Kirk-Othmer Encyclopedia of Chemical Technology.

DEWATERING

Dewatering is the last process applied to separate water from a solid, unless thermal drying (qv) is used. Dewatering is usually a mechanical process that presses residual water from solids or displaces the water with a gas, and the energy required is negligible compared with the heat required for drying (1). Thus there is a significant incentive for adding a dewatering step to a process. Whereas the broader term deliquoring includes the separation of nonaqueous liquids from solids, the discussion herein is specific to water removal.

In municipal wastewater treatment, dewatering is regarded as the final process used to achieve a water content of $\leq$85% in the sludge (2, 3) or to change the behavior of sludge to that of a solid (4) (see Water, sewage). Many other industries regard 85% water content as *feed* to a primary liquid–solid separation device, such as a thickener, and consider 15% moisture (85% solids) an appropriately dewatered product. Dewatering, then, is not defined by moisture content or by the use of a type of equipment (5).

Maximizing mechanical dewatering is a matter of selecting the most appropriate equipment, optimizing the variables that affect dewatering on the equipment, and optimizing the feed. Optimizing the feed is usually most important. However, if the feed contains a product the properties of which should not be changed or if dewatering is easy, then equipment selection is the most important variable. Selection of equipment is dependent on the particular feed stream, for example, cotton (qv), fruit juices (qv), or sewage, and the field is in constant development. Aids to selecting equipment are found in the literature (see General References). Once the choice of equipment has been narrowed, eg, centrifuges, belt presses, or the like, testing on the equipment is extremely important.

1. Interaction of Water and Solids

Water associates with solids in a range of energies (6). The energy needed for water removal is indicated in Figure 1. The highest dewatering energies are associated with a monolayer or less of water, which is not generally considered moisture content.

Dewatering processes, normally concerned with water bound in capillaries, affect the water and solids by changing the size distribution of capillary radii, reducing adhesion of water to the solids, displacing water from the capillaries, and reducing the energy required to cause flow in the capillaries. These effects are achieved by three methods (1). (*1*) The particulate matrix may be compacted by applying stress, that is, forces can be induced by frictional drag of the liquid as it flows through the pores. Body forces can arise from gravity or centrifugal motion, and boundary stresses can be applied with rolls, membranes, pistons or screw presses, or acoustic energy (see Membrane technology). (*2*) The water may be displaced, usually with a gas, by application of vacuum or pressure. Centrifugal force in a pusher centrifuge also results in the water being displaced by a gas. (*3*) An electrical field may be applied to a slurry of charged particles (6).

Although all the techniques are effective, in industrial applications there is rarely time to achieve an equilibrium reduced saturation state (see Filtration), so variables that affect only the kinetics of dewatering

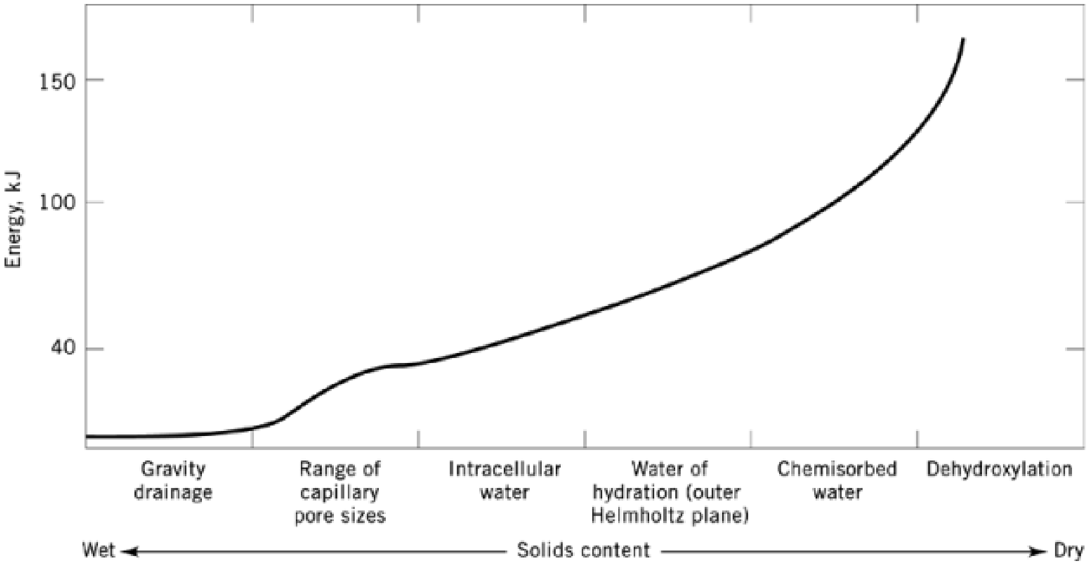

Fig. 1. Energy required for removing 1 mol of water from solids. To convert kJ to kcal, divide by 4.184.

and not the equilibrium and residual moisture are also very important. The most important kinetic variables in displacing the liquid from the solid are increases in pressure differentials and viscosity reduction.

2. Cake Dewatering

The most important function of filtration (qv) is the formation of a filter or centrifuge cake from a slurry (see also Separation, centrifugal). The most important function of dewatering is removal of the liquid from the resulting cake. Theories of cake dewatering are covered elsewhere (7–12). Although theory lags behind practice, the principal variables controlling dewatering have been identified and both dewatering rate as well as equilibrium and residual moisture in fully defined cakes can be predicted. The behavior of relatively incompressible cakes can be modeled using changes in porosity with pressure. For more compressible cakes, empirical models have been developed (13). Theoretical models of expression dewatering of compressible cakes exist (12). Very few industrial applications of dewatering have consistent or fully characterized cakes, and no process in the design stage can fully characterize a filter cake.

Ways to reduce the final moisture content of a centrifuge cake include the use of steam (qv), surfactants (qv), or flocculants (see Flocculating agents), as well as pretreatments by pelletizing, oil agglomeration, thermal treatment, and freeze-thaw processes. The main dewatering variable in the centrifuge itself is centrifugal force sufficient to expel the liquid from the pores in the cake through the filter medium. In some newer centrifuges the pitch of the screw is shortened, applying compression to the cake to further reduce cake pore volume and, with it, entrained water (14). Other basket centrifuge designs incorporate baffles to prevent materials from slipping out of the basket before dewatering (35).

Cake dewatering is related to cake formation; in a filter cake, the final moisture content is dependent on many variables that also control cake formation. Pretreatment processes, for example, affect both cake formation and cake dewatering. Cake dewatering is achieved by compacting the solids; displacing the residual liquid in the cake with another phase, usually a gas; or applying an electrical current to remove the liquid. Each process relies on different properties of the cake.

2.1. Compaction, Compression, and Expression

Compaction is a newer term for compression and is used to describe the movement of particles relative to one another within a device until the matrix of particles gains enough strength to resist further consolidation (16). Compaction occurs in a plate and frame filter both while the chamber is filling and at the end of the cycle when the chamber is nearly full and the pressure rises steeply. Compactibility (or compressibility) describes the reduction in volume of the particle matrix. Compaction also takes place in the bed of a thickener as the solids continuously deposit on the top of the bed and a thickened slurry is withdrawn from the bottom.

Compression virtually always reduces the permeability of the filter cake. The reduced permeability in highly compressible cakes is greatest at the surface of the filter medium, where the pressure drop is greatest. Further dewatering of these cakes in a filter press can be achieved by reversing the flow on a plate-and-frame filter and using the compressed “skin” of filter cake as a membrane to squeeze water from the center of the cake, where pressure differentials are lower (17). Another method of applying compression is by delayed cake formation using continuous pressure filters. These filters easily remove large quantities of water and produce a highly thickened discharge, which sometimes forms a rope as it discharges. Continuous pressure filters can be very effective for thickening dilute slurries and for washing in slurry form (18).

