the simplest to operate, but is limited in the product concentration. Crossflow filtration can obtain greater concentrations than the settler, but typically requires numerous passes of the slurry through the filter. The periodic pressure filter can potentially thicken the slurry to greater concentrations than the crossflow filter in a single pass by using control valves.

Scope of the Work

The work includes designing and setting up an experimental apparatus to test the concept and to obtain experimental data. Ultimately, the apparatus could be used for dewatering slurries such as from soil washing processes. The parameters varied include:

- Applied pressure
- pH of the water
- Residence time in the tube
- Annular space within the tube
- Inlet slurry concentration

There are many other parameters that could also have been varied, but the above are sufficient to prove the concept.

Summary of Results

Experiments were run on dilute clay slurries of 1 and 3% mass concentrations. The thickened slurry concentrations ranged from 7 to over 90% by mass in the experiments. Most commonly, the thickened slurry discharge concentration was in the 30 to 40% range by mass.

The thickened discharge concentration increased slightly with applied pressure and residence time in the tube, indicating a weak functional dependence. Slurry with a pH of about 7.62 (tap water) produced better results than a slurry with a pH of 8.2. The most concentrated discharge was obtained with a $\frac{1}{4}$-inch diameter coaxial aluminum rod in the tube with the slurry filling the annular space. However, the best filtrate rates were obtained with no rods in the tube.

COMPARISON OF FILTRATION PROCESSES

The periodic pressure filtration that is the subject of this work has similarities with the more common dead-end filtration (i.e., cake filtration), crossflow filtration, and the not-so-common dual-functional filtration. Brief descriptions of each of these filtration processes are given in this section for comparison with the periodic pressure filtration process. More extensive descriptions of the processes are available in the cited literature.

Dead-End Filtration

Dead-end filtration is commonly applied to form filter cakes. In cake filtration, particles are deposited on the surface of a relatively thin permeable filter medium by the principle of screening. As soon as the initial layer of cake forms on the surface, the deposition of particles occurs on the surface of the cake and the medium acts as a support. The fluid flow is through the cake and the medium. As the cake builds up, the resistance to fluid flow increases, and this requires a greater applied pressure drop to maintain the flow.

As shown in Fig. 1, the cake continually builds up normal to the medium surface over time. Unless the cake growth is limited by some artificial means, the resistance continues to increase over time as the cake depth increases until the flow decreases to very low rates. If the particles are very small, then a small cake thickness can produce a large resistance, which makes thick cakes impractical.

After the cake is formed and the process is stopped, the cake must be removed. This is done, for example, by opening up a filter press and letting the cake fall off the medium or by scraping the cake off.

In most cases when a "dry" cake with high solids concentration is desired, dead-end filtration is used. The feed concentration of the inlet

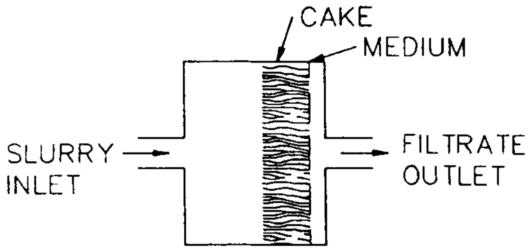

FIG. 1 Dead-end filtration in which particles are stopped by screening them out of the slurry. The filtrate can be discarded or sent to another tank for storage.

slurry has a profound effect on the cycle time and production rate of the filter, and *prethickening* can be of great benefit. The effect of slurry concentration on solids yield can be easily demonstrated using the following equation derived in Appendix I of Svarovsky (9) (neglecting medium resistance):

$$Y = \left(\frac{2\Delta P f c}{\alpha \mu t_c}\right)^{1/2}$$

where ΔP is the pressure drop, c is the feed solids concentration, α is the specific cake resistance, μ is the liquid viscosity, Y is the solids yield (dry cake production in $kg/m^2/s$), f is the ratio of the filtration to cycle time, and t_c is the cycle time. For the same cycle time, if the concentration is increased by a factor of 4, production capacity is doubled. In other words, the filtration area can be halved for the same capacity.

One additional benefit of prethickening is the reduction in cake resistance. If the feed concentration is low, there is a general tendency for particles to pack together more tightly, thus leading to higher resistance to flow. However, with thicker concentrations, many particles approach the filter medium at the same time. They may bridge over the pores, which reduces the particle penetration, and a more permeable cake is formed.

Crossflow Filtration

One method of prethickening the slurry is the crossflow method (3, 4, 6–8) in which the slurry flows at a high velocity parallel to the surface of the filter medium. This is shown in Fig. 2 which represents a cross section of a rectangular or tubular membrane. By this means the cake is prevented from forming during the early stages of the filtration. This can be particularly beneficial when the slurry is flocculated and exhibits shear-thinning

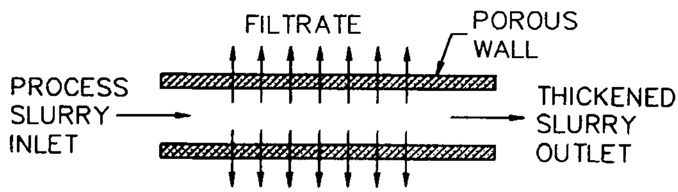

FIG. 2 Crossflow filtration. The slurry flows parallel to the filter medium and prevents significant build up of cake.

non-Newtonian properties. In cases where a dilute solution containing small quantities of solids which tend to blind the filter cloth are to be filtered, crossflow filtration is extensively used. It is the normal mode of operation for ultrafiltration using membranes.

