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Characterization of sludges — Good practice of sludge dewatering

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National foreword

This Published Document is the UK implementation of CEN/TR 16456:2013.

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Characterization of sludges - Good practice of sludge dewatering

Caractérisation des boues - Bonnes pratiques pour la déshydratation des boues

Charakterisierung von Schlämmen - Gute fachliche Praxis der Schlammentwässerung

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Foreword

This document (CEN/TR 16456:2013) has been prepared by Technical Committee CEN/TC 308 “Characterization of sludges”, the secretariat of which is held by AFNOR.

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Introduction

Sludge processing train is a major problem in water and wastewater treatment, as it can account for up to 50 % of total operating costs. The effectiveness and cost of sludge treatment and disposal operations are strongly affected by its volume and, consequently, by its water content or solids concentration. Thickening and dewatering are therefore important steps in the total sludge processing train and have serious impact on subsequent operations.

For illustration, Figure 1 shows the existing solutions for sludge water content reduction, and Figure 2 shows the level of dry matter content required for intended utilisation and disposal routes.

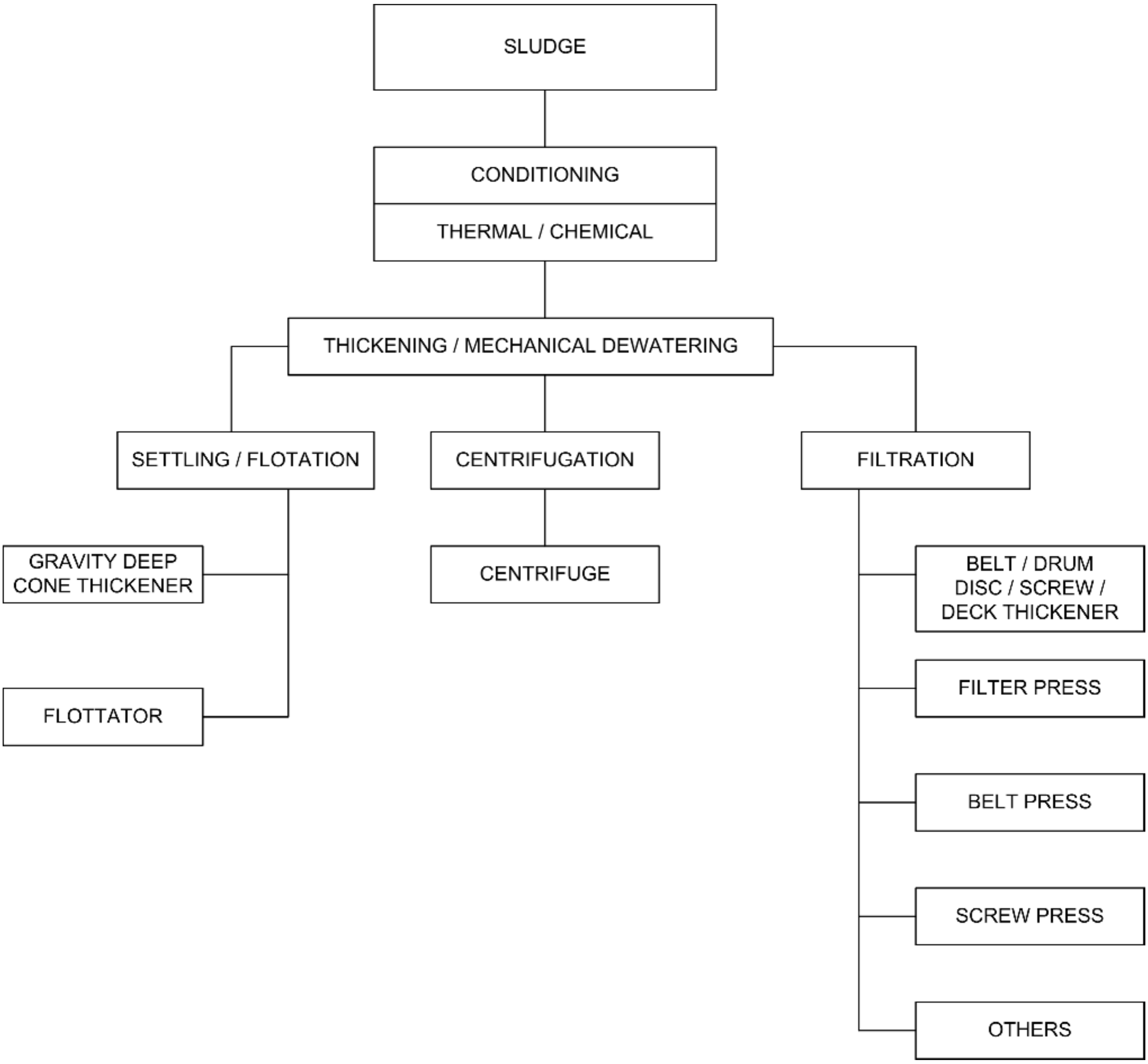


Figure 1 — Principal thickening / dewatering processes

This guide deals with the dewatering and thickening techniques quoted in Figure 1.

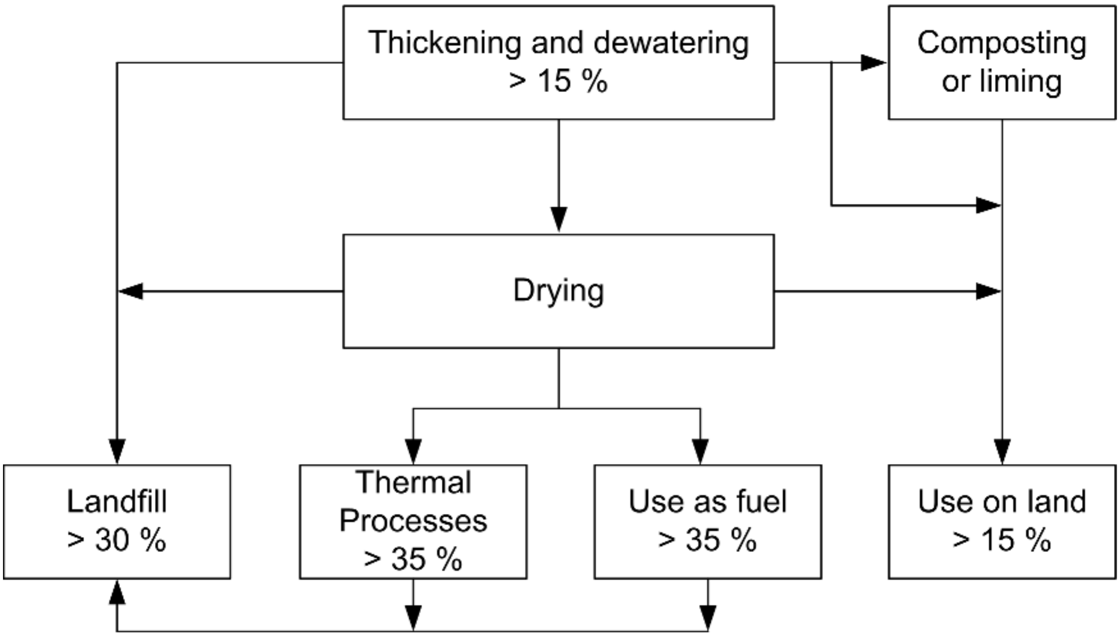


Figure 2 — Percentage Dry Solids (DS) usually required after thickening and dewatering for intended routes

Sludges management options are developed in a series of CEN Technical Reports to which belong the present report, see Figure 3 below.

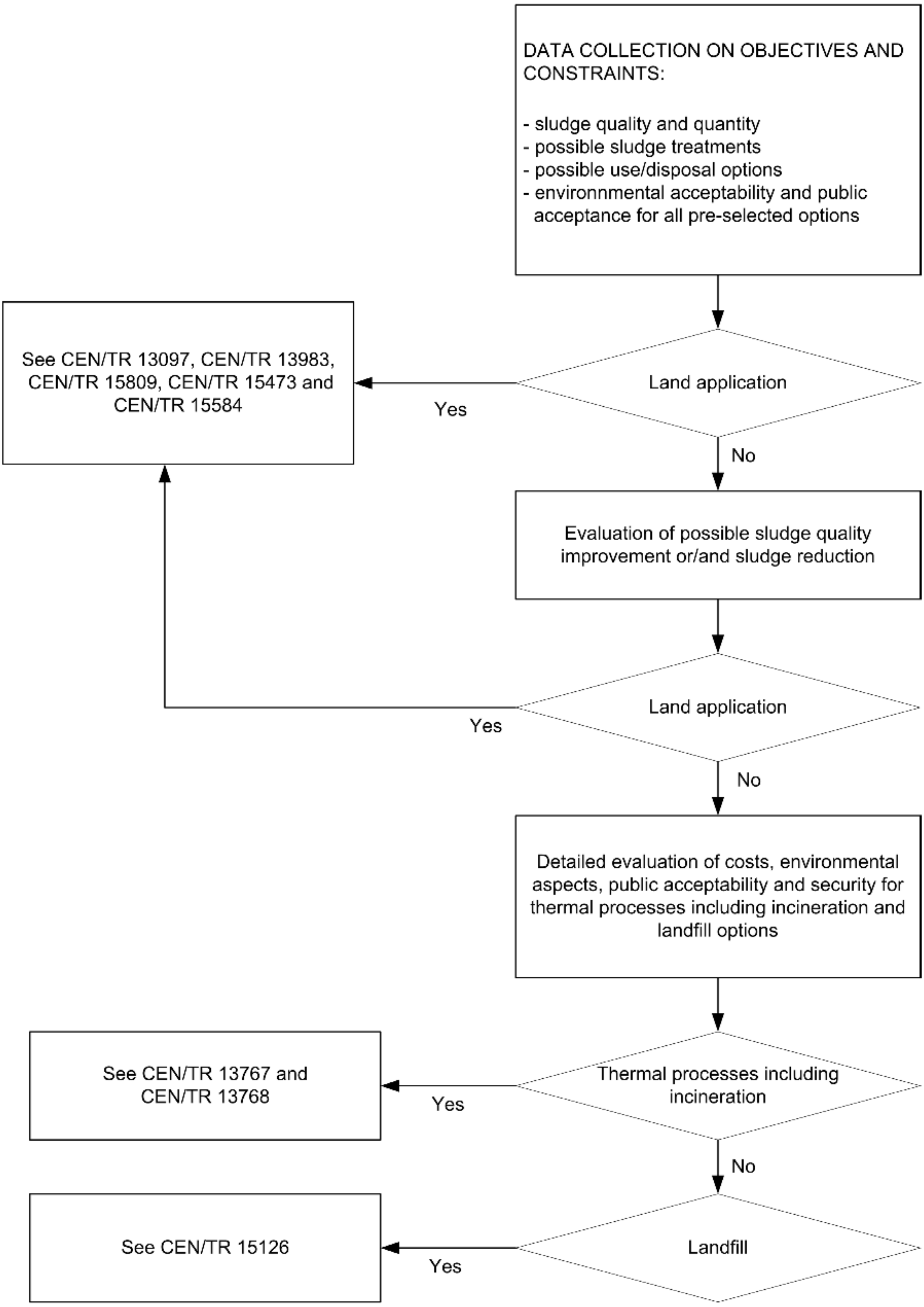


Figure 3 — A basic scheme for deciding on sewage sludge use/disposal options and the relevant CEN/TC 308 guidance documents

1 Scope

This Technical Report describes good practice for sludge dewatering and belongs to a series on sludge management options.