Expression is the application of mechanical stress to a matrix of particles in the fully formed cake (12). Expression, which refers to squeezing the solids rather than the slurry (19), is used to further reduce void space in order to separate more liquid from the solids. Expression dewatering is most effective with compressible cakes (12, 20) of particle sizes below 50 μm (7), superflocculated cakes or cakes otherwise containing loosely entrapped liquid, and organic solids containing liquid-filled cells that must be ruptured for effective dewatering. Filters that use expression include variable-chamber plate-and-frame filters, belt-filter presses, very high pressure belt presses (21, 22), tube presses, and screw presses. Tube presses can exert pressures up to 14 MPa (2000 psi) (23), the highest pressure of any of these expression devices. After pressing, an air-blow step can be added to further reduce the entrained moisture (23). Screw presses are used primarily with fibrous or polymeric materials containing entrapped liquid. Pressures up to 110 MPa (16,000 psi) have been measured in these devices at the points between the screw and screen when solids are present (24).

Significant improvements were made in the 1980s and early 1990s in high capacity, automated variable volume filters that incorporate automatic pressure filtration, expression, washing, and air displacement. Some of the large plate-and-frame automatic presses can operate at up to 2 MPa (ca 285 psig), with up to 100 chambers (25, 26).

If expression is effective, it reduces the permeability of the cake being compacted and, as a consequence, the resistance to flow of the liquid increases considerably (27). The effectiveness of expression is governed by cake thickness, specific resistance, consolidation properties, and shear forces.

2.1.1. Displacement Dewatering

Replacement of the liquid in the voids of a cake by another liquid or a gas is termed displacement dewatering. Air displacement can be accomplished by using a pressure difference to force the liquid from the pores in the cake. The types of filters that provide displacement dewatering include virtually all vacuum filters, rotary pressure disk and drum filters, the Lasta (25), Larox (28), and Vertipress (29) automatic filter presses, hyperbaric filters, tube press filters (23), and a hybrid continuous pressure filter–expression press (30). In a centrifuge, displacement dewatering is accomplished by applying a body force directly to the liquid by the spinning motion. The factors that control displacement dewatering are

Property	Variable
cake	particle size and size distribution, shape, packing, dimensions of the cake
fluid	density, viscosity
interfacial forces	surface tension (gas–liquid), interfacial tension (solid–liquid, gas–solid)
other	temperature, pressure gradient, rate of displacement

in a study on dewatering methods for peat, displacement dewatering was done using acetone, a polar solvent having a lower heat of vaporization than water. Dewatering was improved in terms of both the pressure filtering step and the quantity of heat required. Less heat was required to dry the cake and recover the acetone from the filtrate by distillation (31).

The rate of displacement dewatering increases by increasing the driving force, bed permeability, and filter area, and decreasing viscosity or cake thickness. The dewatered cake becomes drier by increasing the driving force, bed permeability, and the contact angle or decreasing the surface tension. There are a number of techniques to achieve these results.

2.1.2. Expression Dewatering of Fibrous Materials

Fibrous materials are frequently dewatered in belt-filter, screw, disk, and roll presses and in batch pot and cage presses. Table 1 lists applications of screw, roll, and pot presses. Screw and high pressure belt presses are continuous and have replaced batch pot and cage presses in most applications. Traditionally, however, batch presses have been used for squeezing cocoa butter from cocoa beans, which require pressures up to 41 MPa (6000 psi) (39). A description of many types of batch presses is included in Reference 40.

Screw presses (Fig. 2) do not produce a clear liquid product. Frequently, the product is further filtered in a filter press to give a clear liquid product. Press aids are added to feed materials containing fine particles or particles that can deform and plug the slots in the edge of a screw press. Typical press aids include sawdust, rice hulls, perlite, and diatomaceous earth (see Diatomite). A vertical screw press is a continuous press that has been used for dewatering sewage sludge (2).

A disk press, shown in Figure 3, can achieve a compression ratio of about 4:1 and produce a paper pulp having a consistency of 45–50% solids. It has also been used on brewers' spent grains and coffee grounds. The two surfaces of the rotating, converging press disks have a screen backing that retains and presses the solids

Table 1. Applications of Screw, Roll, and Pot Presses[a]

	Liquid, %	
Material	In feed	In product
paper pulp	97	50
	90	65
wood chips	85	50
sugar cane	68	43
oilseeds		
high oil content[b]	>30	3–7
low oil content[c]	<30	3–6
cocoa (separation of cocoa butter)	53	12
food[d]	60–90	10–30
polymers, elastomeric and thermoplastic[e]	60	5–8
rendered tissue	20[f]	6–10
sewage sludge[g]	98	85

[a] Refs. (32–37).

[b] Includes copra, cottonseed, corn germ, peanuts, flax, safflower, sunflower, sesame, palm kernels, and linseed.

[c] Includes soybean, rice bran, and dry-process corn germ.

[d] Includes apples, carrots, coffee grounds, fish, grapes, pineapples, and tomatoes.

[e] Includes ABS, nitriles, styrene–butadiene rubber (SBR), natural rubber, and ethylene–propylene–diene rubber (EPDM).

[f] Fat.

[g] The sludge was steam-heated in the press and treated with CaO and polymer. About 95% of the solids were retained in the cake (38).

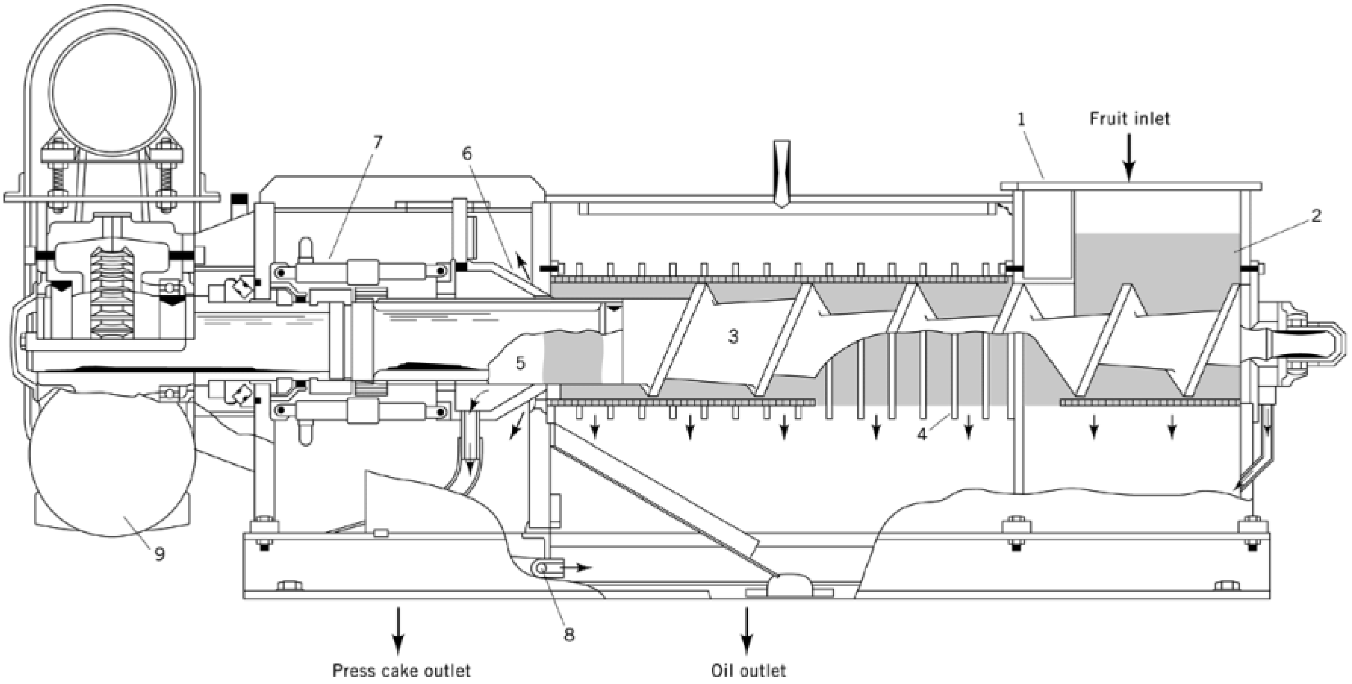

Fig. 2. Cross section of screw press used for fruit juice (32). 1, Hopper; 2, perforated sheets; 3, main shaft; 4, perforated cage; 5, draining cylinder; 6, cone; 7, hydraulic cylinder; 8, draining cylinder oil; 9, gear box.Courtesy of the French Oil Mill Machinery Co.

while letting liquid pass through the screen. Slurry is fed at the wide part of the space between the disks, and the slurry is carried through the maximum compression zone before being released as the disks diverge (41). A similar device, called the shoe rotary press, has been tested on both fine coal and fine coal refuse (42).

