Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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Online publication date: 23 April 2002

To cite this Article Chu, C. P. and Lee, D. J.(2002) 'Centrifugation of polyelectrolyte flocculated clay slurry', Separation Science and Technology, 37: 3, 591 — 605
To link to this Article: DOI: 10.1081/SS-120001449
URL: http://dx.doi.org/10.1081/SS-120001449

SEPARATION SCIENCE AND TECHNOLOGY, 37(3), 591–605 (2002)

CENTRIFUGATION OF POLYELECTROLYTE FLOCCULATED CLAY SLURRY

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ABSTRACT

The effects of polyelectrolyte flocculation on centrifugal sedimentation and filtration stages of clay slurry were highlighted in this study. The moisture removal efficiency was enhanced by flocculation and increasing the rotational speed. Slurry conditioned to charge neutralization point exhibited the best dewaterability. For flocculated sludges, the sedimentation effect became too significant to eliminate the centrifugal filtration stage. Over 93% of the moisture removal was accomplished by simply allowing the filtrate to flow through a compacted filter cake. Optimal flocculant dose and rotational speed were found in the centrifugal tests.

INTRODUCTION

The two most widely employed mechanical methods to dewater sludges are centrifugation and filtration. A centrifuge could provide higher pressure-difference than the conventional filter press, thereby being widely applied to

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remove moisture from hard-to-filter slurries. Zeitsch and Letki (1,2) reviewed the use of centrifuges. Karr and Keinath (21) noted that the indices to characterize sludge filterability, like specific resistance to filtration (SRF) and capillary suction time (CST), are not adequate to describe the dewaterability of sludge through centrifugation.

Industrial-scale centrifuge for sludge dewatering often consists of a cylindrical conical bowl shell with an internal scroll that rotates and scrapes the solid out of the centrifuge. Three moving and one stagnant interfaces could be identified on the centrifuged cell as follows: air–supernatant (gl), supernatant–suspension (ls), suspension–cake (sc), and cake–medium interfaces, whose corresponding radii are r_{gl}, r_{ls}, r_{sc}, and r_{cm}, respectively. Centrifugation of a suspension would include the following dewatering stages: (a) *Centrifugal sedimentation*: since the centrifugal acceleration is generally much greater than the gravitational acceleration g, sedimentation is significant in a centrifuged cell when compared with the pressurized or gravitational filtration cell. Large particles would settle quickly toward the filter medium and a clear supernatant hence appears, with an interface, ls, separating it from the suspension located beneath. (b) *Centrifugal filtration*: filtrate would flow through the filter medium owing to the pressure gradient generated by the centrifugal field. Along with particle settling, the particles would form a saturated cake. The moisture inside the cake is in a "capillary state" (3). An interface, sc, would appear and move upward with the growing cake in the centrifuged cell. (c) *Centrifugal dewatering*: as all suspension- and supernatant- exhausts during centrifugation, both the interfaces gl and ls would merge with the sc. The centrifugal pressure overcomes the capillary suction force to such an extent that it removes the moisture existing in the cake interstices. Thus, the cake saturation would decrease from unity and approach an equilibrium value. The residual moisture is in a "funicular state" (3). The collapse of void structure would also occur, which yields the decrease of cake thickness and cake porosity. (d) *Air drying*: after most of the free moisture in the cake interstice has been removed, air could flow through the void pores in the cake and carry away some residual moisture. The moisture in the cake is in a "pendular state" (3).

Vesilind (4) proposed the concept of settling coefficient to characterize the sludge centrifugeability. Most literature works discussed the centrifugal filtration stage (stage (b)). Both the pressure gradient and the filtration area change with rotational radius and time, hence the centrifugal filtration process could be regarded as a variable-pressure filtration process. Maloni (5) first applied the Carman equation to derive the equation of centrifugal filtration. Subsequent studies extended Maloney's work to describe the pressure difference, flow rate, and cake volume as functions of rotational speed (6–8). Sambuichi et al. (9) further considered the sedimentation effects during centrifugal filtration, thereby describing the positions of all interfaces in the centrifugal filter basket. For determining the porosity distribution in the centrifuged cake, a unified approach (for gravitational sedimentation, pressurized filtration, and centrifugal filtration) was adopted by solving the effective pressure distribution and obtaining the porosity with the assistance of constitutive equations between effective pressure and solidosity (10,11). A similar procedure was also developed in other studies (12).

Interpretation of batch centrifugation tests is difficult since both the filtration areas as well as the interface positions are functions of time. Spinosa and co-workers investigated the centrifugeability of conditioned sludge (13–15).