Some advantages of crossflow filtration over the conventional dead-end filtration are:

1. A higher overall liquid removal rate is achieved by prevention of the formation of an extensive filter cake.
2. The process feed remains in the form of a mobile slurry suitable for further processing.
3. The solids content of the product slurry may be varied over a wide range.
4. It may be possible to fractionate particles of different sizes.

In practice, the filtrate rate falls with time due to membrane fouling. The fouling occurs as particles block the pores in the membrane surface. The rate of fouling depends upon the materials being processed, the membrane used as the filter medium, the crossflow velocity, and the applied pressure.

Eventually, the slurry concentration builds up until the high velocity for crossflow cannot be maintained. The filtration is stopped before the cake build up in the filter makes cake removal difficult.

Dual-Functional Filter

The dual-functional filter makes use of filtration and settling to thicken the slurry (5). As shown in Fig. 3, the filtration occurs in a long tube in which a thin cake is formed on the inside of the tube walls. The thin cake and slurry are discharged from the tube into a receiving vessel where the cake settles to the bottom and the liquid is decanted.

The filtration cycle has three phases: a filtration phase, a dump phase,

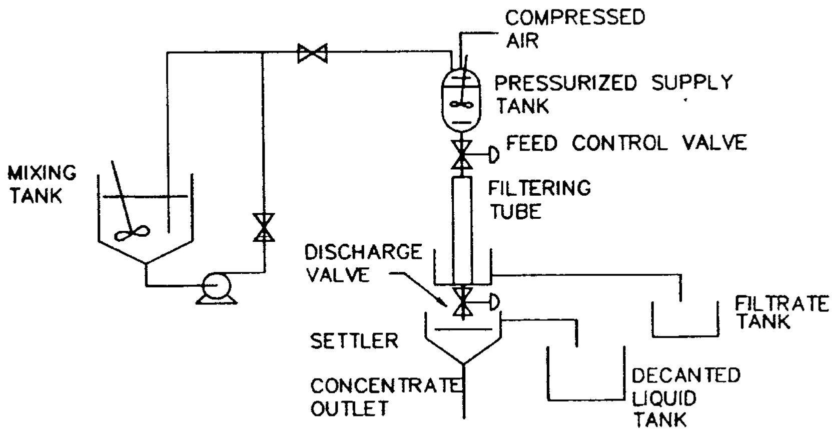

FIG. 3 Dual-functional filter flow diagram.

and a settling phase. The filtration phase starts with the introduction of slurry at the top of the long tube and the valve closed at the bottom of the tube. The filter cake forms on the interior wall of the tube and filtrate passes through the porous walls of the tube to be collected on the outside. The filtration phase stops before the cake fills the inside of the tube. The method of filtration is largely dead-end, though in the tube near the slurry inlet the flow rate may initially be large enough for the filtration to be crossflow.

The dump phase of the cycle starts by closing the feed valve at the top of the tube and opening the discharge valve at the bottom. The resulting pressure release causes the cake and feed slurry in the vertical tube to dump into the receiving vessel. The discharged material consists of cake and a dilute slurry; the cake material does not completely redisperse into the slurry.

The settling phase occurs in the receiving vessel. The cake material readily settles out of the discharge mixture from the tube. The liquid at the top of the settler contains some particles and can be recycled for filtering again.

The dual-functional filter has several process advantages:

1. The rapid cycle of the process produces high filtration rates because the cake does not accumulate to large thickness on the wall.
2. There is no mechanical device required to remove the cake from the walls of the tube.

3. The combination of filtration and settling provides a high degree of thickening of the sludge.
4. Filter aid is usually not needed.
5. The process is mechanically simple and is not labor intensive.

Henry et al. (5) tested the dual-functional filter on neutralized acid mine drainage water and observed thickening of the slurry from 0.2% by weight of solids at the feed inlet to 35% by weight of solids after decanting. They also developed a model for predicting the cake build-up on the inside of the tube and the overall filter performance.

Periodic Pressure Filtration

Periodic pressure filtration is very similar to the dual-functional filter except that the tube is much shorter and near the bottom of the tube the cake is allowed to fill the tube as shown in Fig. 4. As a result, concentrated slurries are possible without the need for the settler shown in Fig. 3, though a settler could be used if further thickening is desired.

The exiting slurry concentration depends largely upon the relative volumes of cake and slurry within the tube. One obvious way of reducing the ratio of slurry volume to cake volume is to reduce the space available for the slurry. This is done by inserting a solid rod within the tube, as shown in Fig. 4. As a result, the cake forms within the annular space.

