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Energy Requirement of Suspension Dewatering

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Abstract: This work estimated the energy required to dewater a clay suspension, considering the total energy input received by the suspension from the dewatering device, the bond strength between adjacent water and solid surface, and the intra-cake friction loss. The centrifugal dewatering and consolidation dewatering were the testing means, and a UK ball clay suspension coagulated with alum was the testing sample. At the initial stage of centrifugal dewatering, most energy input was used to overcome process irreversibilities other than intra-cake friction, giving low-energy efficiency. To rotate faster or to flocculate at optimal dose needed more energy to dewater. On consolidation, most input energy was consumed to break down the bond strength to a critical residual water content, beyond which the friction loss became dominant. The methods presented herein provided a quantitative index to evaluate the efficiency of real dewatering process from an "ideal" dewatering system.

Keywords: Bond strength, friction, coagulation, centrifugation, consolidation

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INTRODUCTION

Energy consumption rate is an essential parameter determining the economy of suspension dewatering using solid-liquid separation (SLS) device. The knowledge on energy cost for a specific SLS process relies on heuristics and experience. Vesilind (1) stated that the "free water" of suspension is "the water not associated with and not influenced by the suspended solids particles." The mechanical dewatering device could only remove the free water part from the suspension (2, 3). The water adjacent to solid surface reveals distinct behavior from bulk water and is frequently regarded as "bound water" of the suspension (4–7).

To remove water from a suspension one needs to (1) break down the bond strength between the adjacent water and the solid surface; and to (2) convey this water out of the suspension system. To point (1), the water of high water-solid bond strength could be transformed into free water if sufficient disruption energy were supplied from surroundings. To point (2), the "freed" water is needed to overcome fluid friction for draining out from the suspension (the system).

Various methods have been proposed for measuring bound water content. A recent review is available by Vaxelaire and Cezac (8). Chen et al. (9) and Chu and Lee (10) utilized the combined thermogravimetry analysis and differantial thermal analysis (TGA/DAT) to estimate the water-solid bond strength as a function of residual moisture content in sludges. Moreover, the modified Darcy's law was commonly used to describe the intrafloc friction (11). The sum of the bond strength and the associated friction loss presented the theoretically minimum work needed to dewater a suspension.

We estimated the minimum energy requirement to dewater a clay suspension, and evaluated the mechanical work done by a lab-scale centrifuge and a lab-scale consolidation tester for comparison. Information on the energy efficiency during suspension dewatering could be extracted from these tests.

ENERGY DEMAND

Energy Input

The work received by the sludge (solids and water remaining in the dewatering device) from external environment is attributable to the change in volume (V) of sludge under shear:

$$\mathrm{d}E_V = (p_{SYS} + \mathrm{d}p_{SYS})(V + \mathrm{d}V) - p_{SYS}V = p_{SYS}\mathrm{d}V + V\mathrm{d}p_{SYS}, \qquad (1)$$

where p_{SYS} is the system pressure. Therefore, based on the solid volume above unit area of filter, the pressure-volume work could be expressed as follows:

$$E_V = V_S \int_0^{\omega_S} \left[p_{SYS}\left(\frac{\partial e}{\partial \omega}\right) + (1 + e)\left(\frac{\partial p_{SYS}}{\partial \omega}\right) \right] \mathrm{d}\omega, \qquad (2)$$

where V_S is the solid volume; ω is the solid volume coordinate per unit area of filter media, including cake, sediment, and supernatant; e the void ratio; and ω_s is the total solid volume above unit filter medium.

To evaluate Eq. (2) the information on the relationship between e, p_{SYS} and ω is needed, which was evaluated using dewatering models and experimental tests (discussed later).