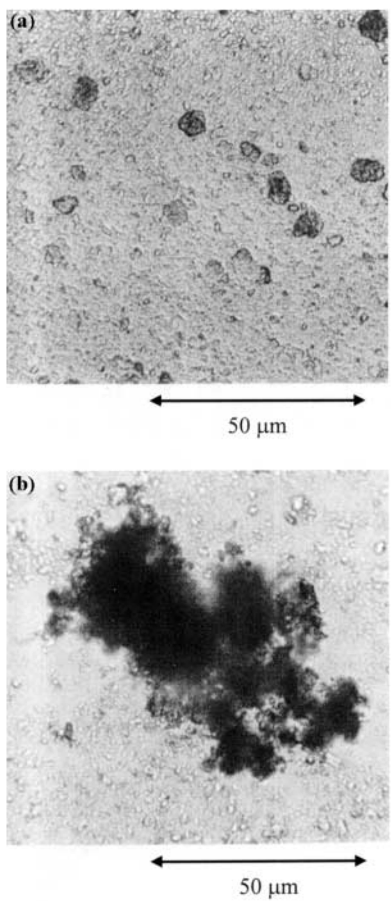

Figure 1. Microphotograph of the flocculated sludge floc. 200×. (a) Original sludge; (b) Flocculated sludge at polyelectrolyte dose = 2.0 g/kg DS.

Hwang et al. (16) applied the "arm-suspended centrifuge" instead of bowl centrifuge to keep the filtration area a constant (Fig. 1). Furthermore, the transparent casting allows direct and clear visual observation of the centrifugation processes. These authors considered the compactibility of three slurries (bentonite, calcium carbonate, and kaolin) and reported that the centrifuged cake may exhibit a maximum resistance to dewatering at a critical rotation speed (800–1000 rpm in their study) since a higher rotational speed may further compact the cake and retard the filtrate flow. Smiles (17) applied the one-dimensional non-linear Fokker–Planck equation and considered the flow and force in the saturated cake. Together with the Darcy's law, he obtained a non-linear water diffusion equation in the centrifuge. Thus the cake porosity could be expressed as a function of radius and time.

Polyelectrolyte flocculation has been employed widely to pretreat slurries for increasing their settleability and the corresponding filterability. Charge neutralization and interparticle bridging are the two major mechanisms to flocculate the particles into large flocs (18). In water and wastewater treatment, polyelectrolyte is commonly applied prior to mechanical separation of moisture (19). The floc size and the resulting cake compactibility are commonly noted to have a marked increase after flocculation, enhancing the floc settlement and inducing possible cake compaction. These factors had not been taken into account in most of the literature works. In fact, information regarding the effects of poyelectrolyte on dewatering efficiency under centrifugal field is still largely lacking. This study used clay slurry as the model system to investigate the changes in moisture removal efficiency during the centrifugal filtration, before and after cationic polyelectrolyte flocculation.

EXPERIMENTAL

Sample and Characterization

The UK ball clay powders have a mean diameter of approximately 4.6 μm. The true solid density was measured as 2584 kg/m^3. The slurry was prepared by mixing the clay particles and 0.1 M $NaClO_4$ in distilled water. The addition of $NaClO_4$ is to provide a high ionic strength to prevent the interference of other ions that might be released from the ball clay particle surfaces. The pH values are fixed at 7. The weight percentage of the original slurry is 5%.

Cationic polyelectrolyte flocculant indicated as polymer T-3052 was obtained from Kai-Guan Inc., Taipei, Taiwan. The polymer T-3052 is a cationic polyacrylamide with an average molecular weight of 10^7 and a charge density of 20%. The mixing unit was a baffled mixing chamber with a stirrer. The weighed sludge was first placed in the mixing chamber into which the polymer solution

Table 1. ζ-Potential and Floc Size of Ball Clay Slurry at Different Flocculant Doses

Flocculant Dose (g/kg DS)	0	0.2	0.5	1.0	2.0	4.0	6.0
ζ potential (mV)	−22.1	−14.5	−10.2	−2.5	1.2	11.8	14.1
Floc size (μm)	2.4	12.1	32.5	55.2	64.1	154.5	188.4

was gradually poured with 200 rpm of stirring for 5 min followed by 50 rpm for another 20 min. After mixing and before settling, a small quantity of sludge–polymer aggregates in the vessel was carefully transferred into the zeta meter (Zeter-Meter System 3.0, Zeter-Meter Inc., Staunton, VA) and the ζ potentials were measured. Some samples were transferred to a particle sizer (LS230, Beckman Coulter, Inc., Fullerton, CA) for measuring the floc-size distribution using light scattering technique. Table 1 lists the measured ζ-potential data and the floc sizes. Notably, for the original sludge the surface charge was neutralized at a polyelectrolyte dose of approximately 2.0 g/kg of dry solid (DS) for the activated sludge. The floc size increases monotonically with flocculant doses regardless of the occurrence of charge neutralization. Figure 1 shows the microphotograph (200×) of the sludge floc flocculated at 2.0 g/kg DS.