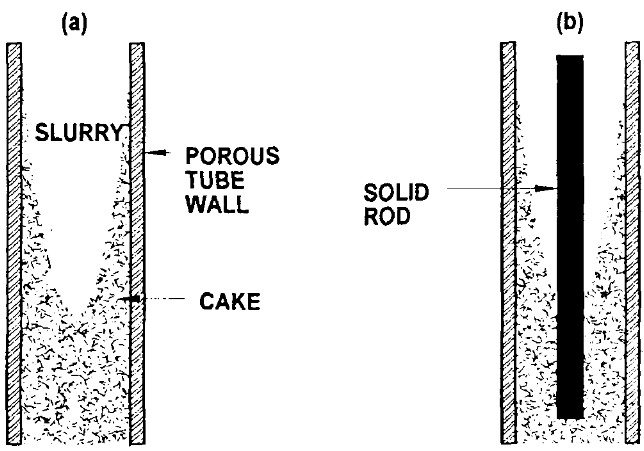

FIG. 4 Periodic pressure filtration forms a cake on the inside tube wall. As shown in (a), the filter cake forms on the wall and the slurry occupies the center of the tube. Near the tube exit at the bottom of the tube the cake fills the inside cross-section of the tube. In (b), a solid rod is placed in the center of the tube to reduce the volume occupied by the slurry.

There is a trade-off in designing the filter this way: while the exiting slurry may be more concentrated, if the annular space is made too small the cake will not readily eject from the tube.

Using a set-up similar to that in Fig. 3 for the dual-functional filter, the periodic pressure filter has a feed inlet valve and a discharge valve which control the operation. When the inlet valve is open and the discharge valve is closed, the slurry enters the tube and cake forms on the walls. When the feed valve is closed and the discharge valve is open, the pressure within the tube and gravity cause the cake to flow downward.

Some techniques could be applied to enhance the operation but were not attempted in this current work. These include:

- Apply air pressure at the top of the tube to force more of the cake out of the tube at the discharge part of the cycle.
- Apply a back pressure of air from the outside of the tube inward to dislodge the cake from the walls of the tube.
- Efflux time for cake discharge can be varied to find an optimum.

Currently, there is no theory for predicting the performance of a periodic pressure filtration. Qualitatively, periodic pressure filtration should work because it has many similarities with existing filter processes. Like the dual-functional filter, it is largely a dead-end filtration with possible crossflow filtration occurring early in the filtration cycle near the feed inlet. Proving that it does work on clay slurries is the subject of the experimental portion of this paper.

EXPERIMENTAL SETUP AND PROCEDURES

In this section the experimental setup and procedures are discussed on how the experiments were run. The experiments were designed to investigate the effects of varying the applied pressure, pH of the water, solid rod diameter, residence time in the tube for the filtration part of the cycle, and inlet slurry concentration.

Experimental Setup

The experimental setup is shown in Fig. 5. The slurry is prepared in the mixing tank and then is pumped into the pressurized tank for the filtration. Air pressure provides the applied pressure driving force for the filtration. The slurry exits the pressurized tank and passes through a pump which circulates the slurry back into the pressurized tank. This

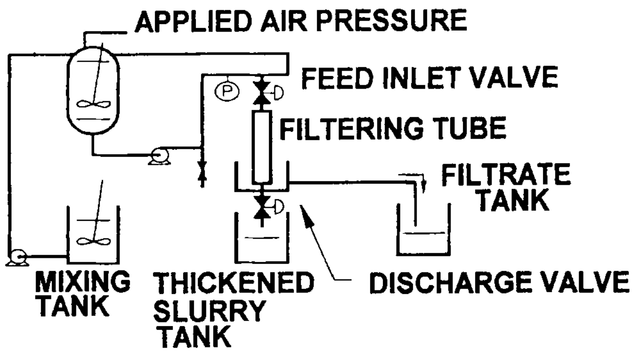

FIG. 5 The experimental setup.

circulation keeps the slurry well suspended in the pipelines during the experiments.

Part of the slurry is diverted into the filtering tube when the feed inlet valve is open. The cake forms in the tube and the filtrate passes through the tube wall and is collected in the filtrate tank. At the end of the residence time in the tube the feed valve closes and the discharge valve opens. The cake and slurry in the tube are discharged into the thickened slurry tank.

The slurry concentration is determined by collecting a sample of the slurry from a sampling valve as it exits the pump and cycles back to the pressurized tank. The pressure is measured directly from a gauge in the slurry feed line. The mass of filtrate and mass of thickened slurry are measured with a weighing scale.

The operation of the filter is controlled by the feed inlet valve and the discharge valve. These valves must be synchronized to keep dilute slurry from passing through the filtering tube and into the thickened slurry tank. Solenoid valves were chosen for this purpose because they can be controlled by electrical signals, which in turn are controlled by a computer (not shown in Fig. 5).

The solenoid valves used in the experiments are nominal $\frac{1}{2}$ inch pipe size Hayward 120 volt 19 watt solenoid valves supplied by Corro-Flo Engineering, Westerville, Ohio. The porous filtering tube is made of polyethylene and manufactured by General Polymeric Corporation, Reading, Pennsylvania. The distribution of the tube pore size reported by the supplier is between 0.5 and 8 μm, with 80% of it in the 2 μm range. The tube is 32 inches long, 2 inches outside diameter, and 1 inch inside diameter.

Procedures

The general procedures for the experiments are described here. About 70 L slurry is prepared by mixing kaolin clay (supplied by the Charles B. Crystal Co., New York, New York) with tap water in the mixing tank in Fig. 5. Any additives to control the pH are also added at this time. Sulfuric acid, H_2SO_4, is used to lower the pH, and sodium hydroxide, NaOH, is used to raise the pH in the experiments. The slurry mixture is mixed for about 1 hour in the mixing tank and then it is pumped into the pressurized tank.