Bond Strength

The bond strength between water and solid phase, H_B, could be estimated by the TGA/DTA technique proposed by Chen et al. (9), with procedures briefly summarized as follows. The TGA and DTA tests are conducted simultaneously to evaluate the heat flow Q and the mass loss rate (m) of sample. Under thermal equilibrium, the specific enthalpy used in water evaporation could be evaluated by ($\Delta H = Q/m$, kJ/kg). As $\Delta H = \Delta H_{fg}$, the standard enthalpy change for the bulk water, the water evaporated exhibits the same energy level as the bulk water. According to Vesilind (1), this water is the free water of the sample. If, on the other hand, $\Delta H > \Delta H_{fg}$, the difference, ΔH-ΔH_{fg}, should be attributed to the existence of the solid phase of the sample, defined as the bond strength of the moisture (H_B, kJ/kg). The moisture exhibiting greater bond strength would require more enthalpy for being separated from the solid surface. Then the total energy to break down the bond strength to a suspension of moisture content of W is given as follows:

$$E_B = V_S\ \rho_S \int_{\infty}^{W} (-H_B)\mathrm{d}W, \tag{3}$$

where W is the residual moisture in the remaining slurry (cake and suspension), and ρ_S is the solid density.

Friction Loss

The friction loss owing to the intra-cake fluid flow is denoted as E_F. The energy loss attributable to the friction loss could be estimated as follows (12):

$$E_F = A_{SYS} \int_0^{\omega_S} \int_0^{\omega_S} \left(\frac{\mu}{K} q_L\right) \mathrm{d}\omega \mathrm{d}\omega, \tag{4}$$

where A_{SYS} is the filter area, μ is the filtrate viscosity, K the local permeability of cake, and q_L, the internal flow rate.

Hence, to remove the moisture from a slurry system, firstly the adjacent moisture should be separated from the solid phase ($+E_B$). Then the freed moisture should be forced out through the cake by overcoming friction loss

($+E_F$) and other internal irreversibilities. The work lost ($E_V - E_F - E_B$) is owing to other process irreversibilities including friction between cake and device's wall (13), filter medium loss, expansion work by moisture at the drainage port, and others.

EXPERIMENTAL

The Sample

A UK ball clay slurry was the testing material. The particle size distribution of the clay sample was determined by Sedigraph 5100C (Micromeritics) as a monodispersed distribution with a mean diameter of approximately 4.6 μm. The solid density was measured by Accupyc Pycometer 1330 (Micromeritics), giving a measure of 2,584 kg/m^3 with a relative deviation of less than 0.5%.

The suspension was prepared by mixing clay particles with distilled water, with addition of 10^{-1} M $NaClO_4$. The solution pH values were adjusted to 7 by $HClO_4$ and NaOH. The mixing unit was a baffled mixing chamber with a stirrer. The weighed powder was first suspended in distilled water. The concentrated alum solution was then gradually poured into the mixing vessel with 200 rpm of stirring for 5 mins followed by 50 rpm for another 20 mins. Alum dosage ranged from 0 to 80,000 ppm. Clay weight percentage in the suspension was 20%.

TGA/DTA Test

Most experimental details for the TGA/DTA test can be found in Chen et al. (9), which is briefly summarized herein for the sake of completeness. The thermal analyzer (SETARAM, 77A-92) was employed for recording the thermographs with argon (Ar) used as the carrying gas, in which the TGA and DTA tests are conducted simultaneously. From the DTA peak, the energy flow rate into the sample cell can be estimated after calibration. The weight-time data represent the changing rate of sample weight.

The sample was first vacuum filtered to remove part of free water. Next, for the sake of uniformity, the resulting filter cake was completely blended, from which the sludge sample was randomly taken. Under each condition three independent tests were conducted and their average was reported. The sample amount was approximately 10 mg to minimize the possible effects of nonuniform temperature distribution and mass-transfer resistance within the sample body. The temperature was raised from room temperature to a fixed temperature of 80°C. With TGA and DTA data, the bond strength vs. residual moisture content can be calculated. The maximum error for estimating the bond strength was estimated 40 kJ/kg.

Dewatering Test

The arm-suspended centrifuge proposed by Chu and Lee (14) was used in the centrifugal tests. This centrifuge allows direct observation on the filtrate amount and cake thickness under the centrifugal field, hence providing rheological information of the centrifugated cake under stress. The rotational speed ranged from 400–1,000 rpm. The corresponding centrifugal force at cake bottom was estimated at 3,000–10,000 Pa for 400 rpm tests, and 10,000–65,000 Pa for 1000 rpm tests.