Centrifugal Tests

Figure 2 shows the arm-suspended centrifuge. Transparent plastics make the filter cell, whose inner diameter and length are 4 and 7 cm respectively, clearer for visual observation. A receiving cell of the same size is attached

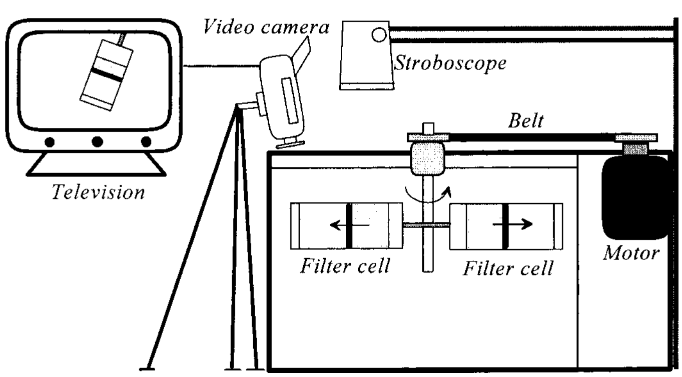

Figure 2. Schematics of centrifugal dewatering device.

beneath the filter cell. A filter medium separated the filter cell and the receiving cell. The filter cell was connected to a rotating arm. The length from the center of rotation to the filter medium was 18.8 cm. The span angle from the center of rotation to the filter medium was measured as approximately 12°. The applied centrifugal field on the suspension thus mimicked a one-dimensional process.

A small amount of the sludge (50 mL) was put into the filter cell. A variable-speed motor drove the belt, where the cell, at a rotational speed in the range 400–1000 rpm, gave acceleration to filter medium at 32–200 g. Moisture in the suspensions was filtered out through the media and was accumulated in the receiving cell. A cake appeared on the filter medium. A stroboscope emitting light synchronized with the rotating cell that "froze" the image of the centrifuged slurry. A video camera recorded the dynamics of all interfaces and the amounts of filtrate with time (16).

RESULTS AND DISCUSSION

Centrifugation Curves: Original Sludge

Figure 3 shows the experimental centrifugation curves for the original sludge. First, consider Fig 3a, which denotes the centrifugation curve for the original sludge at 400 rpm. Owing to the action of centrifugation, the filtrate would flow out of the suspension, with the location of interface gl moving toward, and sc moving away from the septum with time. A clear supernatant appears in the cell. The interface ls moves faster than gl, denoting a strong sedimentation effect. For the original suspension, interface ls merges with sc at approximately 10,000 sec. Restated, suspension filtration and sedimentation occur simultaneously up to 10,000 sec.

Beyond 10,000 sec, the process allows the filtrate to flow through a formed cake. At $t = 15,000$ sec, the interface gl merges with sc, after which the process enters the centrifugal dewatering stage. In accord with the filtrate volume data, approximately 98.7% of the moisture has been removed at this stage. That is, only about 1% of moisture is removed by the centrifugal dewatering stage. Decrease in cake thickness also occurs, which is, however, not apparent for the original sludge.

An increase in the rotational speed to 700 or 1,000 rpm would markedly enhance the moisture removal efficiency. Figure 4 shows the time required for interface gl to merge with sc as a function of rotational speed. The corresponding times the interface gl merges with sc are approximately 7000 and 3500 sec, respectively, only 47 and 23% of that of the original sludge. Since the interface ls moves faster to the septum as the rotational speed increases, a stronger sedimentation effect has been incorporated.