In the pressurized tank the air pressure is raised to the experimental set point and the slurry is agitated with an impeller. The slurry is pumped through the pipeline past the filter and back into the pressurized tank for about an hour to ensure thorough mixing. Samples of the slurry are removed through a sampling valve and analyzed for the actual pH and slurry concentration. This sampling is done to account for any residual materials that may have been left in the system from a previous experiment.

Control of the experiment is turned over to the computer which opens and closes the feed inlet valve and the discharge valve. First the feed inlet valve is opened to allow slurry to enter the filter tube. After a specified residence time the feed inlet valve is closed and the discharge valve is opened. In all of the experiments the discharge valve was opened for 15 seconds while the residence time was varied.

Initially the filtering tube is filled with air. This air must be displaced and cake formed on the walls before any meaningful measurements can be recorded. It was found that by holding the first cycle residence time to at least 4 minutes, the cake was adequately formed and thickened slurry measurements were reproducible after the second or third cycle.

The thickened slurry discharge concentration is determined by collecting the slurry in a small container. The mass of the slurry is determined by weighing, the slurry is dried in an oven, and the particle mass is weighed. The ratio of the weights gives the thickened slurry solids mass concentration.

After the slurry is collected for determining the concentration for a particular residence time or applied pressure, the residence time or applied pressure are changed for the next experiment. The measurement process is repeated. Including the back-to-back experiments, the filtration was repeatedly operated for 1.5 to 2 continuous hours without any adverse effects.

To change the slurry concentration or the pH requires a complete change of the slurry in the tank and pipe system. The entire apparatus is rinsed out five times with tap water before loading in the new slurry.

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental Results

A total of 117 experimental measurements were made by varying the applied pressure, pH, rod diameter, residence time, and slurry concentration. These parameters could have been varied over wider ranges and other parameters also could have been varied, but the experiments that were run are sufficient to prove the concept.

Only one experiment was attempted with an acidic solution (pH of about 6.5). In this experiment the filtrate rate was very slow. When the process switched to the discharge part of the cycle, the cake and slurry blew out of the bottom of the tube under high pressure. Because of this the thickened slurry concentration could not be measured. It is suspected that under basic conditions the clay particles may flocculate, forming larger particles that are easier to filter. Under acidic conditions the individual clay particles disperse and may plug the pores in the tubes. This is consistent with similar observations reported in the literature (10) on the behavior of clay particles.

Some general observations are listed here on the conduct of the experiments:

1. Experiments were run back-to-back with the filter running continuously over periods of 1.5 to 2 hours without the tube becoming clogged.
2. When experiments were stopped, the tube had to be rinsed. Otherwise the cake hardened within the tube and had to be manually removed (usually by striking the outside tube wall).
3. In all cases the cake was viscous and stuck to the tube walls. However, during the operation of the filter the pressure within the tube and gravity were sufficient to make the cake flow downward and out of the discharge valve.
4. The 15 seconds discharge time was not long enough to discharge all of the cake from the tube.
5. The clay mixed very well with the water in the mixing tank. The agitator kept the clay particles well suspended in the tank. Slurry concentrations of 1 and 3% by mass of clay were dilute enough that no pumping problems occurred.
6. No problems were observed with the solenoid valves in opening or closing on the thickened slurry.
7. It was observed that the solenoid valves became hot when operated for long periods of time. However, the temperature was within the manufacturer's specified limits.

8. The clay readily stuck to the aluminum rods when the rods were inserted into the tubes.
9. Since the aluminum rods were attached only at the top of the tube, there is a possibility that the rods did not stay coaxial with the filter tube. Observations at the end of the experiments when the tube and rod were disassembled indicate that this was not a problem.

Discussion

All the experimental data are plotted in Figs. 6 through 13. There are many factors that influence the reproducibility of the data. In particular, the thick viscous nature of the discharge material greatly affects how rapidly the material will discharge. In evaluating the data, only general trends are considered.

In Fig. 6 are plots of the mass of filtrate as a function of number of cycles. These data were plotted to study the steady-state conditions of the system. It is clear from the plots that for the experiments with 3 and 5 minute residence times, steady-state conditions were attained in one or two cycles. For the 1 minute residence time experiment, steady-state conditions appear to be achieved after about three cycles.

Figures 7 through 10 plot the data of the mass percent of clay in the thickened discharge slurry as a function of applied pressure and cake growth residence time in the tube. Each figure plots data for the same water pH of 7.62 and for two inlet slurry concentrations of 1 and 3% by mass. The figures differ by the aluminum rod diameter inserted in the center of the tube; 0 (i.e., no rod), $\frac{1}{8}$, $\frac{1}{4}$, and $\frac{1}{2}$ inch. Figure 10 shows that the $\frac{1}{2}$ inch aluminum rod significantly hampers the discharge slurry concentration compared to 0, $\frac{1}{8}$, or $\frac{1}{4}$ inch rods as shown in Figs. 7 through 9.