A constant head piston press (Triton Electronics Ltd., type 147) was employed in the expression tests. The sludge was placed in a stainless steel cylinder 7.62 cm diameter and 20 cm high. A hydraulic pressure of 2,000–3,000 psi was exerted on the piston to force out the moisture from the sludge sample. The time evolution of the filtrate weight was then automatically recorded by an electronic balance connected to a personal computer. Given these data and the solid density, the time evolution of cake porosity was subsequently obtained. Chang and Lee (15) provided the experimental detail.

RESULTS AND DISCUSSION

TGA/DTA Test

Figure 1 depicts the H_B vs. residual moisture W curves for the alum sludges. The residual moisture contents (W) are directly calculated from the TGA data. The H_B increased when the residual moisture content decreased. At $W > 5$ kg/kg-DS, the bond strength was close to 1 kJ/kg (16). With moisture content less than 0.5 kg/kg-DS, a bond strength exceeding 1,000 kJ/kg was noted, close to that for chemisorption/chemical reaction.

The addition of alum only mildly affected the bond strength of the alum sludge. With 10–40 g/kg-DS dose, the H_B was reduced by up to 100 kJ/kg at $W < 4$ kg/kgDS, indicating that the adjacent water was loosened and became easier to remove by flocculation. Overdosed at 80 g/kg-DS alum would yield the "rebound" of the H_B–W_W curves, probably being attributable to the inclusion of moisture with excess aluminum hydroxides. Nonetheless, the effect of alum addition on H_B is not so significant as that of polyelectrolyte (10).

The H_B curves in Fig. 1 presented the probability density function of the minimum energy required to dewater the alum slurry. If one wished to release 1 kg water in the slurry of moisture content of 4 kg/kg-DS, one needs around 110 kJ for original sludge and less than 45 kJ for 40-g/kg coagulated sludge. Further dewatering to remove 1 kg of moisture from the sludge of 2 kg/kg-DS needs 330 kJ and 250 kJ for the original and the 40-g/kg coagulated sludges, respectively. This amount of energy is close to the standard enthalpy change of water freezing (ca. 320 kJ/kg).

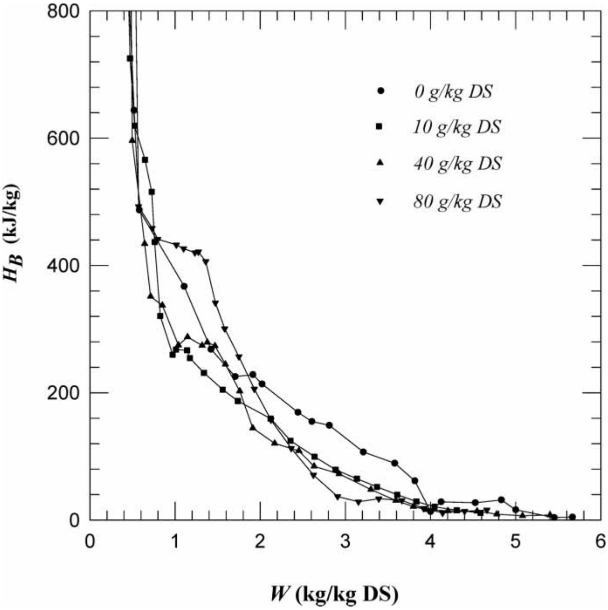

Figure 1. The bond strength H_B for alum coagulated clay suspension.

Centrifugal Dewatering

The centrifugal rate was low for original sludge at 400 rpm centrifugation (Fig. 2a). Increase in centrifugal acceleration or adding alum assisted dewatering rate. Apparently, the dose of 40 g/kg-DS provided the best dewatering rate, while overdosing at 80 g/kg-DS deteriorated the dewatering (Fig. 2b). The "optimal" dose of the present sludge was noted 40 g/kg-DS in the centrifugal test, as mentioned in preceding sections.