It gives guidance on technical and operational aspects of conditioning, thickening and dewatering processes.

Drying, which is another water content reduction process, is not dealt with in this document, but in CEN/TR 15473, *Characterization of sludges — Good practice for sludges drying*.

This report is applicable for sludges from:

- urban wastewater treatment plants;
- treatment plants for industrial wastewater similar to urban wastewater;
- water supply treatment plants.

This document may be applicable to sludges of other origin.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 12832:1999, *Characterization of sludges — Utilization and disposal of sludges — Vocabulary*

prEN 16323:2011, *Glossary of wastewater engineering terms*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 12832:1999, prEN 16323:2011 and the following (taken either from the normative references or from a technical dictionary [1]) apply.

3.1
cake
solid fraction of sludge as resulting from a solid-liquid separation process

3.2
centrate
sludge liquor separated by centrifugation

3.3
centrifugation
partial separation of solid from liquid under centrifugal forces

3.4
charge density
percentage of positive or negative charge

3.5
compressibility
ability of a sludge to be compressed under pressure

3.6
compression point
sludge solids concentration at which compression begins in a sedimentation process

3.7
desaturation
removal of water due to displacement of water by air

3.8
draining / drainage of sludge
separation of water from sludge liquor by gravity filtration

3.9
dryness
ratio of dry solids to sludge mass

3.10
electroosmosis
movement of liquid relative to a stationary charged surface as induced by an electrical field

3.11
expression
removal of sludge water due to deformation of solids under pressure

3.12
filter
device for the removal of sludge water whereby solids are retained on a water-permeable filter medium

3.13
filter medium
material where through a fluid flows and which retains matter contained in the fluid

3.14
filterability
characteristic describing the ability of sludge to be filtered

3.15
filtrate
sludge liquor separated by filtration

3.16
filtration
process of retention of the suspended matter by passing through a medium

3.17
floc
aggregate of particles that results from a flocculation process

3.18
flotation
raising of suspended matter in liquid to the surface by the entrainment of a gas

3.19
“g“
gravitational acceleration (9,81 m/s^2)

3.20
isolelectric point
condition in which a substance has a neutral charge

3.21
mesh
interlacing of crossed wires that determines the openings which can be square, triangular or rectangular

3.22
molecular weight
chain length of a polymer

3.23
particle size distribution
relative amount of particles classified per size ranges

3.24
polymer
class of natural and synthetic materials which are formed by association of structural units (monomers) by covalent bonds

3.25
porosity
ratio of the void volume to the total volume of material

3.26
pre-treatment
improvement of sludge characteristics by physical or chemical means

3.27
rheology
study of flow and deformation properties under the influence of an applied stress

3.28
saturation
ratio of the volumes of water and pores in a solid matrix

3.29
sieve (sludge treatment)
device for removing solids from fluids whereby the fluid flows through slots, perforations or a mesh

3.30
settling
ability for sludge solids to separate from water by sedimentation under gravity

3.31
sludge liquor
liquor separated from sludge. Sludge liquor can be called supernatant, filtrate and centrate

3.32
specific cake resistance
property representing the resistance to filtration of a layer of particles, having a unit mass of dry solids deposited on a unit filtering area

3.33
supernatant
sludge liquor separated by gravity thickening

3.34
water distribution
different physical states of water associated with sludge solid particles

3.35
zeta potential
electrical potential present at the plane of slip when a particle moves relative to its suspending liquid (or vice versa)

4 Description and features of thickening / dewatering systems

4.1 Thickening devices

4.1.1 General

Thickening devices enable the removal of free water from sludge. They are based on:

- natural (static) forces;
- artificial forces.

Thickening presents the following advantages:

- reduction of sludge volume with low energy consumption;
- reduction of storage capacities and volumes for subsequent treatment;
- reduction of transport costs;
- improvement of performance of dewatering machines;
- decrease in quantity of chemicals for dewatering in some cases.

This section discusses the most commonly used devices for thickening.

4.1.2 Devices based on natural forces (gravity)

4.1.2.1 General

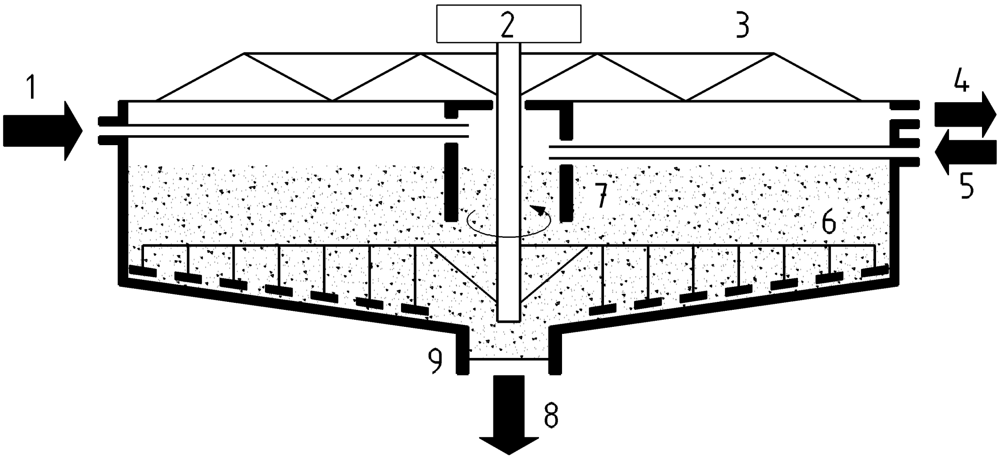
The principle of gravity thickening relies on sludge settling under the effect of gravitational forces. It enables the raising of the concentration of a suspension through sedimentation to produce a thickened sludge with a relatively clear liquid as overflow. Thickeners can be designed to operate in either the batch or continuous mode.

Sludge thickening can be achieved in clarifiers or separate thickeners which provide for a greater sludge storage capacity.

4.1.2.2 Gravity thickener

The traditional gravity thickener (Figure 4) comprises a relatively shallow, open top cylindrical/rectangular tank with either a flat bottom or a bottom shaped in the form of an inverted cone. The feed mixture is gently and continuously introduced to the feedwell. The supernatant is removed via an annular weir at the top of the unit and sludge solids are removed from a well at the bottom. Slowly rotating rakes mounted on a central shaft aid the thickening process by directing thickened solids towards the well for subsequent discharge and by creating channels to release further liquid from the sludge.

Tanks with a diameter smaller than 25 m are usually formed from steel and have bottoms with an angle usually less than 10° equipped with rake arms. Larger tanks between 25 m and 200 m diameter are normally made from a combination of concrete and steel and employ rakes designed to match the angle of the conical bottom.



Key

1	feed	6	rake
2	drive head	7	feedwell
3	walkway	8	thickened suspension (underflow)
4	supernantant (overflow)	9	well
5	flocculant		

Figure 4 — Gravity thickener [1]

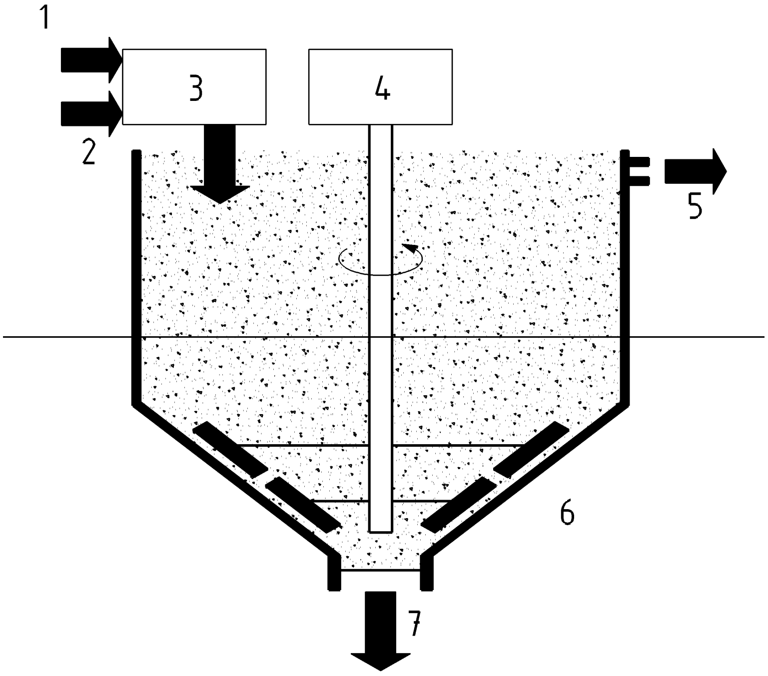
When space is limited, the lamellar separator is used. It is a rectangular tank containing a series of closely spaced rectangular plates inclined at an angle of higher than 50° to the horizontal.

Commercial designs provide three flow patterns, cross-flow, parallel flow and the most common counter–flow where the feed and supernatant flows can be most simply arranged.

The choice of a lamella separator is mainly related to the concentration of the input sludge.

4.1.2.3 Deep cone thickener

A deep cone thickener (Figure 5) has the same operation principle as a conventional circular gravity thickener but the slopes of the bottom are far steeper and have an angle in the region of 37°. Units are available with diameters of up 15 m. A rake rotating at speeds between 0,25 rpm and 2 rpm is usually provided in order to aid the thickening process and increase the underflow concentrations.



Key

1	fast acting flocculant	5	supernatant (overflow)
2	feed	6	rake and scraping arms
3	mixing device	7	thickened suspension (underlow)
4	motor drive		

Figure 5 — Deep cone thickener [1]

4.1.3 Devices based on flotation

Flotation thickeners are process devices wherein solid particles are separated from the liquid phase by becoming attached to air bubbles. The particles float to the water surface and are removed with skimmers. The most common device is dissolved air flotation (Figure 6) which uses pressurised air 300 kPa to 600 kPa and dissolves it in pressurised water. The pressure is then suddenly released to form small bubbles with a diameter of 40 µm to 80 µm. Bubbles are mixed with sludge (direct flotation) or with sludge diluted by underflow water (indirect flotation).