For the 0 and $\frac{1}{8}$ inch rods the data appear to be very similar for the two inlet slurry concentrations. For the $\frac{1}{4}$ inch rod very high concentrations were obtained for the inlet 3% slurry whereas the concentrations for the 1% slurry were slightly lower than in Figs. 7 and 8. This latter observation may indicate that there is an optimum rod size. For the 0 inch rod the increase in residence time seems to improve the mass% of the discharge slurry. Finally, one would expect the applied pressure to affect the cake growth but the results are inconclusive.

Figures 7 and 11 compare the data for experiments with slurries of pH 7.62 and 8.2. In terms of mass% of clay in the discharge, the pH does not have a significant effect.

Perhaps a better measure of the thickening of the slurry is the amount of filtrate removed. Figure 12 plots the mass of filtrate that is removed from the slurry by flowing through the tube walls. The data shown in Fig.

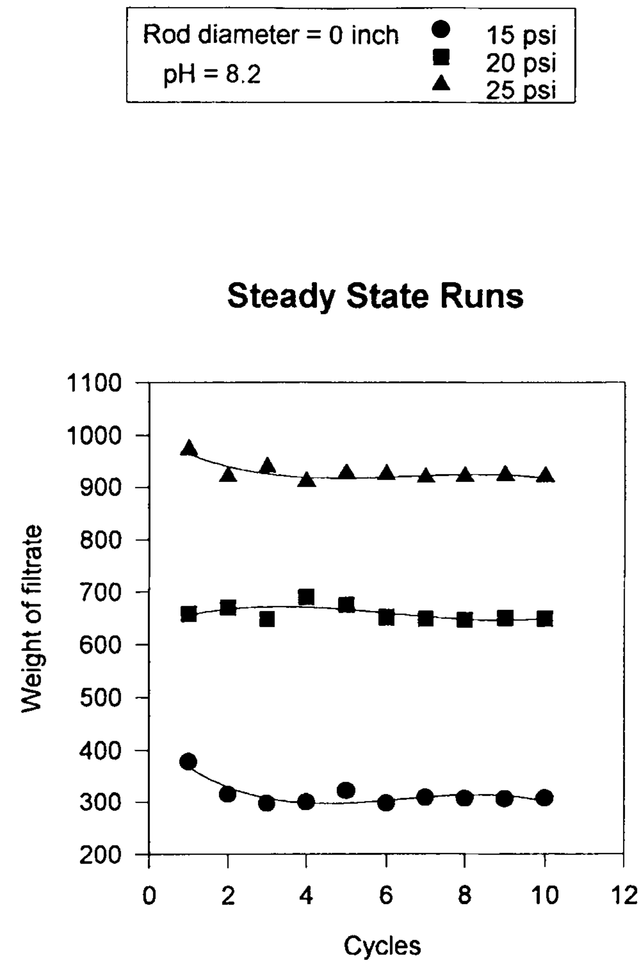

FIG. 6 Plots of weight of filtrate as a function of the number of cycles for a slurry of pH 8.2 and with no rod in the tube.

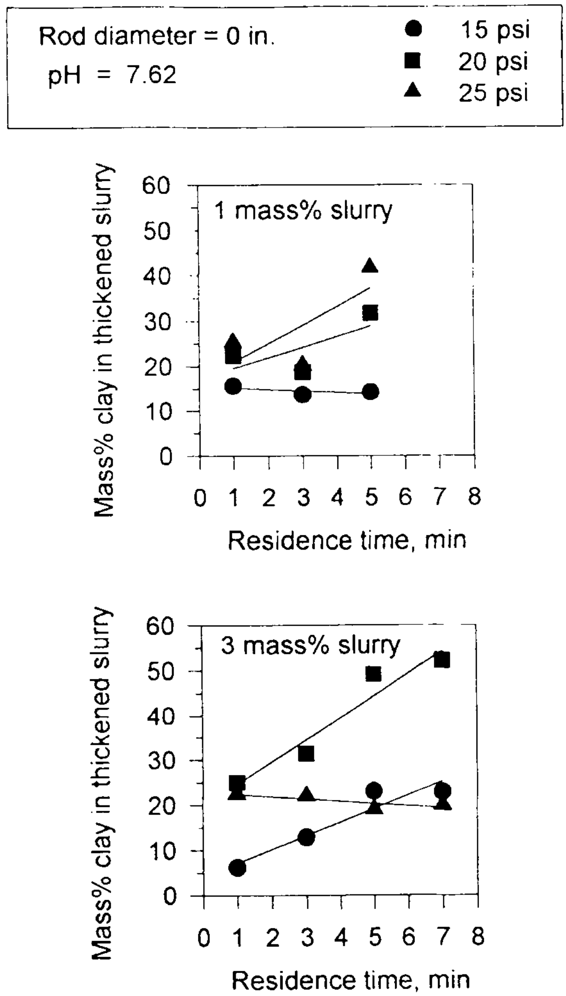

FIG. 7 Plots of mass% of clay in the thickened discharge slurry as a function of residence time and applied pressure for inlet slurry concentrations of 1 and 3% by mass. The data are for a slurry of pH 7.62 and a rod diameter of 0 inches (i.e., no rod).