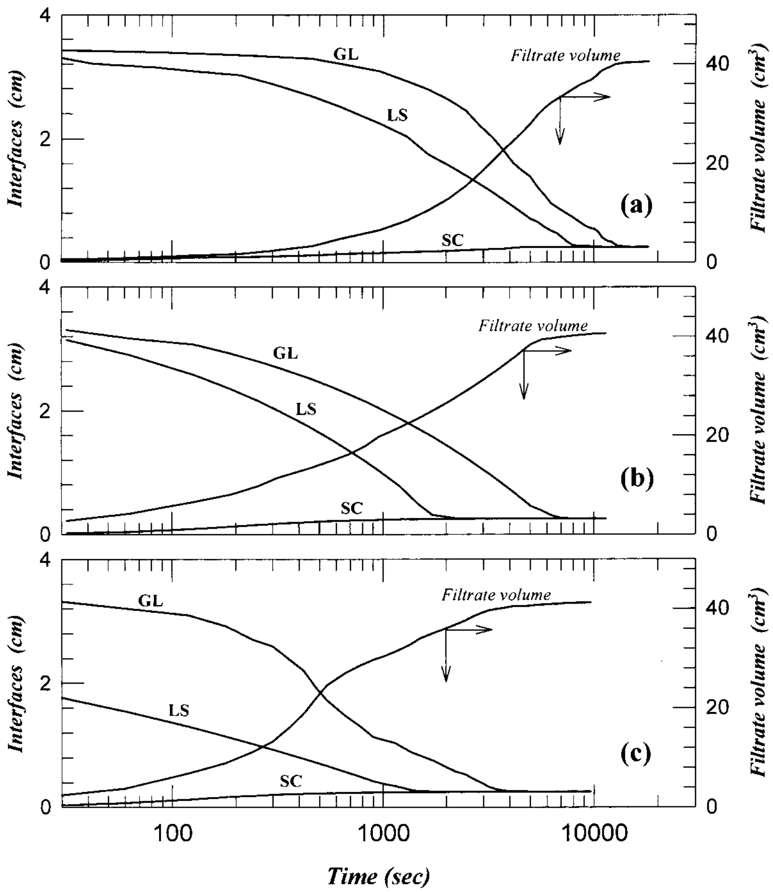

Figure 3. Centrifugation curves of original ball clay slurries under different rotation speeds: (a) $\Omega = 400\,\text{rpm}$, (b) $\Omega = 700\,\text{rpm}$, and (c) $\Omega = 1000\,\text{rpm}$. gl: air–supernatant interface; ls: supernatant–suspension interface; sc: suspension–cake interface.

The cake formed from original slurry deems incompressible under the centrifugal force employed herein. The interface sc increases almost linearly with the filtrate volume over a wide testing period.

Centrifugation Curves: Flocculated Sludge

Figure 5 shows the centrifugation curves at a polyelectrolyte dose to neutralize the surface charge (2 g/kg DS). Figure 6 shows the time evolution of

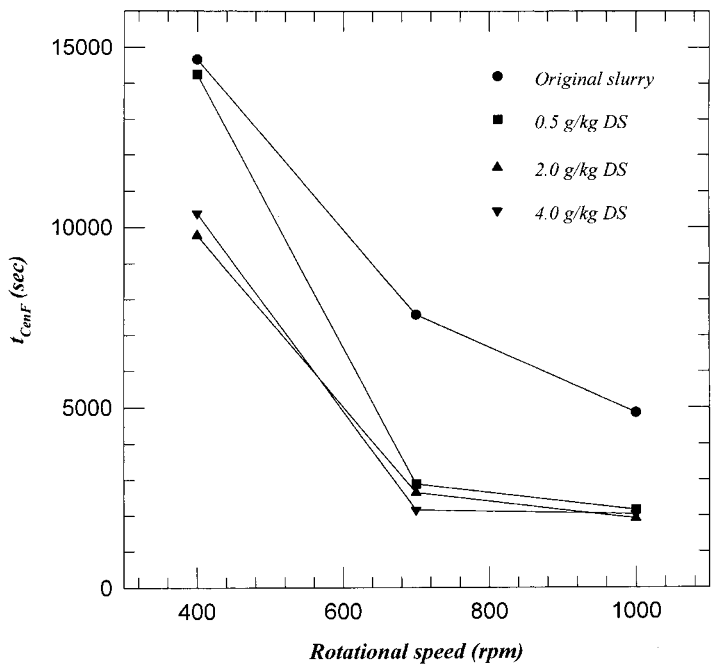

Figure 4. Time required for interface gl to merge with sc as a function of rotational speed.

residual moisture per kilogram of dry solid at different rotation speeds. Black circles denote the point at which the interface gl merges with interface sc.

The basic characteristics for the conditioned sludge resemble those of the original sludge. Nevertheless, there are four distinct points noted for the conditioned sludge compared with the original sludge. First, the moisture removal efficiency for the conditioned sludge has become much higher than that of the original sludge. The interface gl merges with sc at 9000, 2200, and 1800 sec for $\Omega = 400$, 700, and 1000 rpm, respectively. The application of polyelectrolyte is thereby beneficial to centrifugal separation of moisture from the clay sludge.

Secondly, despite the ball clay slurries centrifuged at 400 rpm, the moisture removal rate would first increase with the flocculant dose, after reaching a maximum removal rate at the charge-neutralization dose, and would then decrease when more flocculant is added. The dosage at which surface charge is neutralized hence corresponds to the “optimal” dose for the sludge under centrifugation (the dose at which the sludge has the best centrifugeability). To exceed this dosage dewaterability of the sludge is deteriorated. Such an