During centrifugal dewatering, the centrifugal force (p_{Cent}) could represent the system pressure (p_{SYS}). The centrifugal force acting on the sludge could be estimated as follows (17):

$$p_{Cent} = \Omega^2 \left[\int_{r_{gl}}^{r_{ls}} \rho_L r dr + \int_{r_{ls}}^{r_{sc}} \rho_{Slurry} r dr + \int_{r_{sc}}^{r_{cm}} (\rho_L r + \Delta\rho \varepsilon_S r) dr \right], \qquad (5)$$

where $\Delta\rho$ is the density difference between the solid and the liquid, ε_S is the local solidosity (1-porosity) of the wet cake, and r_{gl}, r_{ls}, r_{sc}, and r_{cm} are the rotational radii of air-supernatant interface, supernatant-suspension interface, the suspension-cake interface, and the cake-media interface, respectively. Substituting Eq. (5) into Eq. (2), the integration yields:

$$E_V = \frac{A_{Cent}\Omega^2}{2} [G_1(t) + G_2(t)] \qquad (6)$$

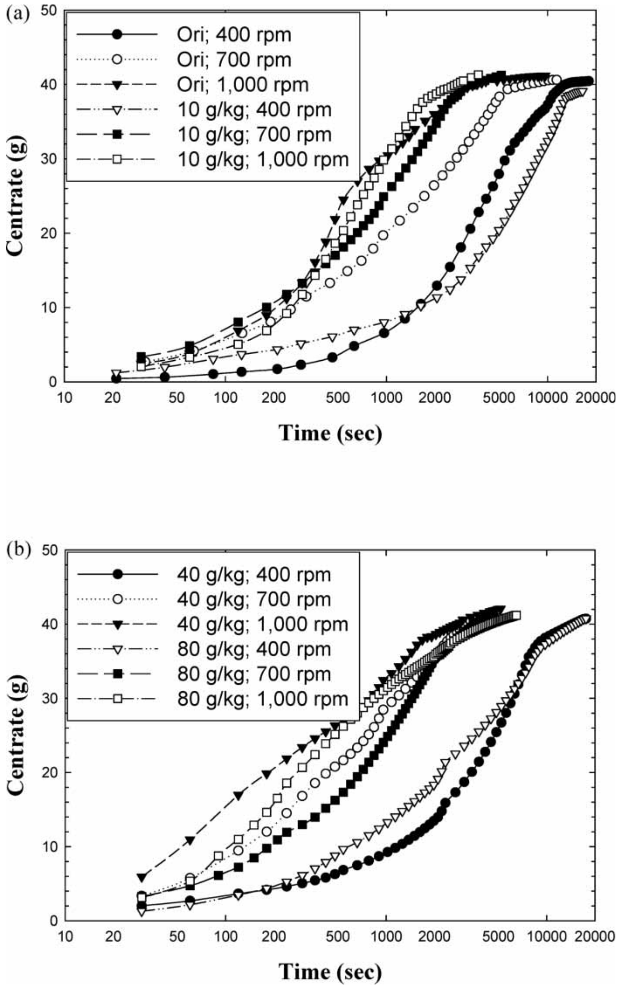

Figure 2. Dewatering curves of centrifugated sludge. (a) Original and 20 g/kg-DS coagulated; (b) 40- and 80-g/kg coagulated.

where A_{Cent} is the filter area, and

$$G_1 = \frac{\begin{array}{c}\rho_L[2r_{gl}^3 + r_{ls}(r_{ls}^2 - 3r_{gl}^2)] + \rho_{Slurry}[2r_{ls}^3 + r_{sc}(r_{sc}^2 - 3r_{ls}^2)] \\ +(\rho_L + \Delta\rho\varepsilon_{S,av})[2r_{sc}^3 + r_{cm}(r_{cm}^2 - 3r_{sc}^2)]\end{array}}{3} \tag{7}$$

$$G_2 = (r_{cm} - r_{gl})[\rho_L(r_{ls}^2 - r_{gl}^2) + \rho_{Slurry}(r_{sc}^2 - r_{ls}^2) + (\rho_L + \Delta\rho\varepsilon_{S,av})(r_{cm}^2 - r_{sc}^2)] \tag{8}$$

$\varepsilon_{S,av}$ is the average solidosity in centrifugated cake, and all interfaces were recorded as functions of time. The differentiation of E_V with respect to W gives the specific P-V work, H_V.

Figure 3 shows the H_V data at centrifugation, with alum dose and centrifugal speed as parameters. The work done by the centrifuge on the sludge increased with increasing centrifugal acceleration and (mildly) with decreasing moisture content. The external work provided by the present centrifuge to remove 1 kg of water from sludge is comparably low, ca. 1 kJ/kg at 400 rpm and 5–6 kJ/kg at 1,000 rpm.