A different type of press is the Vari-Nip shown in Figure 4 (43). A slurry is forced into the vat at up to 240 kPa (20 psig). Two porous rolls rotate in a pressurized vat of pulp slurry. As the rolls rotate together into the slurry, the differential pressure across the face of the rolls forces dewatering of the pulp and deposits fibers on the roll faces, forming fiber mats. The pressate, which has passed through the roll perforations, drains to the discharge ports. As the rotation continues, the mat enters the nip areas, and the rolls press the mat together, forcing dewatering to a high consistency. The resulting mat is then guided to a breaker conveyer (43). This press is somewhat similar to drilled press rolls used in paper making (see Paper).

2.2. Improving Cake Dewatering

2.2.1. Viscosity Reduction

Equations relating the rate of liquid flow through a filter cake can be simplified to

$$\frac{V}{A} = \frac{K\Delta P}{\mu l}$$

where V in units of m^3/s is the flow rate through the cake, A in m^2, is the area of the cake, K, m^2, is the cake permeability, ΔP, Pa, is the pressure drop across the cake, l in m, is the thickness of the cake, and μ is the cake viscosity (Darcy's law). Viscosity, a kinetic variable, does not appear in equations describing reduced saturation levels in a cake (44). Because most practical filtration is limited by the time available for the steps of cake forming and dewatering, an increase in the flow rate of filtrate during dewatering translates directly to lower cake moisture levels. If the liquid is water, the viscosity can drop by a factor of three as the temperature rises from 15°C to 80°C, and consequently the flow rate of water through the cake is tripled. The addition of

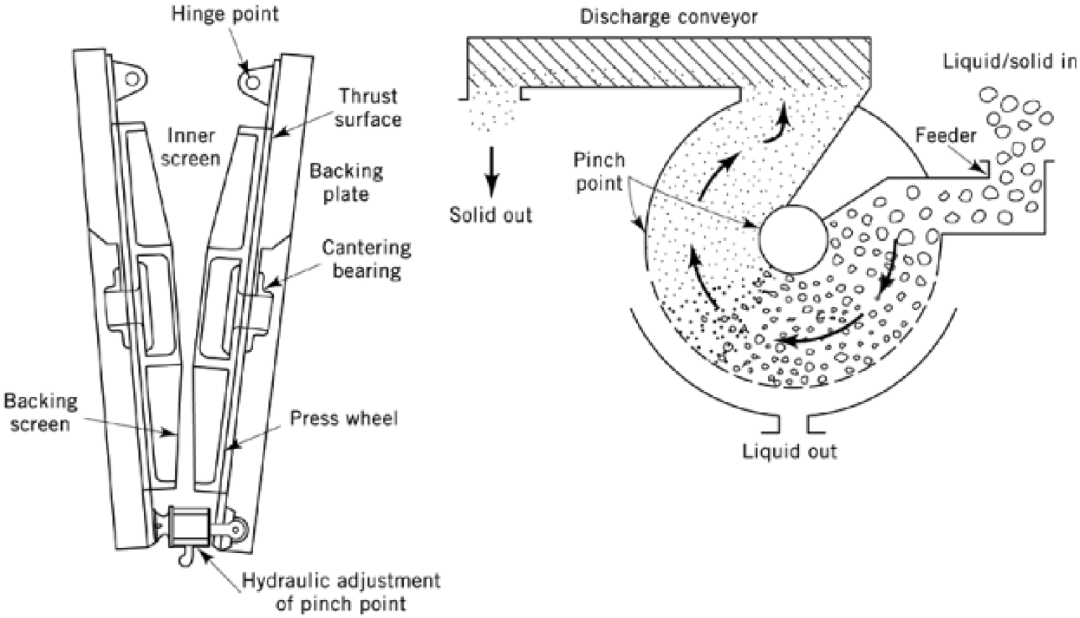

Fig. 3. Schematic of a disk press (41). Courtesy of Bepex Corp., a subsidiary of Berwind Corp.

moderate quantities of salts, polymers, or small amounts of less viscous miscible liquids, such as alcohols, has very little effect on the viscosity of water. Temperature is the most important control of this variable.

The usual method of heating to improve dewatering is to apply low pressure steam to the filter cake as it is in the dewatering phase of the filter cycle. Steam has been used on rotary vacuum filters to dewater fine coal and on horizontal belt filters to dewater pipeline coal. Steaming typically removes an additional 0.7–1.5 kg of water per kilogram of steam applied and reduces moisture levels in coal filter cakes by about 5% (45–47). The effectiveness of steam depends directly on the permeability of the cake. In highly permeable cakes, up to 90% of the contained moisture can be removed. Generally, steam is ineffective on filter cakes in which particles smaller than 10 μm predominate (48). However, permeability is the critical factor: one of the largest installations of steam-assisted filtration is on $<$20 μm nonmagnetic taconites (49).

2.2.2. Use of Surfactants

Although the use of steam to improve dewatering is consistently beneficial, the effects of surfactants on residual moisture are highly inconsistent. Additions of anionic, nonionic, or sometimes cationic surfactants of a few hundredths weight percent of the slurry, 0.02–0.5 kg/t of solids (50), are as effective as viscosity reduction in removing water from a number of filter cakes, including froth-floated coal, metal sulfide concentrates, and fine iron ores (Table 2). A few studies have used both steam and a surfactant on coal and iron ore and found that the effects are additive, giving twice the moisture reduction of either treatment alone (44–46, 49).

Surfactants aid dewatering of filter cakes after the cakes have formed and have very little observed effect on the rate of cake formation. Equations describing the effect of a surfactant show that dewatering is enhanced by lowering the capillary pressure of water in the cake rather than by a kinetic effect. The amount of residual water in a filter cake is related to the capillary forces holding the liquids in the cake. Laplace's equationrelates the capillary pressure (P_c) to surface tension (σ), contact angle of air and liquid on the solid (θ) which is a

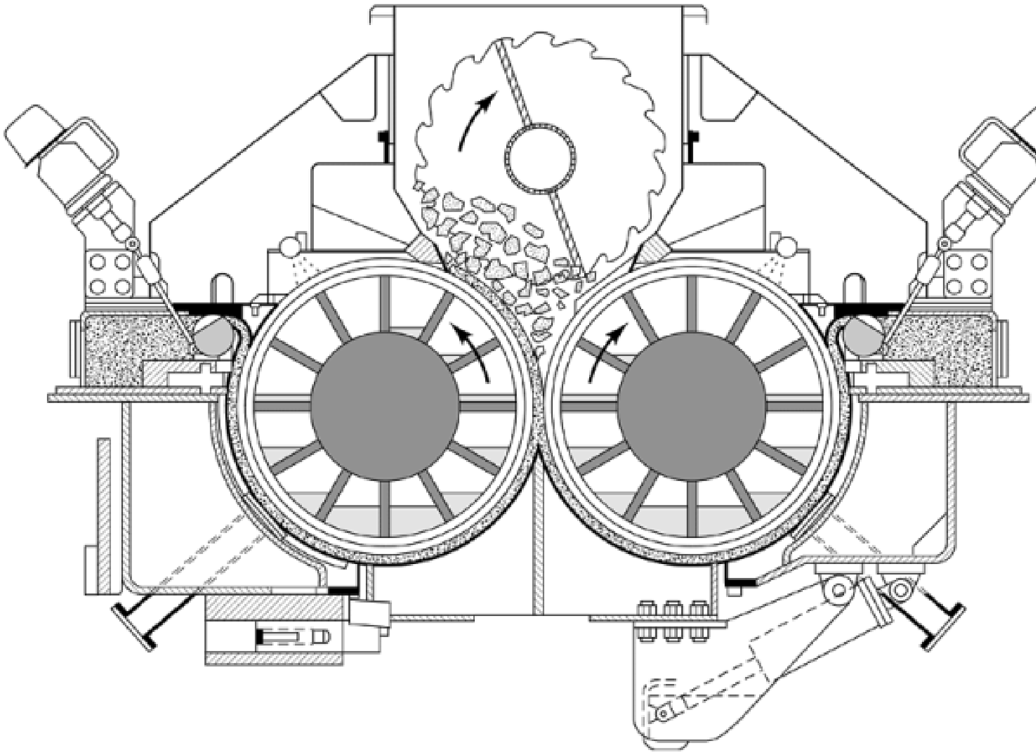

Fig. 4. Schematic of the Vari-Nip press (43). Courtesy of Ingersoll-Rand Co.