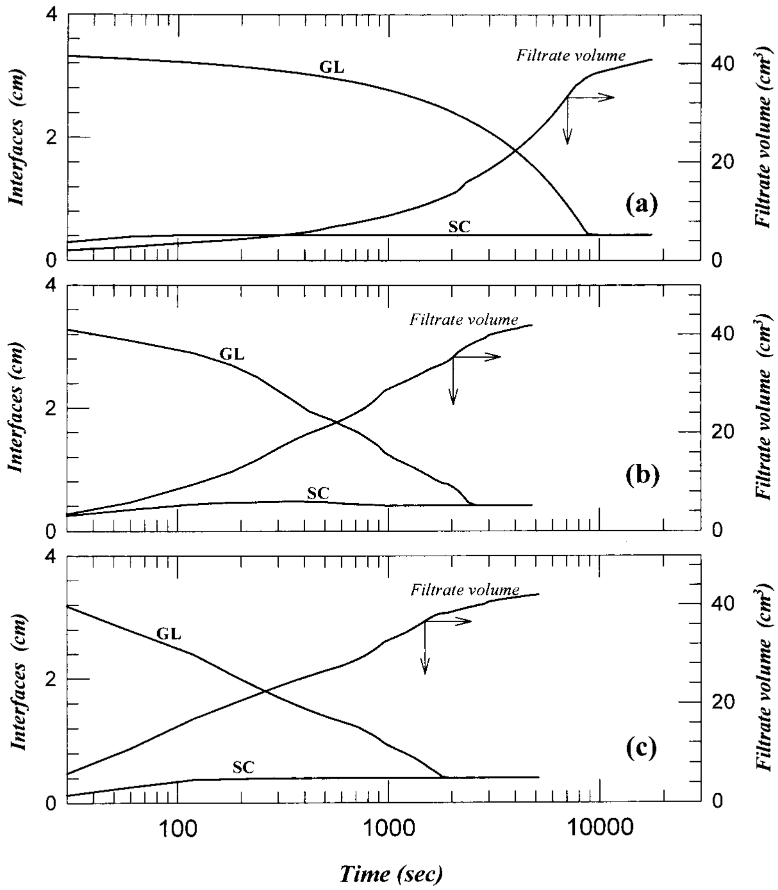

Figure 5. Centrifugation curves of ball clay slurries flocculated at 2.0 g/kg DS under different rotation speeds: (a) $\Omega = 400$ rpm, (b) $\Omega = 700$ rpm, and (c) $\Omega = 1000$ rpm. gl: air–supernatant interface; ls: supernatant–suspension interface; sc: suspension–cake interface.

observation indicates that charge neutralization is a dominant factor for conditioning this sludge. Simply increasing the rotation speed would not necessarily yield a dryer cake.

Thirdly, the sedimentation effect has become too strong to eliminate completely the contribution of centrifugal filtration stage. Restated, as the centrifugation test starts, since the sludge floc has increased from 2.4 μm for the original sludge to 64.1 μm for the conditioned sludge (Table 1), these flocs are noted to move to the filter medium to form a wet cake within 100 sec. The

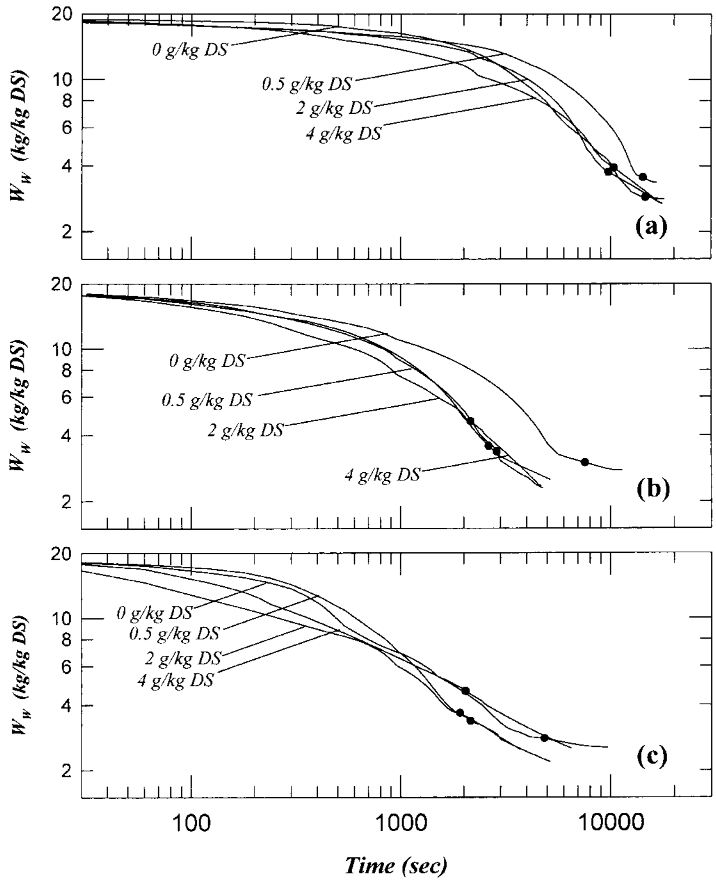

Figure 6. Time evolution of residual water contents of ball clay slurries under different rotation speed: (a) $\Omega = 400$ rpm, (b) $\Omega = 700$ rpm, and (c) $\Omega = 1000$ rpm.

predominant mechanism for moisture removal of conditioned sludge is therefore the supernatant flowing through a porous medium (formed cake). The interface ls could not be detected in these curves. Meanwhile, the residual moisture in the wet cake at the end of filtration is (point where interface gl merges with sc) much higher than that of the original sludge. In accord with the filtrate volume data, about 7% of moisture has been removed by the centrifugal dewatering stage.