Other systems are also used:

- vacuum flotation thickeners employ air that is dissolved at atmospheric pressure followed by a pressure drop to allow the formation of bubbles with a few millimeters diameter;
- induced air flotation thickeners generate bubbles of 0,2 mm to 1 mm diameter by injecting air into water, e.g by means of a Venturi nozzles.

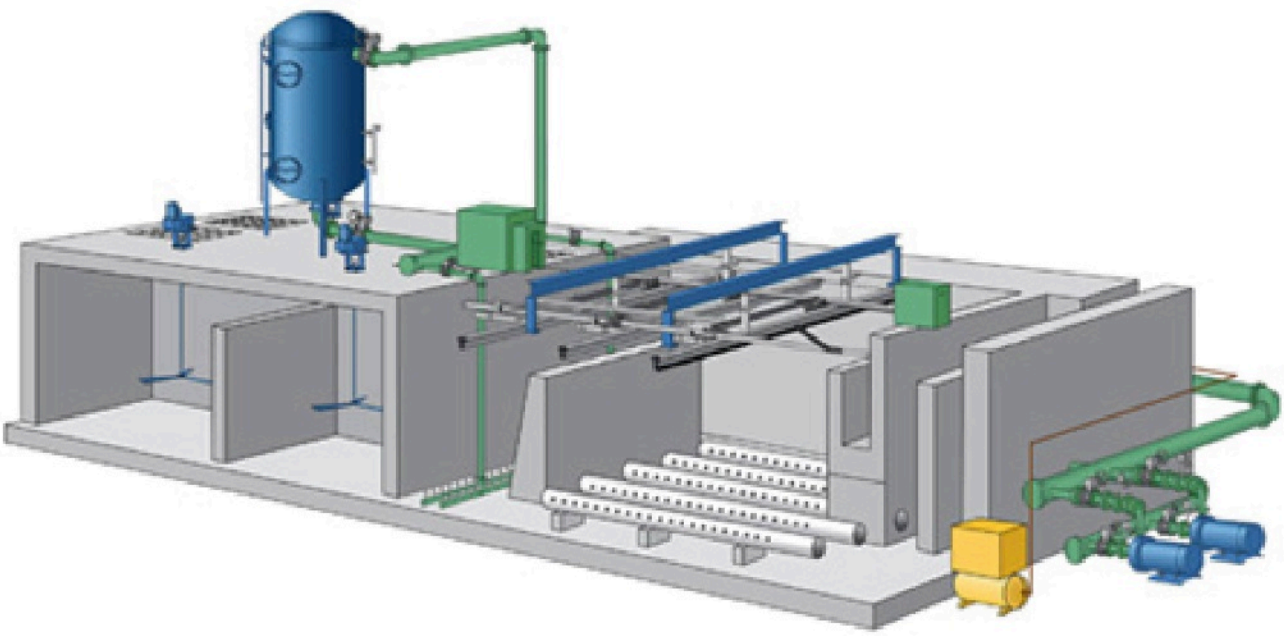


Figure 6 — Dissolved air flotation

4.1.4 Devices based on filtration

4.1.4.1 General

Many kinds of devices are commercially available and the most common ones are described below. They are usually fed with flocculated sludges.

4.1.4.2 Belt thickener

The sludge is uniformly distributed on a travelling filter belt (width: 800 mm to 2 700 mm, length: 2 m to 5 m) that moves slowly (7 m/min to 30 m/min). The filtrate drains through the continuously travelling filter in the horizontal filter zone. Solids are retained on the belt. Specially designed “baffles” divert the sludge in order to facilitate water drainage. Spray nozzles are used to wash the belt while it returns to the front end (Figure 7[1]).

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[1] This belt thickener is an example of a suitable design thickening and dewatering equipment available commercially. This information is given for the convenience of users of this CEN Technical Report and does not constitute an endorsement by CEN of this equipment. The manufacturer has given the authorisation to reproduce the scheme included in Huber documentation (www.huber.de).

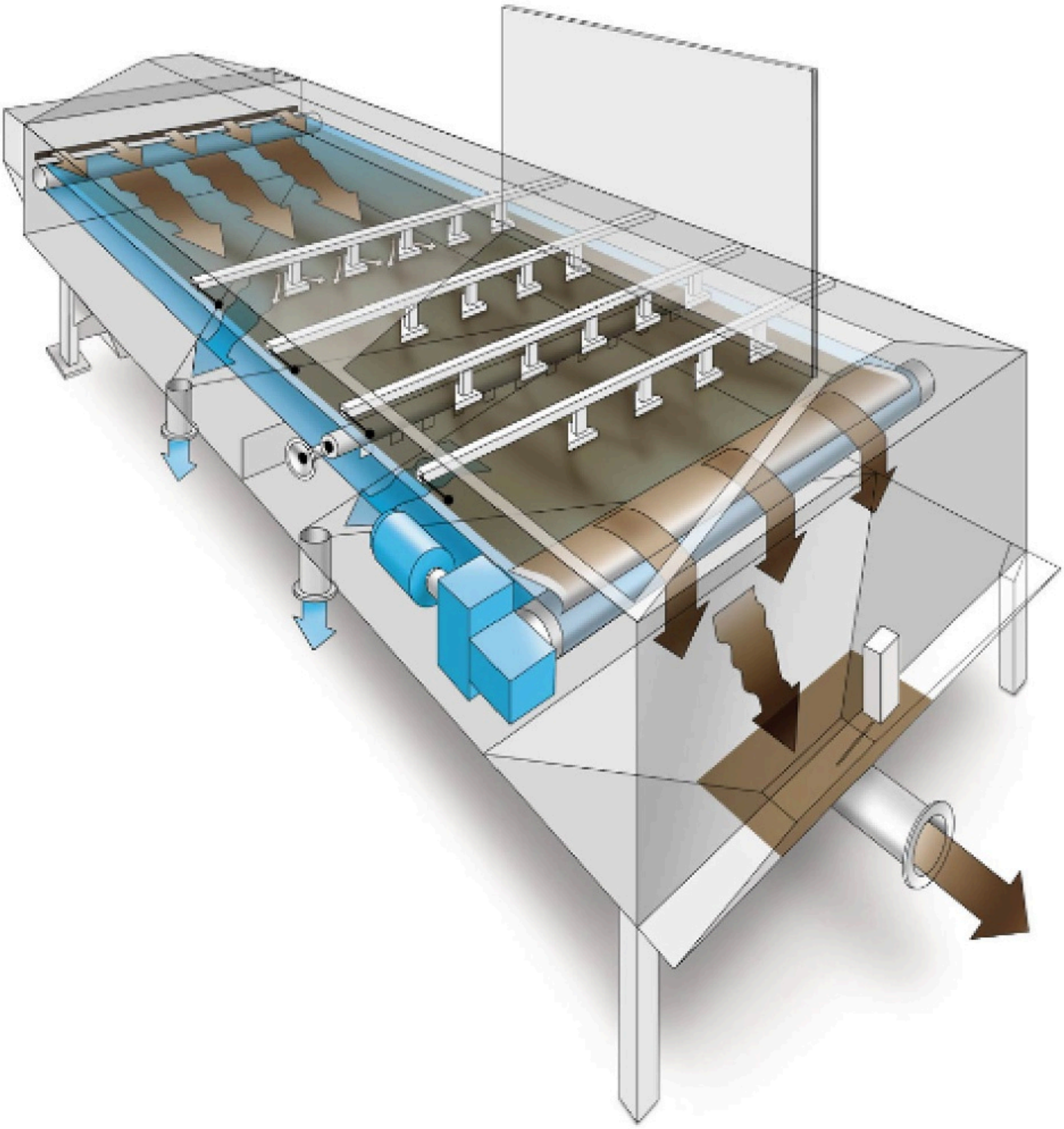

Figure 7 — Belt thickener

4.1.4.3 Disc thickener

Flocculated sludge overflows into the disc thickener consisting of an inclined and slowly rotating disc (diameter: 1 500 mm to 1 800 mm) that is lined with a filter cloth (Figure 8[2]). Sludge water drains by gravity

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[2] This disc thickener is an example of a suitable design of thickening and dewatering equipment available commercially. This information is given for the convenience of users of this CEN Technical Report and does not constitute an endorsement by CEN of this equipment. The manufacturer has given the authorisation to reproduce the scheme included in Huber documentation (www.huber.de).

through the filter. While the sludge moves upwards, it is turned over by ploughs to open up free filter surface in their wake. A scraper removes thickened sludge from the disk at its upper side. Before sludge is fed again, the filter cloth is backwashed by means of a spray bar.

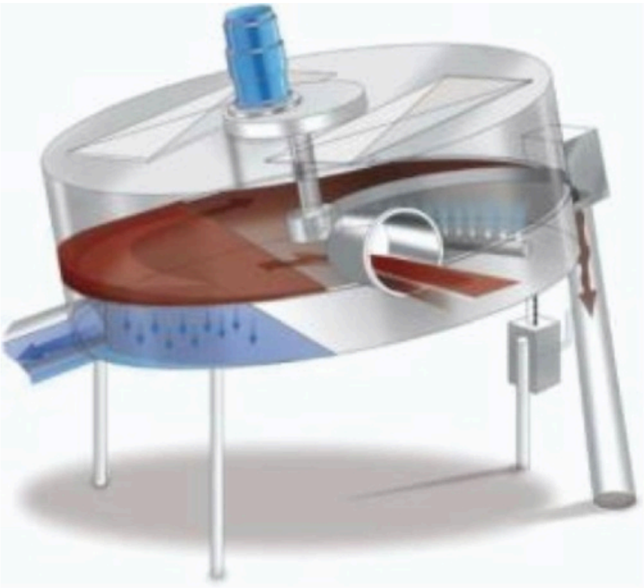

Figure 8 — Disc thickener

4.1.4.4 Drum thickener

Sludge is fed from the bottom and is thickened in a drum (diameter: 600 mm to 1 200 mm) rotating at low speed and equipped with a metallic mesh (500 µm to 600 µm) or belt. Sludge water drains through the mesh and is collected in a trough. Thickened sludge is driven by rotating baffles through the drum (which might be slightly inclined) and drops at the drum’s end into a chute. The exit of the sludge is allowed by the inclination of the drum (Figure 9[3]).

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[3] This drum thickener is an example of a suitable design of thickening and dewatering equipment available commercially. This information is given for the convenience of users of this CEN Technical Report and does not constitute an endorsement by CEN of this equipment. The manufacturer has given the authorisation to reproduce the scheme included in Huber documentation (www.huber.de).