The average permeability of the centrifugated cake could be estimated as follows:

$$K_{av} = \frac{1}{\rho_S \alpha_{av} \varepsilon_{S,av}} \tag{9}$$

where α_{av} is the average specific resistance of centrifugated cake. With the centrate flow rate ($q_1(t)$) obtained and interface positions noted in the centrifugal test, E_F can be estimated as in the following (12):

$$E_F = A_{Cent} \mu \rho_S \alpha_{av} \varepsilon_{S,av} q_1 (r_{cm} - r_{sc})^2 \tag{10}$$

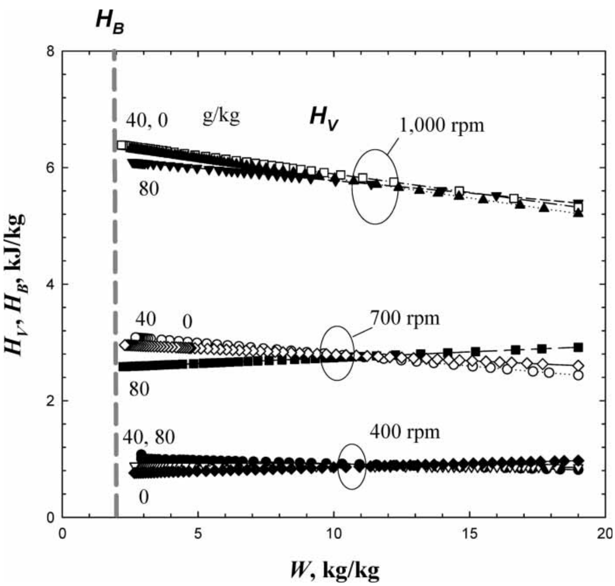

Figure 3. The H_V input during centrifugation and the H_B curves of sludges. The dashed curve presents the experimental data for H_B.

The E_F data thus calculated accounted for lower than 5% of E_V, indicating that most friction loss did not occur in line with intra-cake flow. These data were not shown here for brevity sake.

Consolidation Dewatering

Figure 4 illustrates the expression curves. To remove 280-g, filtrate from the original sludge needed 320 s, while the dose of 20 g/kg-DS alum reduced the corresponding consolidation time to 250 s, depending on the consolidation pressure. Further increasing the dose to 40 g/kg-DS would lead to the best dewaterability, around 95 s to remove 280 g of filtrate at 3,000 psi. Overdosing at 80 g/kg-DS would deteriorate dewaterability, 170 s to remove 280 g of filtrate. The optimal dose identified in consolidation test corresponded to that in centrifugal test (40 g/kg-DS).

In sludge consolidation the solid pressure (p_S) can describe the system pressure p_{SYS}. Shirato et al. (18) analytically derived the distributions of pressure and void ratios in a consolidated cake as follows:

$$p_S = p_{Expr}\left\{1 + \sin\left(\frac{\pi\omega}{2\omega_S}\right)[D_1\exp(h_1 t) + D_2\exp(h_2 t)]\right\} \quad (11)$$

$$e = e_1 - a_E\int_0^t\left(\frac{\partial p_S}{\partial t}\right)\mathrm{d}t - a_C\eta\int_0^{t_{SL}}[p_S\,(\omega,\tau) - p_{S1}]\exp[-\eta(t-\tau)]\mathrm{d}\tau \quad (12)$$

where p_{Expr} is the consolidation pressure and e_1 is the initial void ratio ($t = 0$). Other parameters in Eqs. (11) and (12) are defined as follows:

$$a_E = \frac{1}{\mu\rho_S\alpha_{av,EXP}C_e}, \quad a_C = \varphi a_E, \quad \varphi = \frac{B}{1-B} \quad \text{(13a-c)}$$

$$D_1 = \frac{\pi^2 C_e(\eta + h_1)^2}{4\omega_S^2 h_1[(\eta + h_1)^2 + \beta\eta^2]}, \quad D_2 = \frac{\pi^2 C_e(\eta + h_2)^2}{4\omega_S^2 h_2[(\eta + h_2)^2 + \beta\eta^2]}, \quad \text{(13d-e)}$$