Finally, an increase in the rotational speed would not affect the centrifugation curves for a conditioned sludge so markedly as those for the original sludge. Figure 4 also shows the times required for the interface gl to merge with sc for the conditioned sludge. Although an increase in rotational speed is still effective in the enhancement of moisture removal, the reduction in t_{CenF} at a high rotational speed would not be as significant as that noted in the original sludge. Such an observation may be attributed to the increased cake compactibility of the conditioned sludge. Tiller and Kwon (20) discussed the so-called "unexpected behavior" of a highly compactible sludge cake. For an ultra-compactible filter cake, these authors claimed that the filtrate flow rate would not increase with increase in applied pressure. We may expect a similar characteristic during centrifugal filtration process.

A significant sludge-cake collapse is noted during centrifugation for flocculated filter cake. As Fig. 5 shows, the interface sc first increases with time and after reaching a maximum cake thickness, collapse of cake structure occurs in order to reduce the cake thickness.

Centrifugal Filtration of Sludge

Hence the cumulative centrifugal pressure p_{Cent} introduced by the centrifugal force at a rotational speed of Ω could be obtained by integrating the pressure gradients acting in the supernatant, suspension, and the cake, as follows (11):

$$p_{Cent} = \Omega^2 \left[\int_{r_{gl}}^{r_{ls}} \rho_L r \mathrm{d}r + \int_{r_{ls}}^{r_{sc}} \rho_{Slurry} r \mathrm{d}r + \int_{r_{sc}}^{r_{cm}} (\rho_L r + \Delta\rho \epsilon_S r) \mathrm{d}r \right] \qquad (1)$$

where $\Delta\rho$ is the density difference between the solid and the liquid, and ϵ_S is the local solidosity (1-porosity) of the wet cake.

The unknowns to evaluate in Eq. (1) include the distribution of ϵ_S in the cake and that of the slurry density (ρ_{Slurry}) in the centrifuged suspension, which are not available for the present experimental apparatus. We sampled the suspension during some tests, and noted that the solid concentrations in the suspension layer were around the original value (5% w/w). Therefore, ρ_{Slurry} is taken as a constant to simplify the integration. Mass balance of solid phase is conducted to estimate the average solidosity in the wet cake, i.e., (solid in the cake) = (total solid presented in the sludge)−(solid in the suspension). The average cake solidosity is hence estimated and is denoted as the ϵ_S in the cake. Figure 7 depicts the calculated cumulative centrifugal pressure, p_{Cent} (the pressure difference between interfaces gl and filter medium). For the flocculated sludge, the suspension layer may not appear. In such a case $r_{ls} = r_{sc}$ in evaluation of Eq. (1). Black circles denote the point at which centrifugal filtration stage is accomplished. Notably, at the initial phase of centrifugation p_{Cent} is around 10,000 and 66,000 Pa (0.1 and 0.65 atm) at 400 and 1000 rpm, respectively. As the filtration proceeds, p_{Cent} drops rapidly to a plateau value (3000 Pa at 400 rpm

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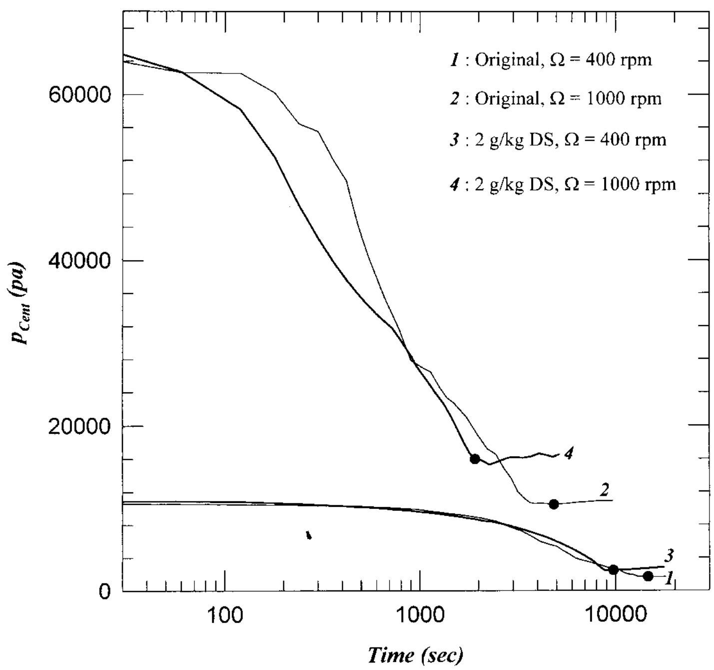

Figure 7. Centrifugal pressure p_{Cent} vs. time t.

and 10,000 Pa at 1000 rpm). Since the flocculated sludge cake exhibits a greater height at equilibrium, its plateau pressure is higher than that of the original sludge.