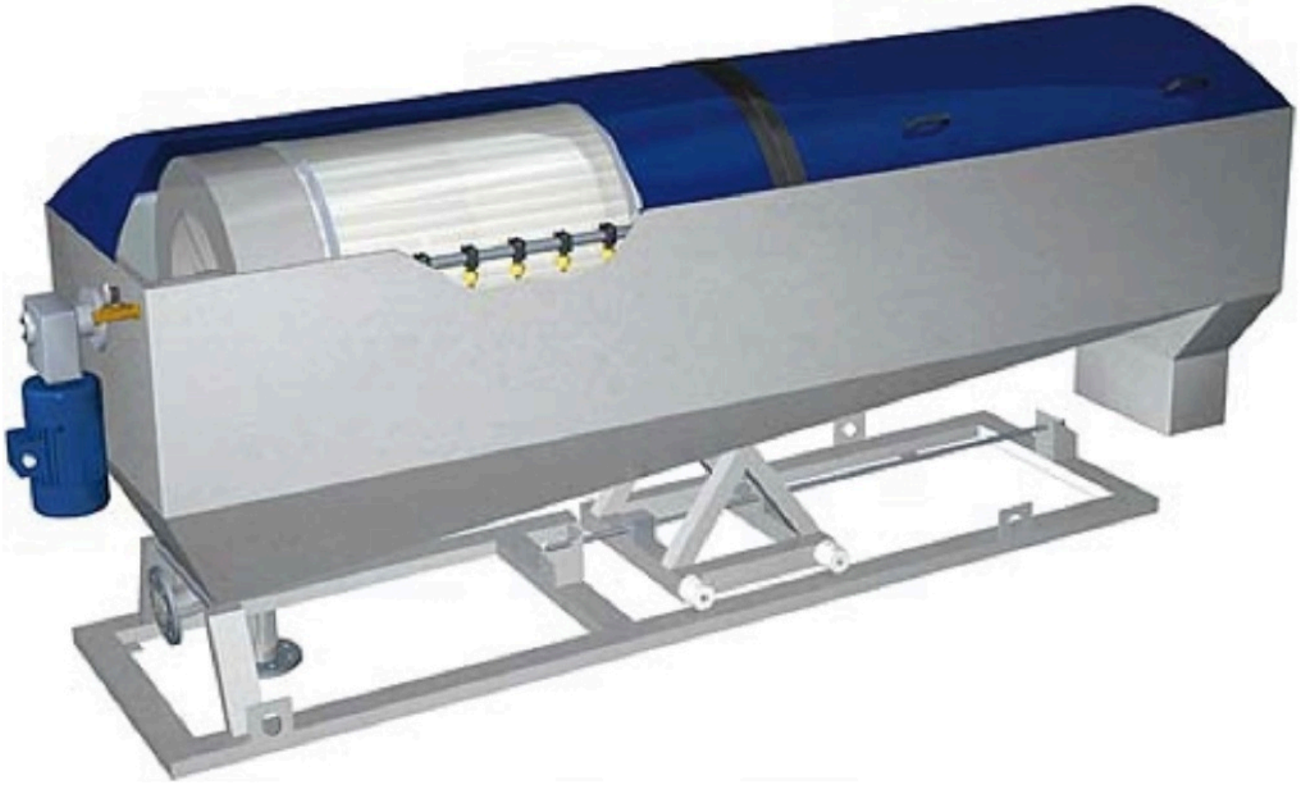


Figure 9 — Drum thickener

4.1.4.5 Screw thickener

Flocculated sludge overflows into the screw thickener consisting of an inclined screen drum (diameter: 300 mm to 1 200 mm) and a flighted screw slowly turning therein (Figure 10). The screen drum is completely filled with sludge. The screw transports the sludge slowly upwards, whereby sludge water drains by gravity through the screen. Thickened sludge is discharged at the upper end of the screen drum. The screen drum is backwashed at regular intervals by means of rotating spray bars.

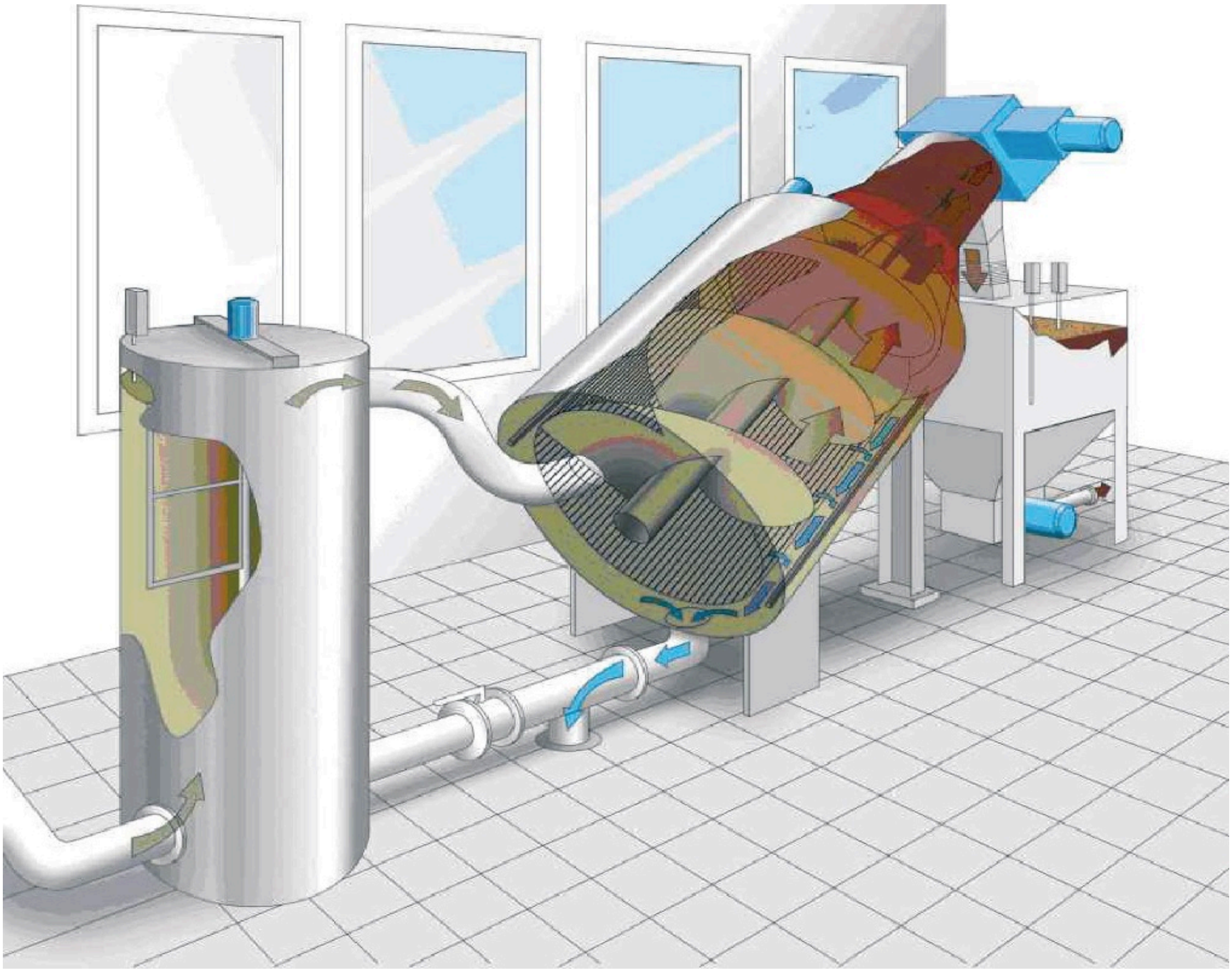


Figure 10 — Screw thickener

4.1.4.6 Draining bag/tubes

Specific synthetic filter cloths of high permeability and mechanical resistance are assembled to form draining bags/tubes into which sludge is pumped while sludge water drains through the cloth. During subsequent storage, consolidation of sludge continues as water evaporates through the pores of the filter cloth (Figure 11).

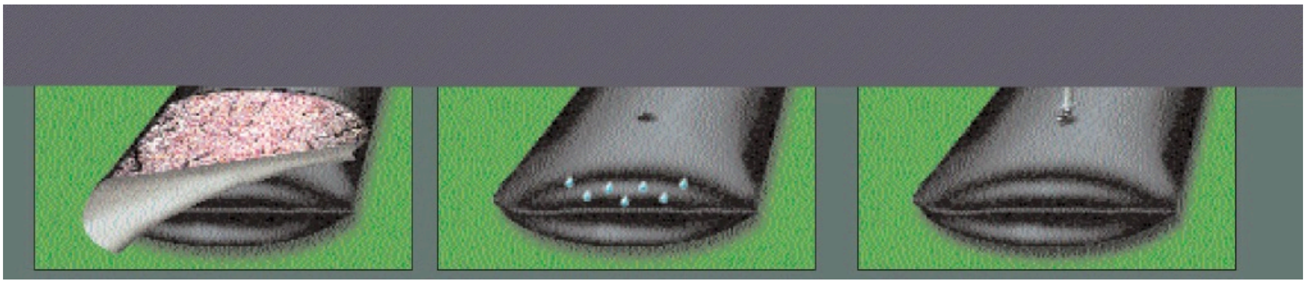


Figure 11 — Draining tubes

4.1.4.7 Horizontal grids / deck thickeners

In these filter thickeners, the separation of the solid and liquid phase is mainly achieved by means of a two dimensional mesh of 100 µm to 500 µm. Flocculated sludge is fed onto the gravity drainage grid/deck (Figure 12), which retains the thickened sludge. Thickened sludge is removed by gravity or by a mechanical scraper or by vibrators. Grids are washed by spray water.

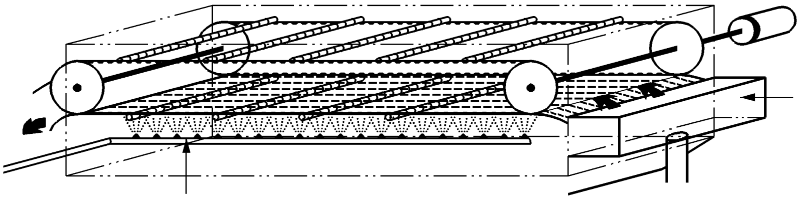
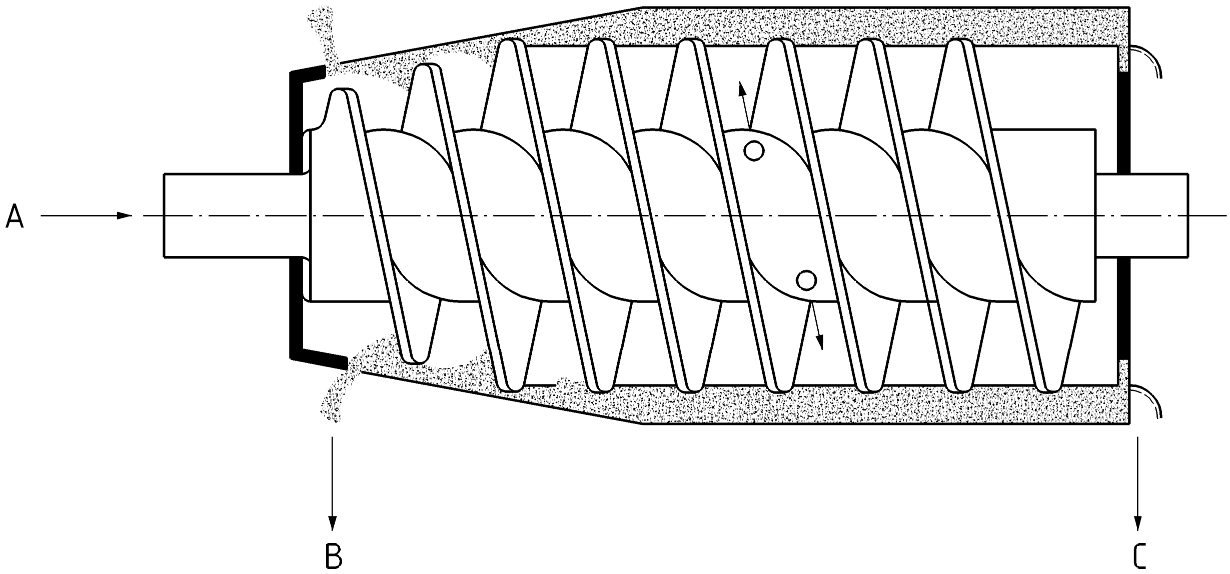


Figure 12 — Horizontal grid with scraper

4.1.5 Devices based on centrifugation

Centrifuges are commonly used both for thickening and dewatering.