measure of wettability, and capillary radius (r_c), or a similar measure applicable to filter cakes.

$$P_c = \frac{2\sigma\cos\theta}{r_c}$$

Table 2. Effect of Surfactants on Residual Moisture in Filter Cakes

	Moisture content, %	
Material	Without surfactant	With surfactant
sulfide flotation concentrates[a]	15	12
	12	9
iron ore	17	15
	21	17
coal	20–22	16
	36–40	30–34
	6	9
silica sand	12	8

[a] $CuFeS_2$, MoS_2, and ZnS.

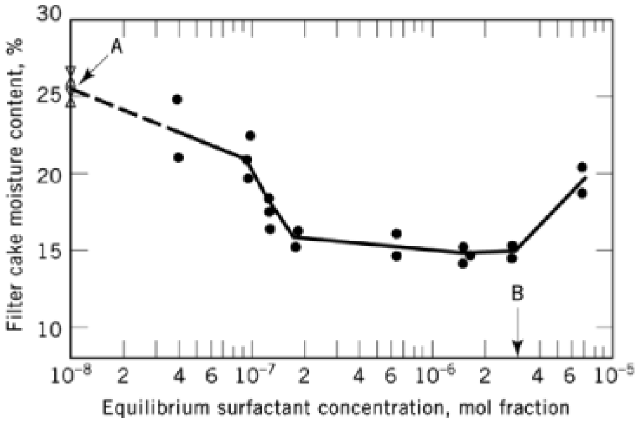

Fig. 5. Effect of surfactant concentration on moisture content of $<500\ \mu m$ coal filter cake (51). Point A represents zero surfactant concentration; Point B, the critical micelle concentration (CMC).

Surfactants lower the surface tension of water, typically from 72 to ca 30–35 mN/m (= dyn/cm), and many surfactants have a strong effect on the contact angle when used at low concentrations. Both changes help dewatering. Too much surfactant, near or above the *critical micelle concentration* (*CMC*), reverses the effect that the surfactant has on contact angle at lower concentrations, and at or above the CMC there is no further lowering of surface tension. At the higher concentrations, the surfactant loses some of its beneficial effect on dewatering, as shown in Figure 5. The beneficial effects of surfactants on dewatering are most pronounced in cakes that have been partially deslimed or in cakes of partially hydrophobic particles (eg, flotation concentrates) that are adsorbed onto each other. Surfactants at or above CMC have little practical effect on extremely fine cakes, where pores are small and the cake has no further opportunity to consolidate. A number of filter cakes do not respond to surfactant addition at any level.

2.2.3. pH Adjustment

Virtually all solids become charged in water, either by reaction with the water to form surface hydroxyl groups that can ionize or by adsorption of ions from the water. The charges on the particles affect how much water is bound to the particle. Reducing the charge on the particle increases the amount of dewatering possible in conventional dewatering equipment. For example, adjusting the pH of peat to approximately 3 increases dewatering, and reducing the charge on coal using pH and metal ions improves the results of pressure and vacuum filtration (2, 52, 53). When an electrical field is externally applied for dewatering, the effect of the charge changes.

2.2.4. Use of Flocculants

In the minerals industry and in water treatment (see Water, municipal water treatment), the primary purpose of flocculants is to improve sedimentation rates and overflow clarity in thickening operations. Flocculants can also have a beneficial effect on dewatering in a filter or centrifuge. Generally, the flocculants that work best on sedimentation are not the best for filtration. For example, large, loose flocs are effective in causing rapid settling but trap water in the filter cake and can deform easily and block the filter medium. Any excess polymer may stick to the filter medium, causing further blinding (54).

Other flocculants are capable of improving filtration rates up to 100 times, especially of fine clay, sludges, or tailings (55). One of the main uses of flocculants in filtration is to make extremely slow filtering slurries filterable at reasonable rates. In addition, flocculants are critical in making belt-filter presses and dewatering

Floc characteristics	Beneficial effects
small	reduces intrafloccular water in the late stages of filtration; reduces pickup problems resulting from gravity settling in the rotary filter chamber
strong	prevents floc breakdown owing to suspending agitation in the filter tank; resists collapse and premature loss of cake permeability in the early interfloccular stage of filtration
equisized	prevents localized breakthrough of air, cake shrinkage, cracking, and early loss of vacuum
good fines capture (into floc structure)	provides good filtrate clarity; prevents cloth binding and poor discharge

centrifuges effective. There are extensive and helpful reviews on the selection of flocculants and the effects on the performance of dewatering devices (1, 56–59). In municipal sludge processing, where often no flocculant is added to the primary thickening devices, flocculants are subsequently chosen to improve dewatering rates.

Although filtration rates can be much faster with flocculants, the final cake moisture is often higher in a flocculated cake (60–63). In contrast, using flocculants optimized for filtration, coal, and other mineral slurries can be dewatered to moisture contents significantly lower than the untreated cake (64–68). The advantages of rapid filtration rates can also be preserved. Flocculants that provide better filtration tend to form flocs having the following characteristics (65):

Pumping a polymer-flocculated slurry to a filter degrades or destroys the floccules. To repair the damage, other flocculants, chosen for their optimum filtration characteristics (68), can be added. For example, to filter froth-floated coal (nominally $<0.5-\mathrm{mm}$ particle size), a medium molecular-weight anionic flocculant (average molecular weight of 10^7) is used. For sedimentation, much higher molecular-weight polymers are more effective (64, 65).

In addition to specifying molecular weight, the chemical structure of polyacrylamide flocculants has a significant effect on final moisture content. Two references (59, 65) show the marked effects of both chemical structure and molecular weight on filtration rates and are useful guides to flocculant selection for coal- and clay-containing fine slurries (Fig. 6). Further dewatering of a flocculated filter cake can be achieved by using a surfactant dewatering aid, as described. The effectiveness of surfactants as dewatering aids seems neither to impair nor be impaired by the flocculant (65). Additions of 1–5 kg/t of an insoluble but highly water-absorbable polyacrylamide superabsorbent to a very sticky coal fines filter cake convert the material from a glue to a friable material that can be handled in normal material handling equipment (66) (see also Water-soluble-polymers).

2.2.5. Sludge Conditioning

Sludge conditioning is the chemical, physical, or heat treatment of wastewater sludges to improve dewatering (2, 3, 69–71). Because sludge handling costs can be 25–50% of the total cost of wastewater treatment, dewatering is critical to cost control. A number of substances have been added to thickened sludge to increase the permeability of the filter or centrifuge cake. In addition to polymer flocculants, coagulants such as ferric and ferrous chloride, alum, and lime have been added, which chemically react in the sludge and improve dewatering. Diatomaceous earth, fly ash, and ash derived from incinerating dewatered sludge or bark have been added as body feeds to improve sludge dewatering.

Biological processing of sludge reduces the amount of sludge needing dewatering and changes the dewatering properties. The changes are not always helpful. A comparison of high biological oxidation of wastewater sludges, to minimize the amount of sludge that needed disposal, showed higher overall disposal costs compared with the costs of less oxidation and twice as much “wasting” (removal and disposal) of sludge (72). In an unusual application of biological conditioning, enzymes have been used to aid in the dewatering of phosphatic clay ponds (73).