The sedimentation–filtration stage considers the dewatering prior to the merging between the interfaces ls and sc. The time evolutions of p_{Cent} (Eq. 1) and filtrate volume could be extracted from experimental data, the average cake resistance α_{av} for the wet cake could be determined as follows:

$$\alpha_{\mathrm{av}} = \frac{2p_{\mathrm{Cent}}A^2}{\varpi\mu}\left(\frac{\mathrm{d}t}{\mathrm{d}V_{\mathrm{F}}^2}\right). \tag{2}$$

In Eq. (2), A is the area of filter cell, V_{F} is filtrate volume, μ is the filtrate viscosity, and ϖ is the dry solid weight per unit volume sludge. The time-average resistance of centrifuged cake, $\alpha_{\mathrm{av,CenF}}$, is evaluated as follows:

$$\alpha_{\mathrm{av,CenF}} = \frac{1}{t_{\mathrm{CenF}}}\int_0^{t_{\mathrm{CenF}}} \alpha_{\mathrm{av}}\mathrm{d}t. \tag{3}$$

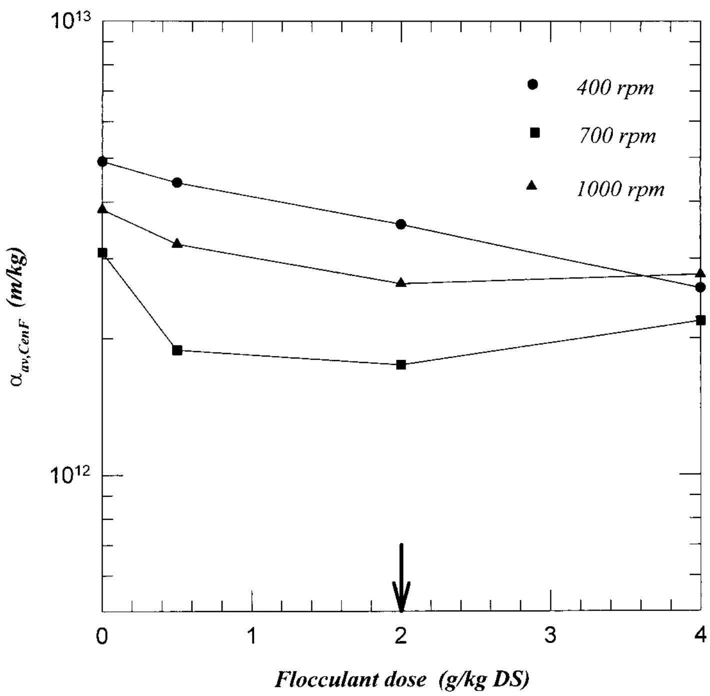

Figure 8. Average cake resistance of filtration $\alpha_{\mathrm{av,CenF}}$ vs. flocculant dose.

Figure 8 shows the calculated results. The arrow denotes the optimal polyelectrolyte dose. Notably, the $\alpha_{\mathrm{av,CenF}}$ is at its minimum value for 700 and 1000 rpm at the optimal dose. Such an occurrence again confirms the predominant role of charge neutralization on centrifugal filtration stage for the present sludge system. Moreover, the $\alpha_{\mathrm{av,CenF}}$ values at 700 rpm are less than those at 400 or 1000 rpm. Restated, there exists an "optimal" rotational speed at which the cake resistance to filtration becomes the least. The cake resistance is taken proportional to the applied pressure and inversely proportional to the filtrate flow rate. The applied pressures during the initial stage at rotational speeds of 400, 700, and 1000 rpm follow approximately the ratio: 1:3:6. The corresponding initial filtrate flow rates for sludge conditioned at 2 g/kg DS are measured as 0.006, 0.019, and 0.022 mL/sec, respectively. To increase the rotational speed from 400 to 700 rpm hence increases the filtrate flow rate to three times at the expense of three times of the applied pressure. However, further increase in the rotational speed from 700 to 1,000 rpm could enhance the filtrate rate only by 20% (resistance hence increases). Detailed mechanisms should involve complicated interactions among particle packing and the subsequent structure changes under centrifugal field. For instance, a higher rotational speed would generate a greater filtrate flow rate, wherein many particles crowded close to the filter medium would produce an open cake structure that exhibits a low cake resistance. However, a loose, open cake structure may not be able to sustain the large centrifugal force acting on it. Cake-structure collapse corresponds to the higher resistance observed at 1,000 rpm. The net effects of the above-mentioned mechanisms thereby yield an optimal rotational speed at 700 rpm.