Centrifuges permit accelerated sedimentation of particles under the force of centrifugation. This centrifugal force is up to 3 000 "g" depending on the machine size and sludge characteristics (Figure 13).



Key

A feed sludge
B cake
C centrate

Figure 13 — Schematic diagram of a centrifuge

The suspension to be treated is introduced via a fixed tube to a rotating distributor. Under centrifugal force, heavy particles settle on the interior wall of the bowl. They are scraped by a conveyor scroll and conveyed towards a cone. The scroll rotates slightly faster or slower than the bowl thanks to a gear box and this difference is called differential speed. Compacted sediment in the cone is driven through nozzles. Centrate flows over a circular and usually adjustable weir.

The weir is adjusted while the machine is stopped.

4.2 Dewatering devices

4.2.1 General

Dewatering devices can also remove interstitial water (water that is attached to solids by surface tension and can be partially removed by sludge compression) and vicinal water (water that is physically bound to solid surfaces and can only be partially removed even by extreme mechanical force) from sludge. Filter presses, belt presses, screw presses and centrifuges are the most common techniques.

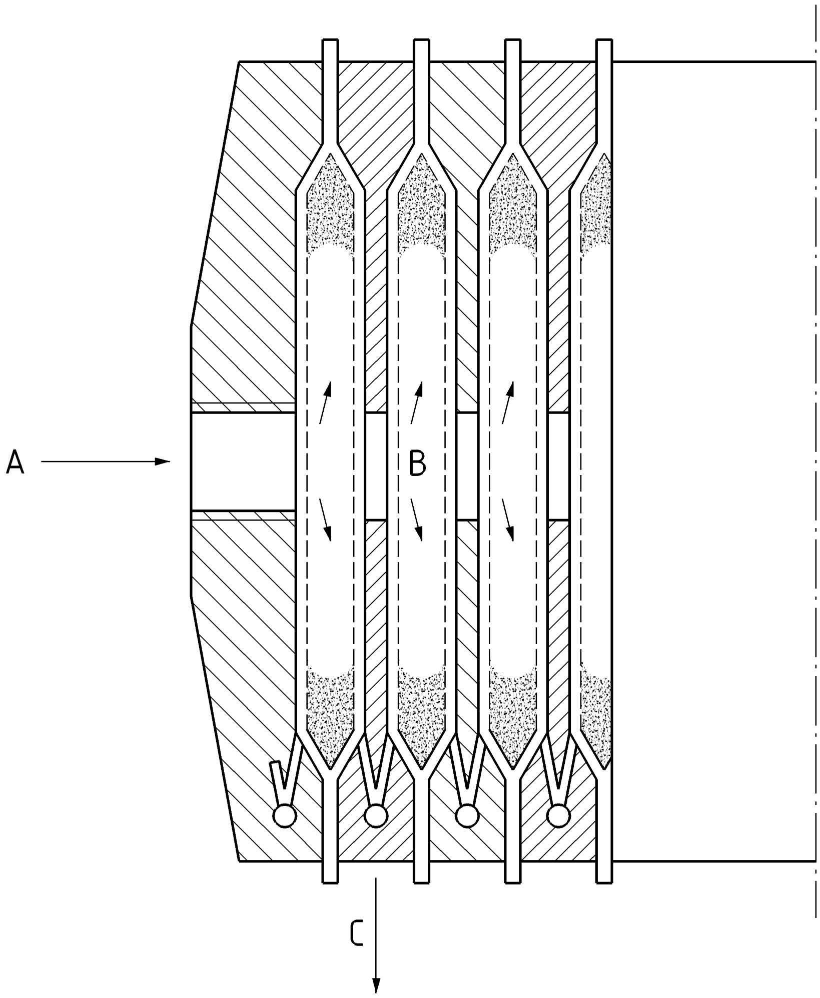
4.2.2 Filter press (plate, membrane)

A filter press includes a plurality of plates arranged in a horizontal stack, together with a head piece and a pressure piece, the latter being hydraulically pushed towards the head piece. The plates and head pieces have a slurry feed port and a number of filtrate outlet ports usually located at the corner of the plates. Each plate has a cloth on both sides with appropriate holes for the feed and filtrate ports, thus creating a series of chambers when the plates are held together (Figure 14).

The sludge is pumped into the chambers allowing solids to build up in the filter and filtrate to flow through the filter cloth and along the ribbed plate surface to their filtrate outlets. The press is fed under pressure until the set pressure is reached and/or until the filtrate flow drops below a minimum value.

In the conventional plate filter press, after a press cycle, the feed ports are blown out with air and the plates are removed from each other, allowing cake to drop out of the bottom of the press. After discharge of all cakes, the press is closed again for the next cycle.

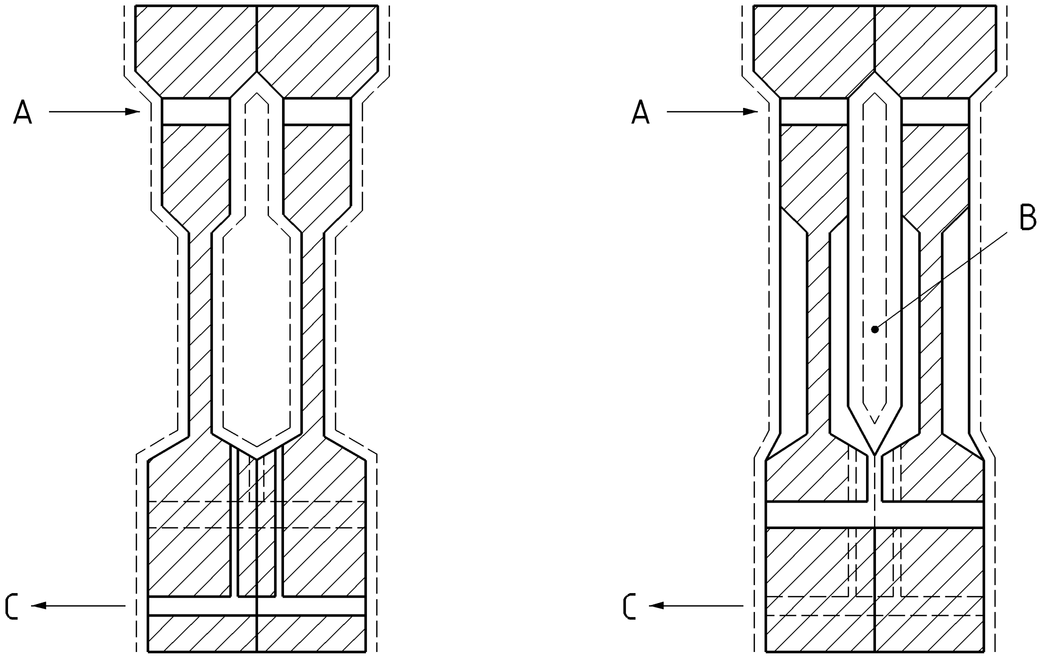
Some filter presses (membrane filter presses) are additionally provided with flexible diaphragms between the filter plates and cloth, whereby a fluid medium (water or air) is pressed into the space between the plates and cloth. This further compresses the filter cake (until 1 500 kPa) in the chamber by inflating the membrane. The compression process also tends to produce more uniform cake. Although membrane presses are more expensive than conventional filter presses, the additional capital and operating costs are often justified by better performance (Figure 15).



Key

A feed sludge
B cake
C filtrate

Figure 14— Schematic diagram of a plate filterpress



a) Filtration phase **b) Compression phase**

Key

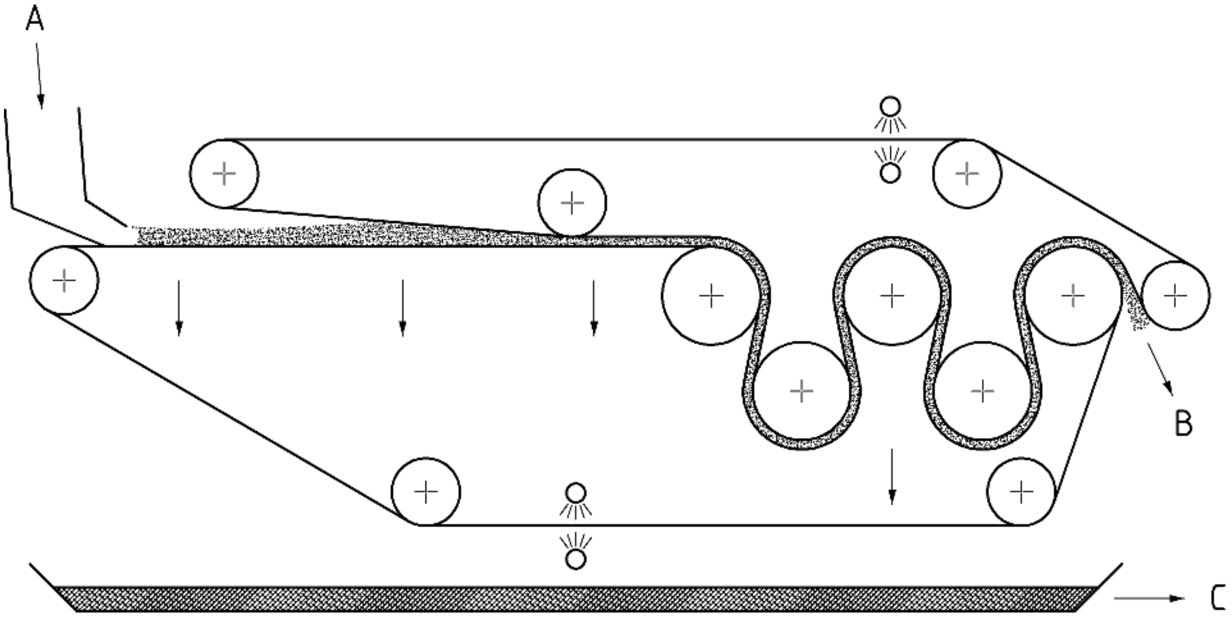
A	feed sludge
B	cake
C	filtrate

Figure 15 — Schematic diagram of a membrane filter press

The chamber volume of filter-presses is in the range: 200 l to 1 500 l with plate dimensions from 0,5 m x 0,5 m up to 3,0 m x 3,0 m. Filter presses can have 200 plates and a filtration area of up to 1 000 m^2.