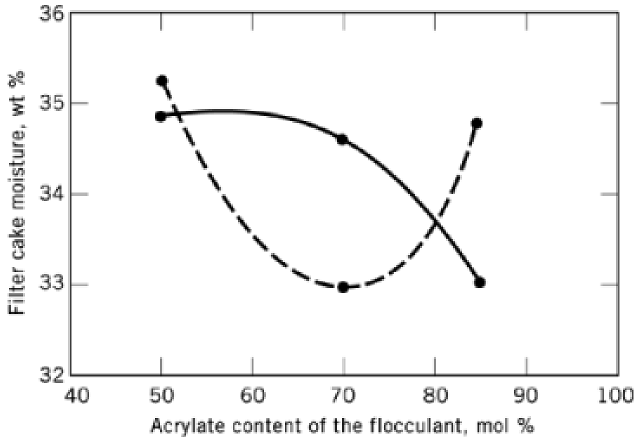

Fig. 6. Effect of acrylate content on coal refuse filter-cake moisture (59): (—), the effect on a longer chain flocculant (mol wt of $_{8\times10^5}$); (— — —), shorter chain flocculant (mol wt of $_{2.5\times10^6}$). Concentration of flocculant is 150 g/t.

Table 3. Comparison of Filters on Aerobically Digested Sludges[a]

>	Belt-filter press		Filter press			
Property	Standard	Vacuum-assisted	Plates[b]	Cloth[b]	Rotary vacuum filter	Centrifuge
cake produced, % solids	12–20	14–25	35–50	35–50	3–6	
operating pressure, MPa[c]	[d]	[d]	0.7–1.4	0.7–1.4	0.1[e]	2000–3000 g[f]
relative space requirements	2.6	2.6	3.0	3.0	1.0	
relative cost, $[e]	2.2	2.8	3.0	5.2	1.0	
maximum size[e], m^2	60	60	400	60	100	
usual sludge conditioning	polymer	polymer	chemical and filter aid	chemical and filter aid	chemical and filter aid	polymer, 0–10 kg/t

[a] Ref. 69.
[b] Movable parts.
[c] MPa unless otherwise noted. To convert MPa to psi, multiply by 145.
[d] Gravity plus pressure rolls.
[e] Values given are approximate.
[f] Values are in units of gravitational acceleration.

The Hi-Compact mechanical dewatering process of Humboldt Wedag takes advantage of sludge conditioning to achieve a high degree of secondary dewatering of highly compressible sludges. The sludge is first flocculated and settled. The thickened sludge is then chopped into pellets that are coated with an incompressible filter aid, such as ash, fine coal, or another material. The coated pellets are then compressed in a batch press at about 5000 kPa (50 atm) to remove 60% of the remaining water. The incompressible coating on the pellets provides a network of channels for the expressed water to follow out of the pressed cake (74).

Comparisons are available on the relative performance and costs for dewatering municipal sludges (2). The relative performance of different filters and conditioners on waste sludges is shown in Table 3. The same sludge was treated on two belt-filter presses, two different centrifuges, and rotary vacuum filter (75). In another study, a variable chamber filter press, fixed-volume filter press, continuous belt-filter press, and rotary vacuum filter were compared for performance, capacity, and capital and operating costs (69).

Figure 7 shows the ranges of solids content achieved by various dewatering methods. The high solids centrifuges can achieve the same or higher solids content achieved by belt presses on municipal sludges. For

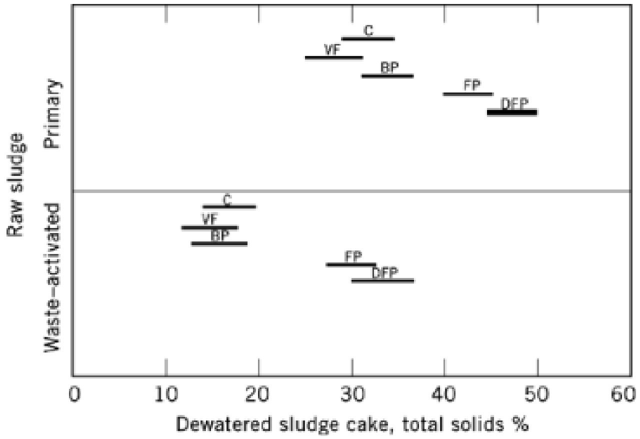

Fig. 7. Solids content of sludges dewatered by C, solid bowl centrifuge; VF, vacuum filter; BP, belt press; FP, filter press, and DFP, diaphragm filter press (2).

recommended test procedures and expected results, consult References (2, 3), and (69–71). Particle size is the most important variable in dewatering municipal sludges (25) and is directly related to many of the other variables correlated with moisture content (76). The amount of $<5\ \mu$ particles is the largest variable, other than the nature of the sludge itself, in determining dewatering behavior (2).

2.3. Use of Mechanical Vibration

Vibration of the sludge or cake can further release entrapped moisture. Pretreatment of organic sludges and highly hydrated inorganic sludges using ultrasonic energy reduced by half the amount of polyelectrolyte polymer needed to achieve the same moisture content of the dewatered cake (77). Vibration of thixotropic slurries improved dewatering on a vacuum filter by breaking up trapped air and improving capillary channels (78). Other devices use ultrasonics to break up loose agglomerates, often of cosmetics (qv), so that these pass through a strainer (79).

3. Less Common Commercial Dewatering Processes

When solids dewatering is known to be a problem early in the process-design stage of a plant or is serious enough to warrant consideration of a range of dewatering alternatives, two approaches are available, and both can be used together. First, processes that begin the dewatering process while in the original suspension may be used. A second approach is to extract water or apply unusual desaturating forces to water present in sludges and cakes.

3.1. Agglomeration of Suspended Solids

3.1.1. Pelletizing Precipitation

Typical, cold, soda lime water softening generates a 5–15% soupy calcium carbonate sludge, which has been dumped into lagoons for disposal. By controlling reaction conditions of lime and hard water and providing for recirculating seeds of sand or calcium carbonate, precipitation of the carbonate can be controlled to form on the sand and to grow to 1.5-mm tight pellets. The pellets dewater by draining to less than 10% moisture (80, 81).

Control of crystal growth and crystal habit is used to improve dewatering in the production of phosphoric acid and in scrubbing of flue gas with lime (82, 83). In each process, a precipitate of gypsum is formed. The most frequent applications of crystal growth regulation are to prevent scaling and to control freezing, for example, of trainloads of coal. The chemical principles are similar.

Additions of new flocculants after conventional thickening produce further dewatering of mineral slimes. A clay flocculated with polyacrylamides and rotated in a drum can produce a growth of compact kaolin pellets (84), which can easily be wet-screened and dewatered. A device called a Dehydrum, which flocculates and pelletizes thickened sludges into round, 3-mm pellets, was developed for this purpose. Several units reported in commercial operation in Japan thicken fine refuse from coal-preparation plants. The product contains 50% moisture, compared with 3% solids fed into the Dehydrum from the thickener underflow (85). In Poland, commercial use of the process to treat coal fines has been reported (86), and is said to compare favorably both economically and technically to thickening and vacuum filtration.

The U.S. Bureau of Mines has run large-scale tests on a similar process for treating $<600-\mu$m coal tailings. The tailings of a flotation cell are treated at a concentration of 3–7% solids. After mixing the slurry with 0.14 kg of polyethylene oxide flocculant per metric ton of dry solids and working for less than 30 s, the solids dewater to 50–70% moisture (87, 88). The process has been demonstrated at a rate of 2300 L/min of waste slurry. Waste phosphate slimes have been similarly successfully consolidated from 4% to 40% solids (87, 89). Mechanisms of flocculation in concentrated suspensions have been studied relatively little; however, conditions favoring pelletizing flocculation are described for colloidal latex suspensions (90).

Other applications include dewatering extremely fine (0.1 μm) laterite leach tailings (91). These pelletizing processes should be compared in flocculant consumption and operating and capital costs with belt-filter presses.