CONCLUSIONS

This study experimentally investigated the centrifugal separation of moisture from clay slurry subject to cationic polyelectrolyte flocculation. An arm-suspended centrifuge was utilized in this study to fix the filter area to simplify subsequent analysis. An increase in rotational speed could enhance moisture removal to a certain level. However, its contribution is shown to be much less than the application of polyelectrolyte. Original ball clay slurry would form compacted sediment during centrifugation. Flocculation would markedly accelerate the settling rate, by doing so, yielding a loose cake at the initial phase of centrifugation. In centrifugal filtration, the $\alpha_{av,CenF}$ is at its minimum value for 700 and 1000 rpm at the charge-neutralized dose. Moreover, there exists an "optimal" rotational speed at which the cake resistance to filtration becomes the least.

REFERENCES

1. Zeitsch, K. Centrifugal Filtration. In *Solid–Liquid Separation*, 3rd Ed. Butterworth: USA, 1990; Chap. 14, 493–510.
2. Letki, A.G. Know When to Turn to Centrifugal Separation. Chem. Eng. Progr. **1998**, *94* (9), 29–44.
3. Schubert, H. Capillary Forces—Modeling and Application in Particulate Technology. Powder Technol. **1984**, *37*, 105.
4. Vesilind, P.A. Characterizing Sludge for Centrifugal Dewatering. Filtr. Sep. **1977**, *20*, 115–120.
5. Maloney, J.O. Centrifugation. Ind. Eng Chem. **1946**, *38*, 24.
6. Haruni, M.M.; Storrow, J.A. Hydroextraction IV: Radial Distribution of Permeability in Cakes. Chem. Eng. Sci. **1952**, *1*, 154.
7. Grace, H.P. Resistance and Compressibility of Filter Cakes. Chem. Eng. Progr. **1953**, *49*, 303.
8. Kouloheris, A.P.; Meek, R.L. Centrifugal Washing of Solids. Chem. Eng. **1968**, *Sept*., 121–126.

9. Sambuichi, M.; Nakakura, H.; Osasa, K.; Tiller, F.M. Theory of Batchwise Centrifugal Filtration. AIChE J. **1987**, *33*, 109.
10. Tiller, F.M.; Yeh, C.S.; Tsai, C.D.; Chen, W. Generalized Approach to Thickening, Filtration and Sedimentation. Filtr. Sep. **1987**, *24*, 121.
11. Tiller, F.M.; Hsyung, N.B. Unifying the Theory of Thickening, Filtration, and Centrifugation. Water. Sci. Technol. **1993**, *28*, 1.
12. Shih, W.H.; Shih, W.Y.; Kim, S.I.; Aksay, I.A. Equilibrium-State Density Profiles of Centrifuged Cakes. J. Am. Ceram. Soc. **1994**, *77* (2), 540–546.
13. Lotito, V.; Spinosa, L. Sewage Sludge Conditioning by Polyelectrolytes. Filtr. Sep. **1990**, *27* (2), 122–125.
14. Lotito, V.; Mininni, G.; Spinosa, L. Models of Sewage Sludge Conditioning. Water. Sci. Technol. **1990**, *22* (12), 163–172.
15. Spinosa, L.; Lotito, V.; Mininni, G. Evaluation of Sewage Sludge Centrifugability. In *Proceedings of Vth World Filtration Congress*; Nice, France, June 5–8, 1990; Elsevier, 1990; Vol. 2, 327–330.
16. Hwang, K.J.; Chiou, Y.C.; Lu, W.M. Studies on Mechanism of Centrifugal Filtration. In *Proceedings of Symposium on Transport Phenomena and Applications*; Dept. Chem. Eng., National Taiwan University, Taipei, Taiwan, 1994; 387–392.
17. Smiles, D.E. Centrifugal Filtration of Particulate Systems. Chem. Eng. Sci. **1999**, *54*, 215.
18. Hunter, R.J. *Foundations of Colloid Science*; Clarendon Press: London, UK, 1989; Vol. I.
19. Chu, C.P.; Lee, D.J. Moisture Distributions in Sludges: Effects of Cationic Polymer Conditioning. J. Environ. Eng. ASCE **1999**, *125*, 340–345.
20. Tiller, F.M.; Kwon, J.H. The Role of Porosity in Filtration. XIII: Unexpected Behavior of Highly Compactible Cakes. AIChE J. **1998**, *44*, 2159.
21. Karr, P.R.; Keinath, T.M. Limitations of the Specific Resistance and CST Tests for Sludge Dewatering. Filtration and Separation **1978**, *15*, 543–544.

Received November 2000
Revised April 2001