$$h_1 = \frac{-\Psi}{2} - \frac{1}{2}\sqrt{\Psi^2 - \frac{C_e\eta\pi^2}{\omega_S^2}}, \quad h_2 = \frac{-\Psi}{2} + \frac{1}{2}\sqrt{\Psi^2 - \frac{C_e\eta\pi^2}{\omega_S^2}} \quad \text{(13f-g)}$$

$$\Psi = \beta\eta + \eta + \frac{C_e\pi^2}{4\omega_S^2} \quad \text{(13h)}$$

where p_L is the liquid pressure, the B the ratio of secondary consolidation to the total consolidation, and Ce the consolidation coefficient (15).

Substituting Eqs. (11)–(13) into Eq. (2) leads to the following form of E_V:

$$E_V = V_S\{a_E a_C\eta p_{Expr}^2 F_1[F_2 + 1]\cdot[F_2 - D_1 - D_2] - (1 + e_1)p_{Expr}F_2\} \quad (14)$$

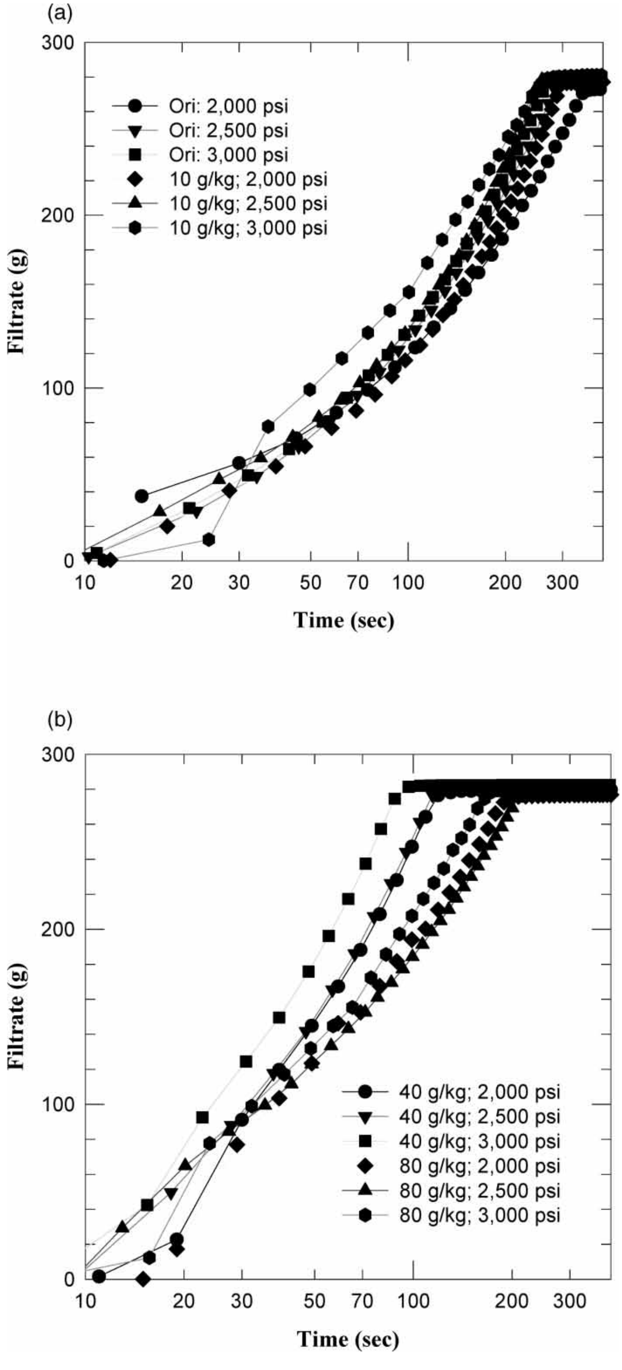

Figure 4. Dewatering curves of consolidated sludge. (a) Original and 20-g/kg coagulated; (b) 40- and 80-g/kg coagulated.

where

$$F_1 = \frac{1 - \exp(-\eta t)}{\eta} + D_1\left[\frac{\exp(h_1 t) - \exp(-\eta t)}{h_1 + \eta}\right] + D_2\left[\frac{\exp(h_2 t) - \exp(-\eta t)}{h_2 + \eta}\right] \tag{15a}$$

$$F_2 = D_1 \exp(h_1 t) + D_2 \exp(h_2 t). \tag{15b}$$

The differentiation of E_V with respect to W gives the specific P-V work, H_V. It is worthy noting that various models describe the rheological behavior of a consolidated cake. However, if only the models could well represent the cake behavior, the corresponding E_V evaluated would be little affected by the model selected.