3.1.2. Oil Agglomeration

Pelletizing can also be accomplished using chemicals which make hydrophilic particles hydrophobic and thus agglomerate the particles into tight hydrophobic clusters (92, 93). These processes, eg, Cattermole and Murex, were first used to make selective separations of a relatively minor amount of sulfide minerals (1–2%) in a slurry containing mostly silicates and carbonates. A more recent agglomeration process that was selective for coal added Freon to a slurry of <30 μm coal and mineral matter. The Freon caused the fine coal to agglomerate into large pellets that were recovered from the slurry on coarse static screens. The only remaining water was occluded in the pellets. The Freon, with its low heat capacity and boiling point (24°C), was recovered in a dryer (94).

A successful variation of oil agglomeration was used for removal and dewatering of soot from a 1–3% solids suspension consisting of $<5-\mu$m particles in refinery process waters (Fig. 8). Heavy oil was added to the dilute slurry and intensely agitated in a multistage mixer. The soot agglomerated with the oil to form 3–5 mm pellets that were easily screened from the water (95). The pellets contained only 5–10% water. The process was modified to recover very fine clean coal, and it produced highly uniform, hard, spherical pellets 1–2 mm in diameter.

This process has been applied to certain mineral oxides. Examples include recovery of cassiterite, SnO_2, from silicates (96), gold from ores (97), and ilmenite, $FeTiO_2$, from silicates (98). In each case, the normally hydrophilic mineral was treated with a surfactant (often a fatty acid) under conditions that would selectively coat the desired mineral. Additional oil is then added to agglomerate the treated minerals. Because of the cost of added reagent, the particles should have some intrinsic value. If no excess oil is added, but enough reagent is added and highly agitated, the pelletizing process is known as shear flocculation (99–101).

Another modification of dewatering methods using oil-agglomeration techniques combines the water exclusion of agglomeration with the ability of froth flotation to thicken. *Dissolved air flotation* (*DAF*) or induced air flotation (102) is used in over 300 municipalities for thickening wastewater solids and is also used at a much larger number of oil-well sites, refineries, and food-processing and rendering plants for removal of oil from

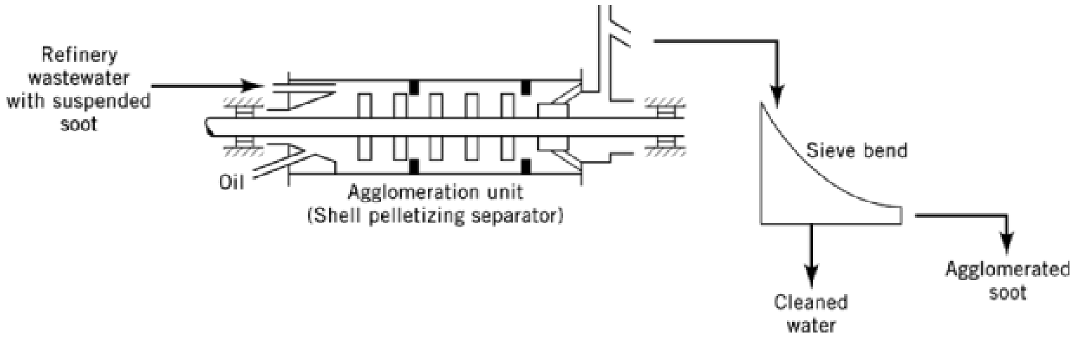

Fig. 8. Shell pelletizing separator (92).

wastewater. For oily wastes, or for selective removal of oily solids, DAF works very effectively. Typically, however, the thickened product contains only 2–4% solids. Because of poor performance, high energy consumption, and problems with controlling volatile organic gases and odors in the excess air, use as a thickening device is declining in favor of centrifuges and belt presses. On food and industrial wastes, as a separator of oily wastes, DAF usage is strong. Preceding the operation with oil agglomeration or shear flocculation is particularly useful for inorganic particles finer than 15 μm.

3.2. Extraction Processes

3.2.1. Oil-Phase Extraction

In processes of dewatering by wetting a solid with an immiscible phase, another step in water displacement is possible. The use of very large quantities of an immiscible liquid allows extraction or transfer of the particles from one phase into the other, and the particles remain in a dispersed state in the new phase. To extract solids (as small as 0.1 μm) from water, a hydrophobic surface on the solid is needed. This surface is usually provided by using flotation reagents such as long-chain fatty acids, alkyl sulfonates, amines, or xanthates. Conversely, water has been used to agglomerate and extract hydrophilic solids that are dispersed in inorganic liquids (103). Crud, a concentration of solids at the liquid–liquid interface in normal solvent extraction, represents partial extraction (104). Pigment flushing is a technique used in paint (qv) and ink (qv) manufacture for transferring paint particles from an aqueous solution, where formation takes place, to a dispersed state in a nonaqueous carrier (105, 106). Because the pigments (qv) are first filtered to remove soluble salts but are not dried before dispersion in the oil phase, the process function includes dewatering. Similarly, a process for manufacturing ferrofluids (stable dispersions of submicrometer magnetite in kerosene) consists of precipitating magnetite from water, adding oleic acid to coat the fine precipitate, and then contacting the wet filter cake with kerosene. The magnetite transfers into the kerosene and forms a stable suspension (107).

3.2.2. Solvent Extraction of the Liquid

Water contained in a cake or slurry can be extracted from the solids by dissolving the water in a solvent that is less expensive to evaporate than the contained water alone. The Institute of Gas Technology (IGT) has developed a laboratory process called solvent dewatering based on the principle that the solubility of water in selected solvents changes significantly with a change in temperature. In one example, hot solvent is mixed with wet peat and the water–solvent solution is then decanted. Upon cooling, the water precipitates as a separate phase (108). As of this writing, the process has not proved economical. The Resource Conservation Company has used chilled triethylamine (TEA) to dissolve water from sludge, and then warmed the extracted liquid to form an immiscible water phase. The effect of temperature on water solubility is opposite to the IGT solvent.

TEA requires only 309 kJ/kg (129 Btu/lb) to evaporate, less than water (93, 109). Similar processes have been considered for desalination (see Water, supply and desalination).

3.3. Thermal Processes

3.3.1. Thermal Drying

The solvent-extraction processes discussed have progressively included evaporation (qv). In this aspect, the Carver-Greenfield process of multiple-effect evaporation of water from sludges is an important alternative to very late stage dewatering. Organic sludges of about 20% solids are fed to the unit, along with enough oil to keep the sludge moving in the processing equipment. Using three effects in the evaporators, only 700–900 kJ/kg (300–387 Btu/lb) of evaporated water are required, compared with the 2.3 MJ/kg (1000 Btu/lb) needed in a single-effect evaporator (38 + 110) (see Drying). A plant using this process to treat municipal wastewater sludges began operations in 1991 in Ocean County, New Jersey.

3.3.2. Thermal Treatment

A number of dewatering processes alter the interaction of solid with liquid. Most depend on making a hydrophilic solid hydrophobic by adding small quantities of surfactants and oils. Many biological sludges cannot be economically treated with reagents to provide hydrophobicity, and such treatments would have no effect on water bound inside the mycelium. Thermal treatment is intended for these organic sludges. Partial wet-air oxidation lowers the specific cake resistance of many biological gels and colloidal sludges by 50–100 times. For example, if a municipal sludge that normally thickens to 5% solids is successfully thermally treated, it thickens to 10–15% solids. On filtering the thickened sludge, the cake formed from the untreated sludge has about 15% solids. The thermally treated sludge can be filtered to 30–50% solids (2, 111).

Thermal treatment consists of heating the sludge under a pressure of about 2.4 MPa (350 psi) and to temperatures of 150–225°C (111) for 15–40 min either with (low pressure oxidation) or without (heat treatment) additional air (2). Reactions, including partial oxidation, occur that change the nature and consume 1–5% of the solids. Unfortunately, this process produces significant quantities of acetic acid and other short-chain, soluble organics. Whereas in 1979 there were over 100 installations operating on sewage sludge, in 1992, because of improvements in mechanical dewatering processes, only 30 to 35 remain.