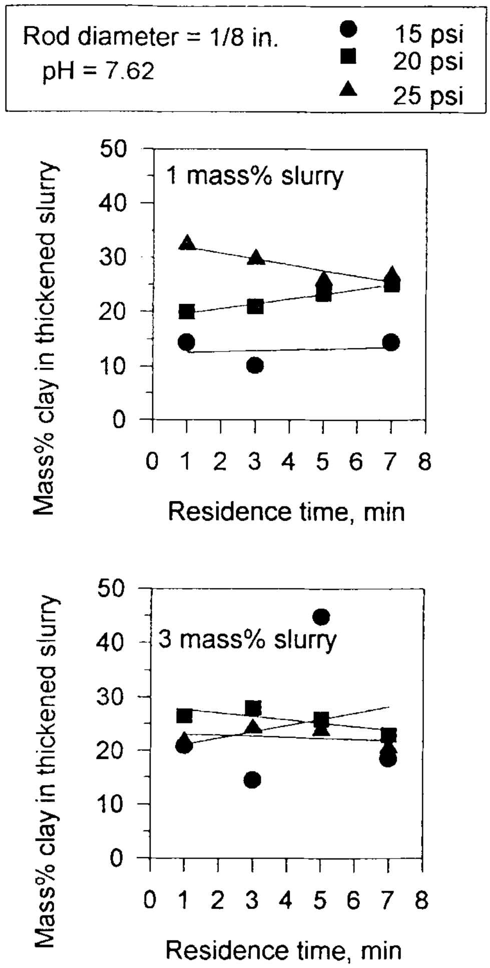

FIG. 8 Plots of mass% of clay in the thickened discharge slurry as a function of residence time and applied pressure for inlet slurry concentrations of 1 and 3% by mass. The data are for a slurry of pH 7.62 and a rod diameter of $\frac{1}{8}$ inch.

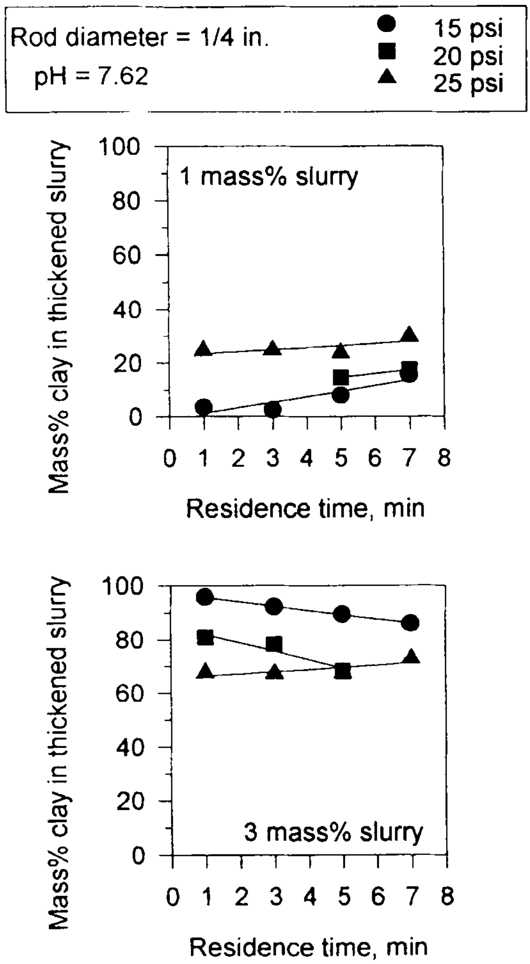

FIG. 9 Plots of mass% of clay in the thickened discharge slurry as a function of residence time and applied pressure for inlet slurry concentrations of 1 and 3% by mass. The data are for a slurry of pH 7.62 and a rod diameter of $\frac{1}{4}$ inch.

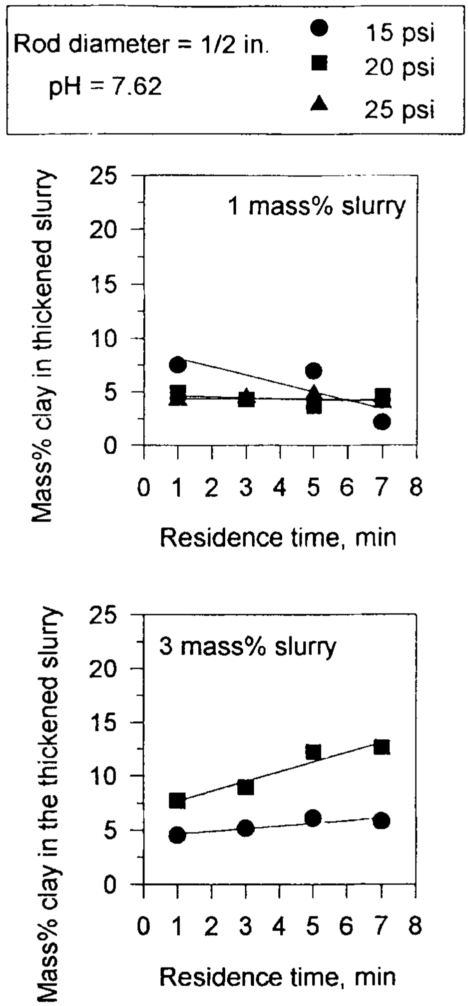

FIG. 10 Plots of mass% of clay in the thickened discharge slurry as a function of residence time and applied pressure for inlet slurry concentrations of 1 and 3% by mass. The data are for a slurry of pH 7.62 and a rod diameter of $\frac{1}{2}$ inch.