Figure 5 shows the H_V data under consolidation, with alum dose and consolidation pressure as parameters. The external work done by the piston increased with increasing pressure and with decreasing moisture content. Also, at the optimal dose of 40 g/kg identified in Fig. 4b, the H_V was lower than under- or overdosed regime. At 40-g/kg dose and the consolidation pressure of 2,000 psi, the external work provided by the present consolidation tester was not significant until $W = 0.6$ kg/kg-DS. The 40-g/kg coagulated sludge could hence be easily dewatered to a residual moisture of 0.6 kg/kg using consolidation. For original sludge, on the other hand, to dewater the sludge at 2,000 psi to a moisture content of 0.9 kg/kg-DS needed external work greater than 100 kJ. The present flocculation conditioning was effective to enhance sludge dewaterability by reducing the bond strength between moisture and solid phase.

The friction drag loss could be stated using the Darcy's law as follows:

$$E_F = A_{FIL}\int_0^{\omega_S}\int_0^{\omega_S}\left(-\frac{\partial p_L}{\partial \omega}\right)\mathrm{d}\omega\mathrm{d}\omega = A_{FIL}\int_0^{\omega_S}\int_0^{\omega_S}\left(\frac{\partial p_S}{\partial \omega}\right)\mathrm{d}\omega\mathrm{d}\omega$$

Or equivalently,

$$H_F = \frac{dE_F}{d\omega} = p_{Expr}A_{FIL}F_2 \tag{16}$$

The H_F data thus estimated were lower than 10% of H_V and were thereby not shown in the figures for simplicity.

Discussion

As demonstrated in the present centrifugation and consolidation tests, $H_V > H_F$, indicating that the resistance of internal flow through filter cake was not dominating.

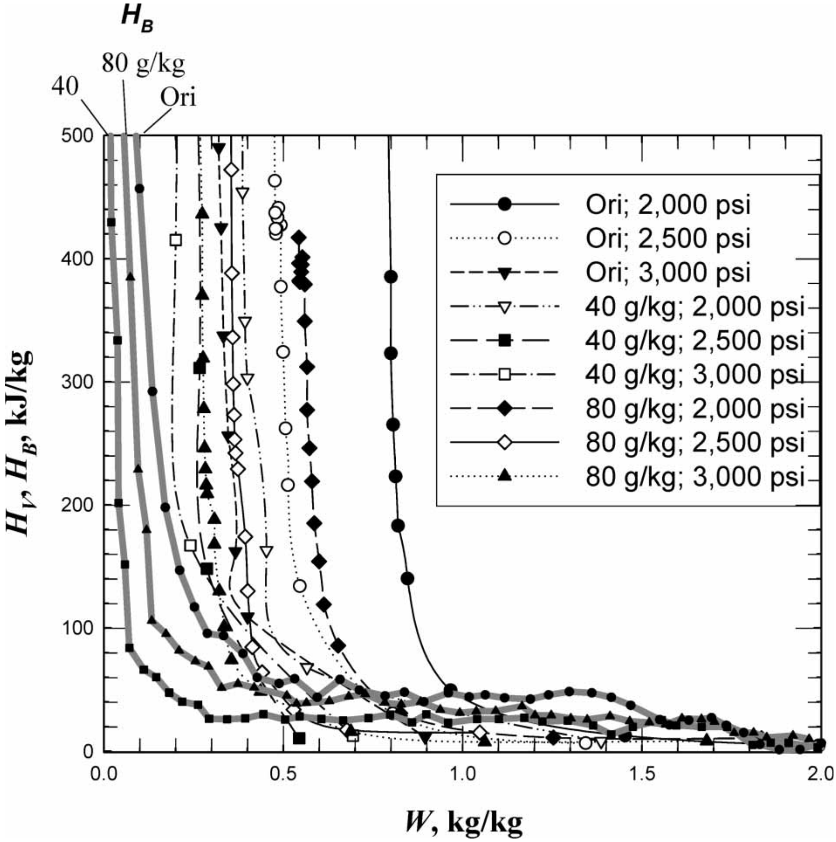

Figure 5. The H_V input during consolidation and the H_B (bold) curves of sludges.