At least five related dewatering processes have been applied to peat and lignite. Peat and lignite have a high absorbed-moisture content (90% in peat and 40–50% water in lignite) and have a tendency to break down to undesirable fines and to become pyrophoric when dried (see Lignite and brown coal). Steam drying comprises a family of processes very different from steam dewatering of filter cakes. These processes involve heating the peat or lignite containing the initial water content in an autoclave to temperatures of 150–200°C under pressures of about 1.3 MPa (189 psi) for about 15 min. This treatment causes the solids to shrink, eliminating water from pores and removing carboxylic acid and its salts from the surface. The steam treatment itself, considered separately from subsequent evaporative flashing, allows 30–50% of the initial water to drain or be pressure filtered from the product (112). Higher temperature and pressure lead to greater dewatering, and pressures up to 10 MPa (1500 psi) have been tested (113). These high pressures produce a completely dewatered lignite having high stability and little tendency to reabsorb moisture.

The only commercially used process in this group is the Fleissner process, developed in 1927 for drying lignite. One plant, operating in Austria between 1927 and 1960, achieved a capacity of 1700 t/d. In 1982, a number of other plants licensed by Fleissner were operating (114). There were also related processes in the pilot-plant stage (95, 113–116), including one for dewatering peat with a capacity of 50,000 metric tons per year (117).

By raising the pressure, temperature, and available oxygen, virtually all the organic solids can be oxidized to CO_2 and H_2O. Ignition occurs at 200–225°C and wet-air oxidation is then autogenous. At 250–300°C, reactions occur rapidly. The vapor pressure of water at 300°C is about 9 MPa (1300 psi). Rather than needing

25–30% solids to achieve autogenous combustion of a sludge in air, only 0.5–1% organics in water is needed for autogenous wet-air oxidation (118). In *supercritical water oxidation* (*SCWO*), the temperature and pressure are raised still further to the critical point of water, 374°C and 22 MPa (3190 psi), which completely burns sewage sludge and toxic organics (119–121).

3.3.3. Freeze–Thaw Dewatering

Slow freezing of hydroxide, clay, and municipal sludges affects the water-retention properties of the solids when the frozen slurry is thawed. Two plants used this process on water-treatment sludges. The sludge is gelatinous aluminum hydroxide with organic and inorganic matter that typically thickens to 1–3% solids. In tests in the United Kingdom, the sludge, after a cycle of freezing and thawing, became a sandy, granular material that drained without needing a filter. A few small plants use freeze–thaw dewatering for municipal wastewater sludges (3–7% solids) and achieve a solids content of 25% with natural drainage after thawing the frozen sludge (2). The probable mechanisms of dewatering by freezing have been described (12). The ability to withstand freeze–thaw cycling is an important consideration in latex-paint manufacture (106). Similar considerations must be important in some frozen-food formulations (see Food processing).

3.3.4. Freeze Crystallization

Freezing may be used to form pure ice crystals, which are then removed from the slurry by screens sized to pass the fine solids but to catch the crystals and leave behind a more concentrated slurry. The process has been considered mostly for solutions, not suspensions. However, freeze crystallization has been tested for concentrating orange juice where solids are present (see Fruit juices). Commercial applications include fruit juices, coffee, beer, wine (qv), and vinegar (qv). A test on milk was begun in 1989 (123). Freeze crystallization has concentrated pulp and paper black liquor from 6% to 30% dissolved solids and showed energy savings of over 75% compared with multiple-effect evaporation. Only 35–46 kJ/kg (15–20 Btu/lb) of water removed was consumed in the process (124).

3.3.5. Clathrate Freezing

Clathrate freezing uses methane or ethane under pressure, where 1 mol of ethane traps 18 mol of water. Methane clathrates apparently can form in natural gas pipelines at room temperature. The process has been studied for dewatering wastewater treatment sludge, using Freon 11 (125). It has also been considered for removing water from the black liquor derived in the Kraft pulping process for making paper fiber.

3.4. Capillary Suction Processes

The force needed to remove water from capillaries increases proportionately with a decrease in capillary radius, exceeding 1400 kPa (200 psi) in a 1-μm-diameter capillary. Some attempts have been made to use this force as a way to dewater sludges and cakes by providing smaller dry capillaries to suck up the water (27). Sectors of a vacuum filter have been made of microporous ceramic, which conducts the moisture from the cake into the sector and removes the water on the inside by vacuum. Pore size is sufficiently small that the difference in pressure during vacuum is insufficient to displace water from the sector material, thus allowing a smaller vacuum pump to be effective (126).

3.5. Electromagnetic Processes

3.5.1. Electrical Enhancement of Dewatering

Electrophoresis (qv) can be used to prevent a filter cake from forming on a filter medium while allowing water to pass through the medium from the slurry. Electrophoresis is used to move the particles upstream, opposite to the liquid movement, in order to prevent blinding of the medium.

Table 4. Effect of Particle Size on Capillary Retention Force

	Diameter, μm				
Parameter	50	20	15	12	1
$r_c = 0.165d/2$, μm	4.125	1.65	1.24	0.99	0.0825
P_c[a], kPa[b]	35.5	88.2	117	147	1760
P_E[c], kPa[b]				17.2	2430

[a] $P_c = 2\sigma\cos\theta/r_c$, capillary pressure.
[b] To convert kPa to psi, multiply by 0.145.
[c] P_E = electrical pressure.

Once a matrix of particles is formed, whether filter cake, thickened underflow, or soil, applying a current to the fluid causes a movement of ions in the water and, with the ions, water of hydration. The phenomenon is called electroosmosis. The pressure generated on the fluid is given by (127):

$$P = \frac{2\zeta ED}{\pi r^2}$$

where P = pressure in Pa; ζ = zeta potential in V; E = electric field in V/m; D = dielectric constant; r = radius of capillary in m. The amount of water moved is proportional to the intensity and time that power is applied, proportional to the zeta potential of the solid, and inversely proportional to the conductivity of the fluid (128). Results are often measured in kWh/t of dewatered product or in kWh/t of water removed.

High pressures are generated in the small capillary openings. Unlike pressure generated on a fluid by an externally applied force, however, the largest forces are generated at the shear plane of the liquid and the solid in the pores. The effect of a particle size on capillary retention force is shown in Table 4 (26). To calculate the pore radius used in the table, it is assumed that the pore is a cylinder that can just pass between three monosized spheres. The entries following P_E are the pressures developed by electroosmosis in those same pores, assuming a field of 3000 V/m. To generate that field in an electrolyte, a current of 600 A/m^2 must flow, and, in this case, it is assumed to be created in a 10^{-4} M, 1:1 electrolyte (0.2 S/m conductivity) (129).

In most applications, far less current and lower voltages are used. For example, in dewatering clay soils to stabilize dams, foundations, or dredged spoil, 20–100 V/m are commonly applied (130, 131). In soil stabilization (qv), power is applied for weeks to months.

The effectiveness and costs of electroosmotic dewatering on a large number of clay-containing tailings from metallic, nonmetallic, and coal mines has been shown (132, 133). The process can be used *in situ* or in a batch dewatering cell. One large test dewatered a very old, stable, 50% solid slime generated by a coal-washing plant. Applying 37 kWh/t of the final product, moisture was reduced to 19% in 24 h. Using a batch dewatering cell, 1100 t/week of slimes were dewatered (132). There is interest in using the technique to dewater hazardous waste sludge ponds before excavating. In the Netherlands, electroosmosis is used for *in situ* washing of metals from the soil.

3.5.2. Electroosmosis with Vibration

A commercially available *electroacoustic dewatering* (*EAD*) filter combines ultrasonic vibration of the cake with electroosmosis of water in the cake to achieve greater dewatering. Figure 9 shows a 2-m wide commercial machine developed for processing the cakes produced by conventional dewatering methods. The electrical current provides the force to move the liquid; an appropriate level of ultrasonic agitation helps to consolidate the cake, releases trapped gases and liquids, and maintains a liquid continuum for current to low. Typically, half the remaining water is removed from the dewatered cake fed to the EAD filter (135).