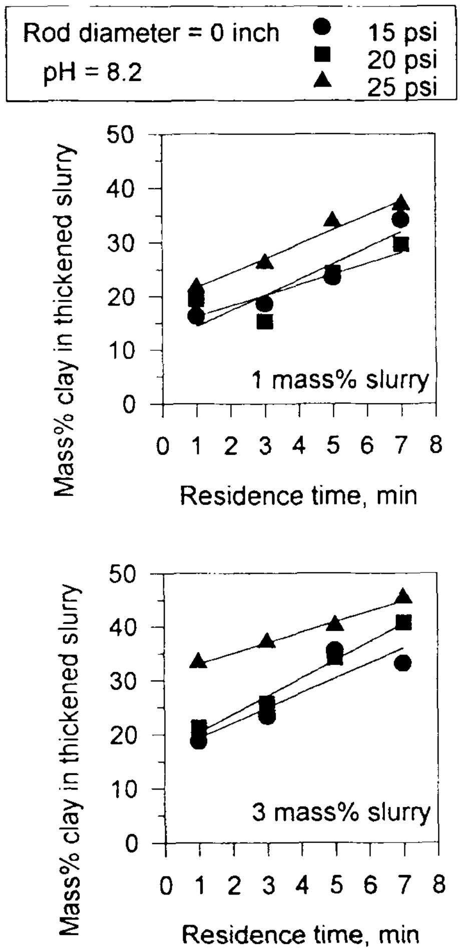

FIG. 11 Plots of mass% of clay in the thickened discharge slurry as a function of residence time and applied pressure for inlet slurry concentrations of 1 and 3% by mass. The data are for a slurry of pH 8.2 and a rod diameter of 0 inches (i.e., no rod).

12 are for no aluminum rod (0 inch diameter). As expected, the mass of filtrate increases with the residence time. Since most of the data can be fitted to a straight line, this suggests that the clay particles were not plugging the pores in the tube wall; the same conclusion is made that the change in pH from 7.62 to 8.2 had little effect.

Plots similar to Fig. 12 can also be made for the rest of the data. When we take the slope of these lines, we get an estimate of the filtrate rate

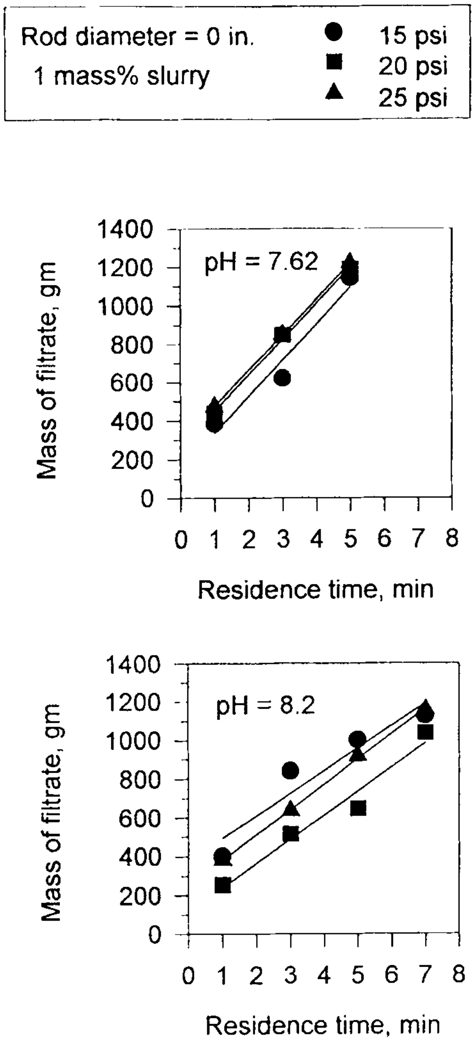

FIG. 12 Plots of mass of filtrate removed from the filtering tube as a function of residence time and applied pressure for the experiments with (no rod), 1% by mass of inlet slurry, and pH 7.62 and 8.2.

(mass per time). These filtrate rates are plotted in Fig. 13 for all of the experiments as a function of the applied pressure and the rod diameter.

In Fig. 13 we see that the filtrate rates are best for no rod in the tube and worst for the $\frac{1}{2}$ inch rod. The applied pressure and inlet slurry concentration may have some effect on the filtrate rate, but their influence is not