4.2.3 Belt (filter) press

Flocculated sludge is spread on a filter belt (width from 0,5 m to 3 m). In a pre-dewatering or draining zone the belt and the sludge thereon travel more or less horizontally. Baffles, e.g. in the form of ploughs, are usually provided to turn over the sludge and open up a free filter area in their wake. Sludge water drains by gravity through the belt. In a wedge zone the sludge is squeezed between a pair of belts whereby gradually rising pressure is applied on the sludge. In a press-shear zone the two belts travel around rollers with decreasing diameters, whereby the sludge pressure increases. Alternating shear forces are generated by slightly different belt velocities supporting sludge compression. At the end of the press-shear zone sludge cake is released and scraped off the belts with blades. Filtrate from the various zones is collected in one or several troughs. Sludge cake can drop directly into a container or can be transported with a belt or a screw conveyor. The belts are continuously cleaned by high pressure spray water (Figure 16).



Key

A feed sludge

B cake

C filtrate

Figure 16 — Schematic diagram of a belt press

Filtration surfaces are in the following range: 3 m^2 to 15 m^2 for a low pressure machine (400 kPa), 8 m^2 to 25 m^2 for a medium pressure machine (500 kPa) and 14 m^2 to 46 m^2 for a high pressure machine (700 kPa).

4.2.4 Centrifuge

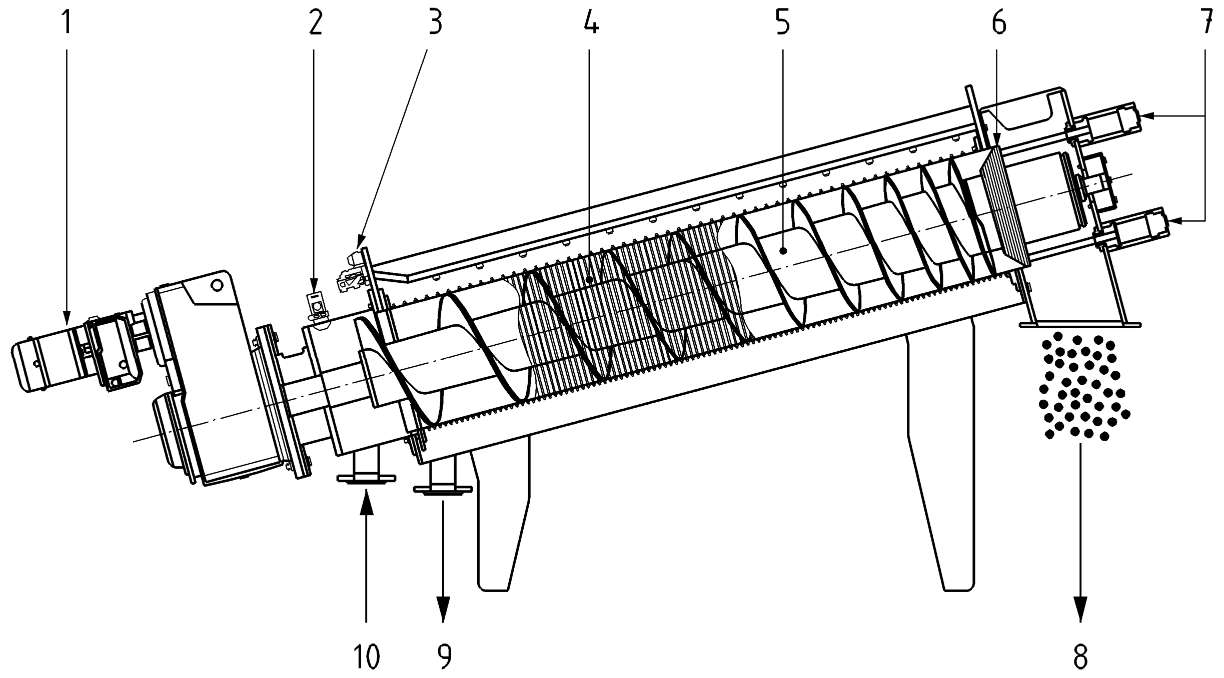
The principle of a centrifuge has already been described (4.1.5). The counterflow principle has become dominant for sludge dewatering. The differential speed of modern dewatering centrifuges is very low (1 rpm to 10 rpm) in order to maximise the solid mass in the rotating bowl and thus its retention time. Under such conditions, the torque and energy consumption is increased but this leads to higher solids concentration. Centrates are somewhat more concentrated in suspended solids than filtrates obtained by filtration processes.

Centrifuges operate up to 4 000 g to achieve maximal performance (solids concentration, centrate quality) depending on sludge characteristics.

The main differences between dewatering and thickening centrifuges are higher “g” force, lower differential speed, torque based control and higher overflow weir.

4.2.5 Screw press

A screw turns (0,2 rpm to 1,5 rpm) within a cylindrical screen. Its flight generates pressure and sludge water is driven out through the screen. Pressure is controlled by screw speed and an adjustable cone at the discharge end. The cone is either adjusted manually or moved by pneumatic cylinders, depending on type and quality of the sludge. Sludge cake is squeezed through a ring gap between the cone and an orifice. Brushes on the screw's flight keep the screen open from the inside; the screen is also periodically washed with spray water from the outside. Filtrate is collected in an enclosure (Figure 17[4]).



Key

1	motor drive	6	pressure cone
2	pressure probe	7	compressed air
3	service water	8	solids discharge
4	screen basket	9	filtrate outlet
5	screw shaft	10	sludge feeding

Figure 17 — Schematic diagram of a screw press

4.2.6 Others

Devices listed below are less common but are still used for some applications.

The following are examples:

- vacuum rotating drum filter;
- lamellar centrifuge system;
- rotary press;
- drying beds and lagoons;

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[4] This screw press is an example of a suitable design of thickening and dewatering equipment available commercially. This information is given for the convenience of users of this CEN Technical Report and does not constitute an endorsement by CEN of this equipment. The manufacturer has given the authorisation to reproduce the scheme included in Huber documentation (www.huber.de).

- centrifuge dryer;
- vacuum filter dryer;
- electrosmosis systems;
- dewatering containers.

Their performances are compared to classical systems in Clause 8.

5 Conditioning

5.1 General

Sludge conditioning is a pre-treatment to improve the removal of water during the thickening/dewatering process and a wide range of products/processes are commercially available to do that.

5.2 Conditioning processes

5.2.1 General

Conditioning can be carried out by chemical and/or physical means. The chemical conditioning includes coagulation (charge neutralisation) and flocculation (bridging to form larger flocs). The most appropriate conditioning system has to be chosen depending on the sludge properties, dewatering equipment and the desired degree of thickening or dewatering.

5.2.2 Coagulation

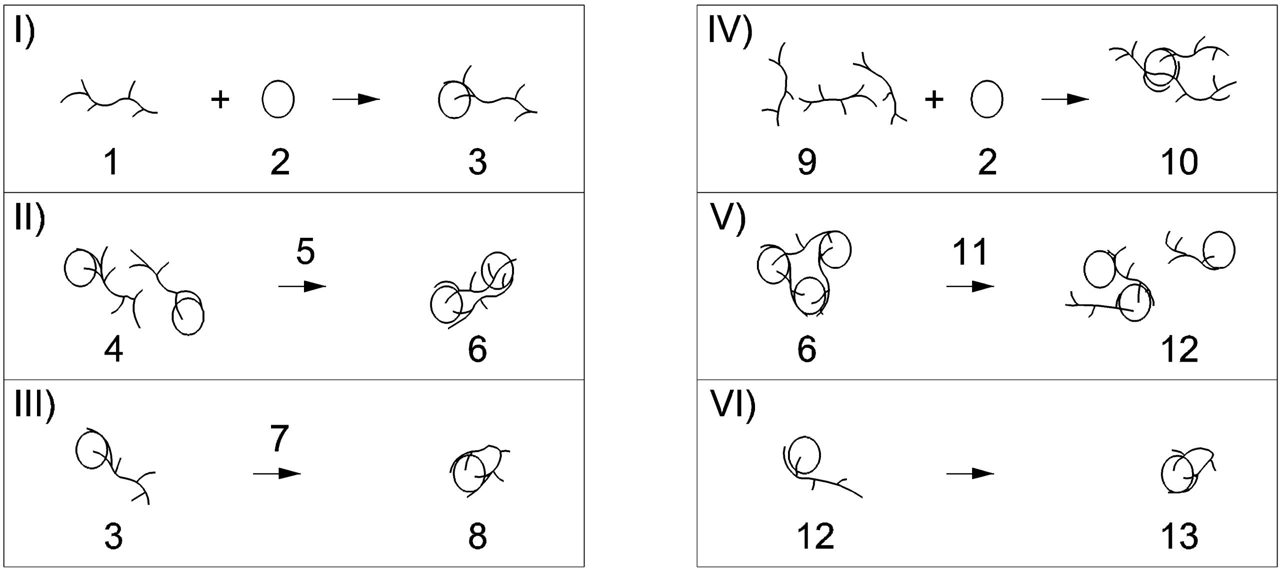
A suspension of dispersed particles is stabilised by electrical charges on the particle surface, causing it to repel neighboring particles [2]. This prevents charged particles from aggregating to form larger flocs, so solids-liquid separation is difficult. Coagulation is the destabilisation of these suspensions by neutralising the charges that keep them apart.

Coagulants can be synthetic or natural products. They are essentially 100 % charged and have low molecular weights. Since sludges possess a surface charge, the chemical that is used to neutralise that charge should be the opposite.