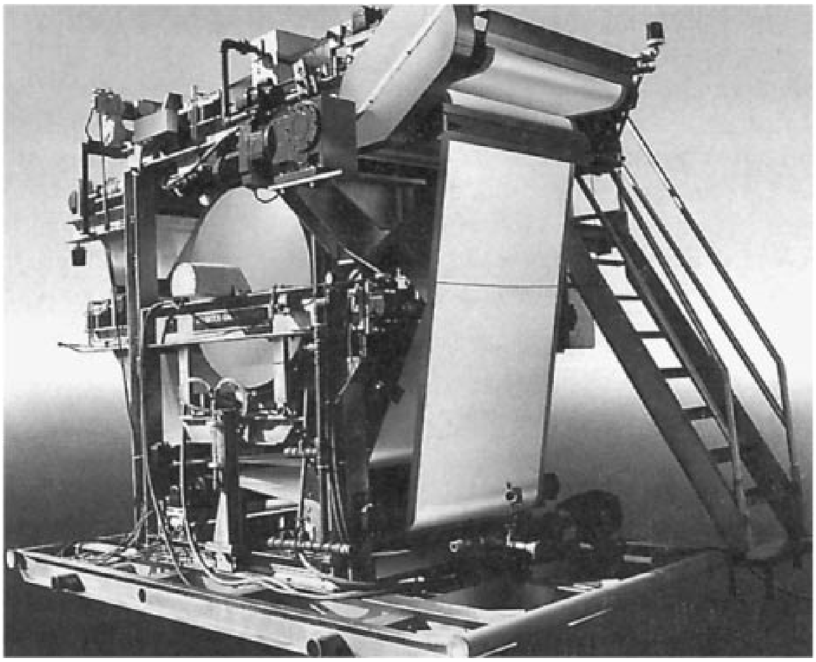

Fig. 9. Two-meter wide electroacoustic dewatering press (134). Courtesy of Ashbrook-Simon-Hartley (134).

3.6. Magnetic Enhancement of Dewatering

3.6.1. Liquid–Solid Separation

When magnetic forces are considered for liquid–solid separations, it is usually for thickening and filtration rather than for dewatering. The Frantz Ferrofilter, commonly used to remove suspended ferromagnetic impurities from liquids, is somewhat analogous to a depth filter in its use of multiple collection sites and lack of a definable porous filter medium surface (135). The Ferrofilter principle has been extended to very large magnetized volumes of 1.7 m^3 and at high fields, from 0.15 T (1500 gauss) for the Ferrofilter to 2.0 T (2×10^4 gauss) for the new machines. The large, high gradient magnetic filters use a depth filter medium of 430 stainless-steel wool to form high gradients in the high field. Commercially, these are widely used for removing paramagnetic impurities from kaolin (136), and new superconducting magnets are now also commercially used (137). Less intense versions are used to separate and dewater magnetic iron ores and nonferromagnetic iron ores, for example, itabirite, and other ores containing specular hematite (138, 139).

Large-volume magnetic separators have been used to remove 90% of the suspended mill scale solids in steel rolling-mill wastewater, and for cleanup of steam-boiler water (see Separation, magnetic). A much wider range of potential uses of magnetic separation for clarifying, filtering, and dewatering is possible when nonmagnetic impurities are made magnetic. In Japan, plating wastes with dissolved Cr, Mn, Cu, Zn, Cd, and so on, have been precipitated as magnetic ferrites (qv) and recovered from the wastewater with a simple magnetic separator. Details of this commercial process have been reported (140, 141).

A simple separator used to recover the magnetic particles consists of a series of disks mounted on a shaft. Each disk has a number of permanent magnets mounted flush with the surface at its perimeter. The disks rotate into and out of the liquid containing the suspended magnetic material and lift the magnetic particles out of the stream. The magnets are then scraped clean (Fig. 10). Very low residence times are needed for removal of the particles compared to settling or flotation (142).

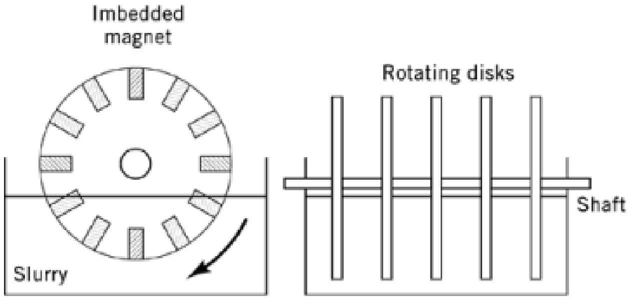

Fig. 10. Rotating magnetic-disk separator (142).

Adsorption of nonmagnetic suspended materials onto magnetic seeds has been proposed and tested for removal of suspended solids from drinking water (143) and of bacteria from municipal wastewater effluent. Using aluminum sulfate as a coagulant and 100–1000 ppm of magnetite, 80–90% of the suspended solids were removed (144). In laboratory experiments, 0.1% of magnetite was added to sewage, and the magnetite quickly became coated with biological flocs. These settled under the influence of a fairly weak magnetic field of 0.04 T in 4% of the time required for settling the untreated feed. The authors estimated that this would allow a fourfold increase in flow rate, a fivefold decrease in sludge volume, and an effluent with half the normal BOD content over normal waste-water treatment (146).

At least one study has specifically evaluated the use of a high gradient magnetic separator for dewatering a paramagnetic mineral slurry, malachite, $CuCO_3 \cdot Cu(OH)_2$, of an average particle size of 4 μm. Initial slurries of 2–12% solids were passed through the magnetic matrix and allowed to drain. When the field was turned off, the mineral could be successfully washed off the matrix to give a 40% solid slurry (146).

Finally, selective separation and dewatering of one suspended substance in a slurry containing different minerals or precipitates is possible by selectively adsorbing a magnetic material (usually hydrophobic) onto a solid that is also naturally or chemically conditioned to a hydrophobic state. This process (Murex) was used on both sulfide ores and some oxides (145). More recently, hydrocarbon-based ferrofluids were tested and shown to selectively adsorb on coal from slurries of coal and mineral matter, allowing magnetic recovery (147). Copper and zinc sulfides were similarly recoverable as a dewatered product from waste-rock slurries (148).

4. Economic Aspects

Dewatering, a part of the liquid–solid separation equipment and supplies market, is not well segmented. The same equipment is often used for both separation and dewatering. The larger market for U.S. industrial and municipal liquid–solid separation equipment, not including disposable cartridges or membranes or high purity electronic or pharmaceuticals filtration, has been estimated at $1 billion for 1991 (149). Earlier estimates of the European market were $1.2 billion in 1988. Municipal water and wastewater treatment accounts for about $300 million, the largest segment, followed by the chemicals and allied industries segment, at $160 million. Other market segments are pulp and paper, general manufacturing, food and beverages, mineral processing, and oil and gas exploration and production, and electric utilities.

The market for filter equipment alone was about $580 million in 1991 (149), and pressure filters are on the order of $115–$160 million of the total filter market. About 500 U.S. companies manufacture liquid–solid separation equipment. Some of the manufacturers in this worldwide business include Ametek, Anderson International Corp., Arus-Andritz Inc., Ashbrook-Simon-Hartley, Bird Machine Co., Inc., Bepex Corp., Black Clawson, Centrifugal and Mechanical Industries, Denver Process Equipment Co., Dorr-Oliver Inc., Ebara

Infilco, Envirex Inc., Eimco Process Equipment Co., Hitachi Plant Engineering and Construction Co., Ltd., Infilco-Degremont Inc., Ingersoll Rand Co., JWI Inc., KHD Humboldt Wedag, Krauss-Maffei Corp., Komline-Sanderson Engineering Corp., Kurita Machinery Manufacturing Co., Ltd., Larox Oy, Mitsubishi Kakoki Kaisha, Ltd., Rosenmund Inc., Sharples Division, Alfa-Laval Separation Inc., Sparkler Filters Inc., U.S. Filter, Wemco, and Zimpro-Passavant Environmental Systems Inc.

Flocculants and coagulantsare sometimes used as pretreatments before dewatering. The market for flocculants and coagulants for water and wastewater treatment in the United States for 1989 was about $250 million, or 68,000 t, provided by 18 companies. In Europe, 22,000 t of flocculants and coagulants, made by 15 companies, had a market value of $115 million. In Japan, 12 companies made 23,000 t, valued at $184 million (150).

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