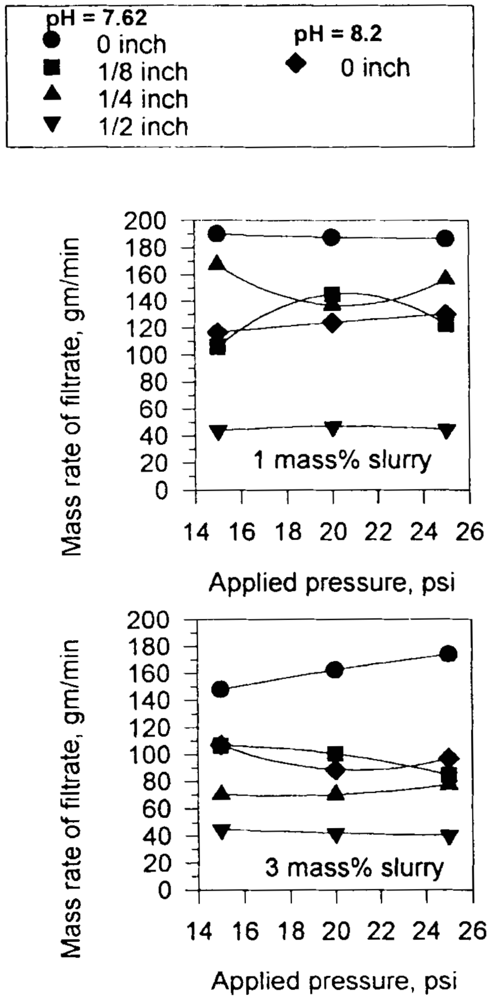

FIG. 13 Plots of mass rate of filtrate from the filtering tube as a function of applied pressure and rod diameter for inlet slurry concentrations of 1 and 3% by mass.

very strong under these experimental conditions. Comparing the curves for the 0 inch rod and pH 7.62 to pH 8.2 indicates that the slurry with pH 7.62 had the best filtrate rates.

To estimate scale-up of the periodic pressure filter, Fig. 14 plots the liters of filtrate and the kilograms of thickened slurry for the best and worst cases as a linear function of number of tubes for inlet slurry concen-

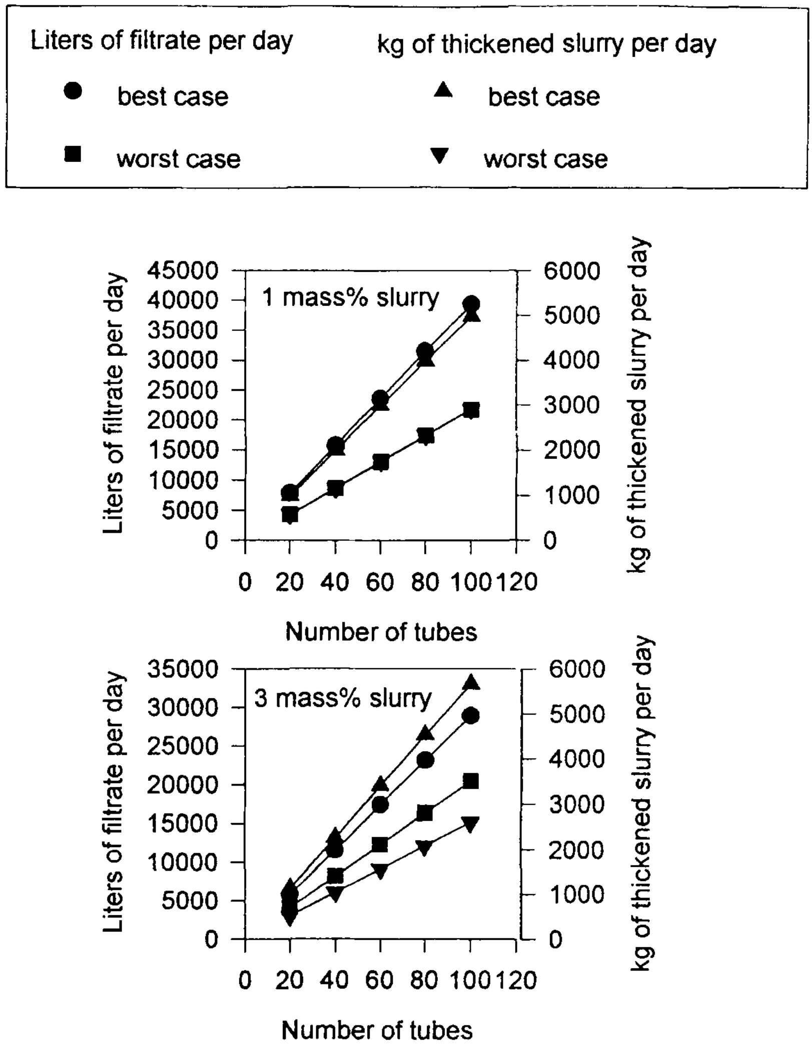

FIG. 14 Plots of liters of filtrate and the kilograms of thickened slurry for the best and worst cases as a function of number of tubes for inlet concentrations of 1 and 3% mass.

trations of 1 and 3% mass. This assumes that in scale-up the production for one tube can be multiplied by the number of tubes to get the total.

CONCLUSIONS AND RECOMMENDATIONS

The experiments show that the filtration is best run with no aluminum rod and with tap water of pH 7.62. Applied pressures in the range of 15 to 25 psi do not have a great effect on the thickening of the slurry though some of the data suggests that increasing the applied-pressure and residence time increases the discharge concentration. The process ran equally well with 1 and 3% slurries.

The purpose of this project is to prove that the concept of periodic pressure filtration does work to thicken clay slurries. This is proven by the experimental data which show that the slurry can be thickened from 1 or 3% to an average of about 30 to 40% and as much as 90% or greater (Fig. 9) under the best conditions.

The work here only explored several of the operating and design variables. Future work can investigate the effects of varying tube diameter, tube length, and discharge time. Greater ranges in applied pressure and residence times should also be evaluated.

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