5.2.3 Flocculation

5.2.3.1 Floculation by polymers

While coagulation neutralises electro-static forces, the flocculation process bridges particles. This leads to bigger flocs that are easily separable from the liquid phase with different mechanisms. This is illustrated in Figure 18.



a) Initial adsorption

b) Floc formation

Key

I) initial adsorption at the optimum polymer dosage
II) floc formation
III) secondary adsorption of polymer
IV) initial adsorption excess polymer dosage
V) rupture of floc
VI) secondary adsorption of polymer

1 polymer
2 particle
3 destabilised particle
4 destabilised particles
5 flocculation
6 floc particle
7 no contact with vacant sites on another particle
8 restabilised particle
9 excess polymer
10 stable particle (no vacant sites)
11 intense or prolonged agitation
12 floc fragments
13 restabilised floc fragment

Figure 18 — Representation of the bridging model for the destabilisation of colloids by polymers (in six steps) [3]

Factors affecting flocculation are:

- energy input or mixing intensity: It enables the number of collisions to be improved because particles need to collide before forming aggregates. However, too much energy could have a detrimental effect on the collision efficiency by breaking up already formed floc. When two colloidal particles having the same charge approach each other, the possibility of their coagulation will depend on the difference in their electrostatic charge which is reduced by coagulant addition (zeta potential) and their kinetic energies which are supplied by turbulent mixing;
- energy input time: Coagulation normally requires an initial short time of high mixing energy followed by a longer time of lower energy mixing;
- amount of solids: The lower the amount of suspended particles, the lower the flocculation rate because of collision infrequency. Thus, a longer mixing time can be required with more dilute solution and smaller particles;

- flocculant addition: flocculants are chemicals that increase particle size by bridging particles together. Underdosage leads to small flocs difficult to dewater and overdosage increases the viscosity of water and leads to big and sticky flocs;
- temperature: it will affect flocculation efficiency. Decrease of temperature increases viscosity of interstitial water causing an increase in chemical demand or a decrease of liquid-solid separation efficiency. Temperatures higher than 60 °C can cause the degradation of the polymer.

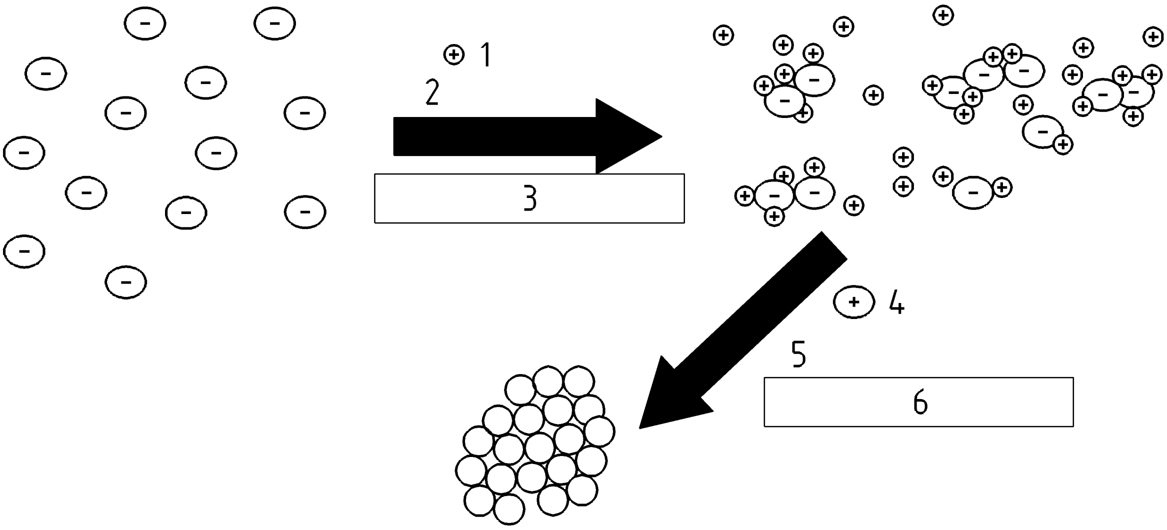
5.2.3.2 Flocculation by inorganic chemicals

Inorganic conditioning consists of 2 consecutive steps (Figure 19).

First, in case there is negatively charged sludge, bivalent or trivalent salt is added to the sludge in order to enhance the neutralisation (e.g. at a pH lower than the isoelectrical point for the metal hydroxides)

Secondly, lime can be added as calcium hydroxide, to increase pH for rapid precipitation of amorphous gels ($Fe(OH)_3$, $Al(OH)_3$) which act as inorganic polymers bridging particles. Lime is often used together with iron chloride. Lime also reacts with bicarbonate to form calcium carbonate, which provides the sludge with additional structural integrity and the porosity needed to increase its dewaterability.

In addition to inorganic conditioning alone, a combination with organic polymers could be useful.



Key

1 $FeCl_3$ addition
2 Zeta poential decrease
3 first step: Coagulation
4 lime addition
5 Fe $(OH)_3$ precipitation
6 second step: Floculation

Figure 19 — Representation of conditioning by inorganic chemicals

5.2.4 Physical processes

Physical conditioning processes include mechanical, thermal and freeze conditioning.

Mechanical conditioning alters the structure of the sludge and enhances its dewaterability by the addition of inert inorganic or organic additives (ashes, fine coal, sawdust, sand or gravel products).

In thermal conditioning, the sludge is heated to temperatures between 180 °C to 230 °C under pressure (10 bar to 25 bar) for 30 min to 60 min, whereby the cell structures of organic substances will be broken, so water removal is improved. Another positive effect is the hygienisation of sludges [4].

This conditioning method can be used with both raw sludges as well as stabilised sludge. An additional chemical stabilisation is not necessary.

With this process a large part of the organic substances go into solution which leads to an increase in the organic load of filtrate/centrate.

In addition attention is drawn to the problem of odour formation, which requires a relevant gas treatment.

Freezing is frequently used for natural sludge conditioning in cold climate zones.

5.3 Conditioners

5.3.1 General

There exist various types of conditioning chemicals. Organic polymers, trivalent metal salts (aluminum or iron), or polymeric aluminum are generally used for this purpose.

5.3.2 Polymers

Polymers for water and sludge treatment are larger water-soluble organic molecules (polymers). They can act as coagulants and/or flocculants. Organic polymers overcome the problems inherent in the use of inorganic products. Less sludge is generated using organic polymers since they do not add solids or chemically combine with hydroxides to form a precipitate. Organic polymers do not affect the pH of the water or sludge, and generally pH does not need to be adjusted for effective use of polymers.

Polymers are characterised by:

- molecular weight;
- charge density (cationic or anionic charge);
- chemical composition (type of monomers used);
- chemical structure (e.g. linear, cross-linked).

Polymer flocculants, unlike coagulants, are not selected for charge neutralisation but for floc formation and free water separation. Table 1 lists some characteristics of commonly used organic coagulants and flocculants used in sludge treatment.

Table 1 — Some characteristics of organic polymers

Class	Molecular weight	Typical form
Cationic coagulants:	50 000 Million to 1,5 Million	Liquid /dry
Cationic Flocculants:	Over 5 Million	Emulsion, powder or water based
Nonionic Flocculant:	Over 5 Million	Emulsion, powder
Anionic Flocculants:	Over 5 Million	Emulsion, powder or water based
Natural products	Up to 5 Million	Liquid / dry

The various Molecular Weight (Mw) coagulants function differently depending on the particle surface structure. Surfaces that are rough or porous, allow the low Mw polymers to enter the interior of the particle and the polymer is not neutralising the surface charge. Higher Mw polymers tend to remain on the surface where charge neutralisation is needed for coagulation. Overdose of any coagulant can cause a charge reversal and cause the redispersion of the particles.

5.3.3 Inorganic chemicals (multivalent salts, lime)

The most common inorganic conditioners are:

- Lime: (CaO, $Ca(OH)_2$) and Ca salts (Chloride, Sulphate, Hydroxides);
- Fe salts: Chloride ($FeCl_3$), Sulphate ($Fe_2(SO4)_3$, $FeSO_4.7H_2O$);
- Al salts: Chlorohydrate ($Al_2Cl(OH)_5$), Sulphate ($Al_2(SO_4)_3$).

Many mineral electrolytes with a multivalent cation can be used, but for economical and efficiency reasons, iron and aluminium salts are the most commonly used as mineral coagulants.

For economic reasons and basicity properties, lime is most commonly used in association with Iron chloride for sludge conditioning.

In this process of flocculation, lime has to be in the hydroxide form to enhance a pH increase. A preliminary step of hydration/ slaking of lime or specific reagent (delayed reactivity quicklime, ready to use milk of lime) will be used for this purpose.

Therefore practically, lime could be used in the form of milk of lime (delivered already processed and ready-to use or prepared on site from either quicklime or hydrated lime) or in powder form (delayed reactivity quicklime).

The main disadvantage of the use of mineral reagents as a flocculant is the increase in dry matter content of the sludge that has to be dewatered.

5.3.4 Other products

Other products such as cellulosic filter aids, magnesium hydroxide, talc, ashes, are sometimes used in specific applications but remain uncommon.

5.4 Technical aspects

5.4.1 Storage of conditioner

Coagulant solutions of ferric chloride are very corrosive owing to their acid properties and high concentration in chloride ions. Materials such as ebonite steel, polyester, polyethylene (quality high pressure) will be used.

Flocculants are delivered as powder, granules, emulsion or aqueous solution forms. Powders will be kept in a dry atmosphere because they are very hygroscopic. Storing time is about 6 months for emulsions, 12 months for other liquids and 24 months for powders.

5.4.2 Selection of conditioner

5.4.2.1 General

Main factors influencing the selection of a conditioner:

- sludge properties (mineral, organic, digested or not, pH, ionic strength, concentration, etc.);
- dewatering equipment;
- final use or disposal.

Laboratory tests are usually needed to make the selection of a conditioner, depending on the sludge characteristics and thickening/dewatering equipment. The procedure for laboratory conditioning is described in 5.4.2.5 and methods to evaluate floc behaviour are described in Clause 6.

5.4.2.2 Sludge properties

Table 2 below shows a first guideline for product selection for types of sludge.

Table 2 — Product guideline

Sludge type	Conditioner type
Sewage sludge (Primary, Biological, Digested)	Cationic
Chemically precipitated	Anionic and cationic
Inorganic Sludge (Ceramic, Sand, Blast Furnace Gas, Hydroxide, Alkaline Sludge, Clays, etc.)	Anionic
Industrial organic (Food, Textile, Paper, Pharmaceuticals, etc.)	Cationic

5.4.2.3 Dewatering equipment

The dosage of a conditioner depends on the origin and contents of the treated sludge and has to be evaluated in tests with original sludge samples. Inorganic and organic conditioners can be used alone or in combination for a dewatering purpose.