The H_B curves were also plotted on Figs. 3 and 5 for comparison. At the initial stage of centrifugal dewatering, the moisture content was high, corresponding to low H_B. The H_V provided by the centrifuge was even lower. Most energy input was used to overcome process irreversibilities other than intra-cake friction. The dewatering rate was thereby not correlated with $H_B - W$ curve till the later became lower than 2 kg/kg-DS. At higher rotational speed or at the optimal dose of alum the H_V was higher, indicating that greater process irreversibility had occurred. This occurrence was probably attributable to the deterioration of well-developed network structure of optimally flocculated sludge cake under centrifugal field. To release adjacent water from solid surface did not affect dewatering rate under such a circumstance. Since the H_V-W curves exhibit less slope than the H_B-W curve, dewatering ceased at $H_V = H_B$. Moreover, although the dewatering rate was the fastest at optimal dose or at highest rotational speed (Fig. 2), their energy demand may be otherwise maximized. A compromise between process time and energy demand is needed.

The present consolidation tester could provide a much higher H_V on sludge than the tested centrifuge, since p_{Exp} (4000 psi) was much higher than p_{Cent} (0.44–9.7 psi). Depending on the alum dose, the H_B was close to H_V until a critical moisture content was reached. Afterward, $H_V > H_B$. For instance, the H_V for consolidating original sludge at 3,000 psi was close to H_B up to $W = 0.6$ kg/kg-DS, or at 2,000 psi to $W = 1.1$ kg/kg-DS. Therefore, most energy consumed during consolidation test was attributed to releasing adjacent moisture from solid surface. Other process irreversibilities were relatively insignificant. At $W < 0.6$ or 1.1 kg/kg-DS at 3,000 or 2,000 psi, H_V became higher than H_B at lower W. Most energy consumed was attributed to overcome internal frictions and possible particle reorientation. The H_V had become so large that further dewatering using mechanical means below $W = 0.35$ kg/kg-DS was practically impossible. Lee and Hsu (2) regarded this moisture content as the bound water determined using consolidation test. The H_V (or H_B) vs. W curves for flocculated sludge resemble in characteristic to the original sludge. Just as H_B was reduced at optimal dose (40 g/kg), the corresponding H_V curves shifted leftward to the low-W regime. The H_V-W curves followed closely the H_B-W curve at $W > 0.6$ or >0.8 kg/kg-DS under 3,000 or 2,000 psi, respectively. The critical moisture reduced at optimal dose, indicating that the cake became dryer when consolidation reached mechanical equilibrium.

CONCLUSIONS

This study presented an analysis on the energy requirement to dewater a clay suspension, considering the energy input received by the suspension from the dewatering device (E_V), the bond strength between adjacent water and solid surface (E_B), and the intra-cake friction loss (E_F). A UK ball clay suspension, original or alum coagulated, was taken as testing example. The bond strength of water was estimated using the thermal method proposed by Chen et al. (9), with excess enthalpy to evaporate water as the bond strength considered. The friction loss was evaluated using modified Darcy's law, whose evaluation needed information on suspension rheology and dewatering rate as model parameters. We derived the forms of E_V and E_F using centrifugal dewatering and pressure consolidation as demonstration examples.

At the initial stage of centrifugal dewatering, most input energy was used to overcome process irreversibilities other than intra-cake friction, such as cake structure deterioration, leading to a low-energy efficiency. To rotation faster needed higher energy input. Since the present centrifuge could not provide sufficiently high energy, dewatering ceased when the breakdown of bond strength became important in dewatering. On consolidation test, most input energy was consumed to break down bond strength up to a critical residual water content. Further dehydration exceeding this critical water content required extremely high energy input. To consolidate at higher pressure or to coagulate at optimal dose yielded lower critical water content. The methods presented herein could be used to evaluate the efficiency of real dewatering device and how far the system deviated from an "ideal" system.

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