General trends are given below for the main dewatering systems. Usual dosage concentrations are expressed as grams of active matter per kilogram of sludge dry matter:

- Belt press: good drainability is required. The cross-linked structure enables fast removal of water. Medium to low molecular weights and high to medium charge density polymers give good results. Usual dosage is in the range 4 g/kg DS to 10 g/kg DS for belt press and also for belt thickener;

- Centrifuge: flocs resistant to high mechanical stresses are required. Medium to high molecular weight are preferable. Usual dosage is in the range 2 g/kg DS to 5 g/kg DS in thickening, 5 g/kg DS to 12 g/kg DS in dewatering;

- Filter-press: flocs resistant to high pressure, and non-sticky cake of low compressibility are required. For the above reasons, inorganic chemicals are often used. Polyelectrolytes with low to medium molecular weight and high to medium charge density are generally preferred. Usual dosages (expressed as grams of active matters per kilogram of sludge dry matter) for conditioners are 20 g/kg DS to 30 g/kg DS for iron(III)salts, 150 g/kg DS to 350 g/kg DS treated sludge for lime (as CaO), 3 g/kg DS to 6 g/kg DS for polymers (mostly in combination with other conditioners).

5.4.2.4 Final use or disposal

For each possible utilisation /disposal options, there could be specific requirements for the characteristics of the dewatered sludge (e.g. consistency of the sludge) and thus, a different cost for the conditioning and the degree of dewatering.

This can take place through physical, chemical or thermal treatment steps. With physical conditioning processes such as, addition of inert materials, the aim is to increase the dry residue or the heating value of the sludge mixture.

5.4.2.5 Laboratory procedure for conditioning

The search for the best flocculation conditions at plant scale are time consuming. Several quick and easy tests have to be available to screen chemicals and their dosage at laboratory scale. The objective is to narrow the number of products to be tested in full scale experiments and to adapt flocculation conditions to the sludge variability. It is necessary to flocculate sludges under repeatable and quantified conditions for a good comparison of products

The traditional “jar-test”, widely used in wastewater treatment, can’t be applied to sludge conditioning owing to the high solids concentration and higher viscosity of flocculated suspension, preventing the sludge from settling. Specific test equipment combining flocculation and drainage cells are under development for sludge flocculation [5].

5.4.3 Preparation of conditioners

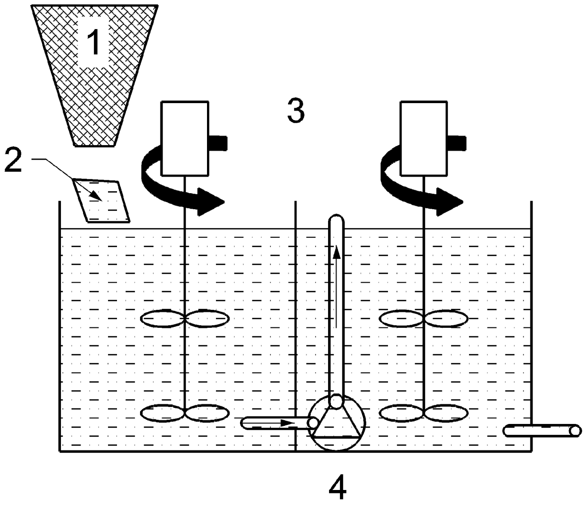
5.4.3.1 Organic conditioners

Organic coagulants are typically liquid products which are dosed directly into the process. Their viscosity is low enough to allow dosing with diaphragm pumps as well as positive displacement pumps. Sometimes, they need dilution before use.

A coagulant feeder can be designed for online process application so that solutions can be dosed directly without an intermediate storage tank. If required the system can also be operated in batch operation mode using a mixing tank with a dosing pump.

The flocculants are normally diluted in a polymer make-up system. The system design depends on the polymer type:

- Dry powder polymers (Figure 18) – The powder is dissolved into water in a mixing vessel with fast mixing for dispersion in water followed by a slow mixing in an aging tank. Post-dilution with water could sometimes be necessary to ensure good mixing properties and could be done in an additional tank.

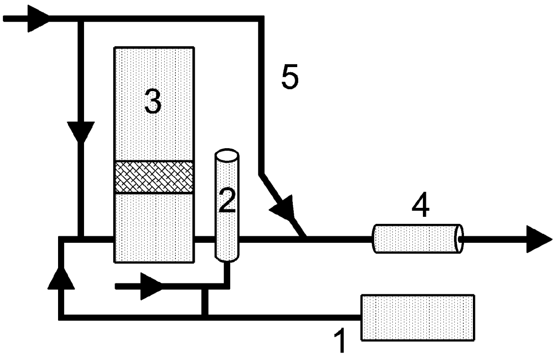


Key

1 powder container
2 water addition
3 mechanical mixer
4 transfer pump

Figure 20 — Preparation with dry powders

- Latex emulsion polymers (Figure 21) – These polymers are dispersed in an oil carrier fluid, making them much easier to handle than powders. Before feeding the polymers to the process, they have to be diluted in water with high energy mixing. Aging is faster than with powders, it takes around 30 min.



Key

1 pump
2 calibration tube
3 dynamic mixer
4 static mixer
5 post dilution

Figure 21 — Latex emulsion preparation

- Dispersion polymers are water based, making the dilution and dosing much easier. Polymer make-up with water is still required, but shorter aging time is needed (around 15 min).

A full automatic dosage station can be used as for the coagulants.

5.4.3.2 Inorganic (mineral) conditioners

Trivalent salts are commonly delivered as a solution, so that no preparation is needed.

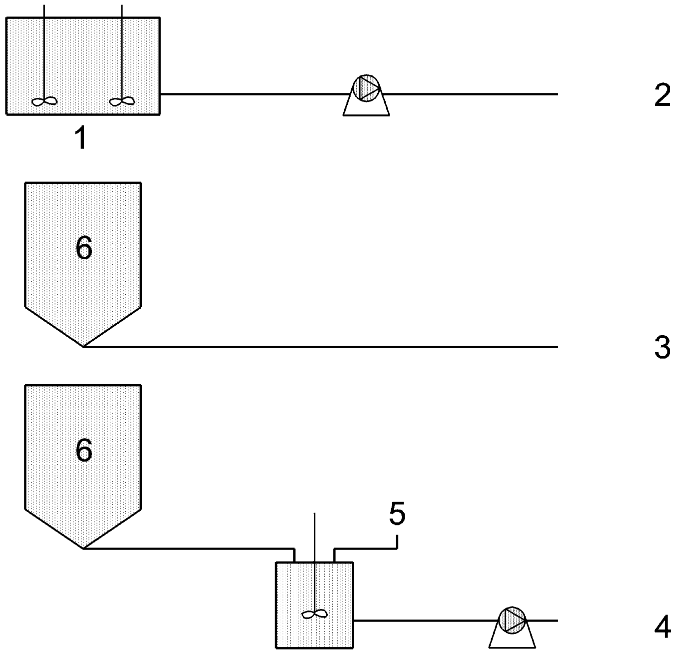
Lime-based reagent can be used directly as powder (delayed reactivity quicklime) or after preparation. It is quite common (especially in the case of mineral conditioning before press-filter) to prepare a milk of lime on site from either quicklime or hydrated lime (Figure 22).

Preparation of milk of lime from hydrated lime has to be focused on a high energy mixing of hydrated lime with water in order to get a reactive dispersion.

When preparing milk of lime from quicklime, it should be noted that the hydration reaction of quicklime is an exothermic reaction which transforms calcium oxide into calcium hydroxide (hydrated lime).

Quicklime quality (> 94 % CaO, high reactivity), water quality (the presence of sulfate, phosphate as well as carbonate influences the hydration kinetic) and process conditions (temperature higher than 70 °C and aging time for further dilution and injection to the process) have an impact on the milk of lime quality.

For transport and handling it is important to avoid settling zones. During storage it is necessary to use a stirred tank and circulation loops.



Key

1	lime slurry tank	4	milk of lime preparation
2	ready-to-use milk of lime	5	water
3	delayed reactivity quicklime	6	lime silo

Figure 22 — Lime injection

5.4.4 Injection, dosing and mixing with sludge

Intensive mixing is important for coagulation and flocculation reaction to achieve the effective collision between particles and added chemicals [6]. There are two possibilities:

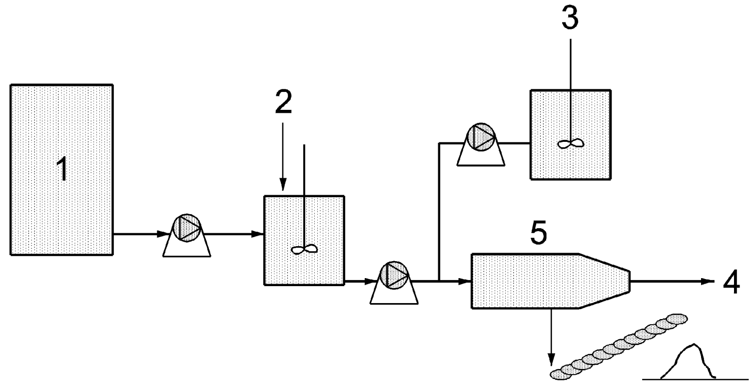
- creating turbulence in the flow regime with e.g. hydraulic jumps in open channels, Venturi flumes, pipelines with bends, in-line static mixers, pumps;
- induced mixing in tanks with mechanical stirrers or air.

The injection and dosing process is related to the dewatering equipment in use.

In a continuous thickening/dewatering process, the dosage is done by injection inline before entering the dewatering equipment. During the dewatering process polymer can be added additionally at a second dosage point directly into the centrifuge (example for centrifuge in Figures 23a) and 23 b)).

In a batch thickening/dewatering process, the dosage is commonly done directly in a sludge collecting tank (example for filter press in Figures 24a) and 24b)).

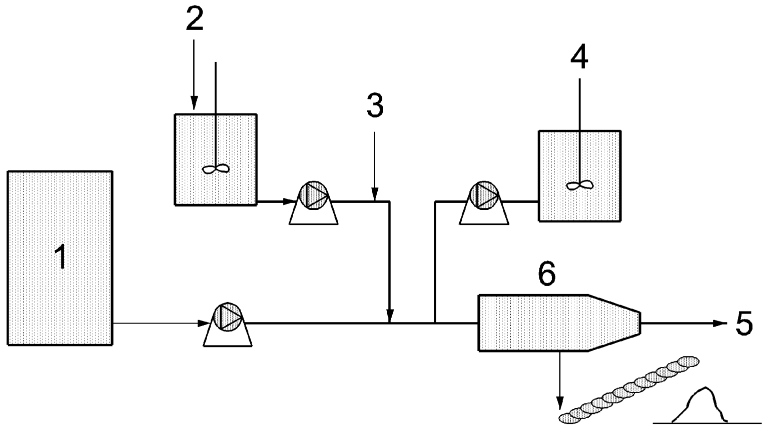
Lime is added on line as milk of lime or solid calcium oxide (Delayed Reactivity Lime) before polymer.



Key

1 sludge storage tank
2 lime is added in sludge directly as delayed reactivity Lime powder
3 polymer preparation
4 centrate to head to plant
5 dewatering device

a) Example of continuous conditioning with powder lime in centrifugation

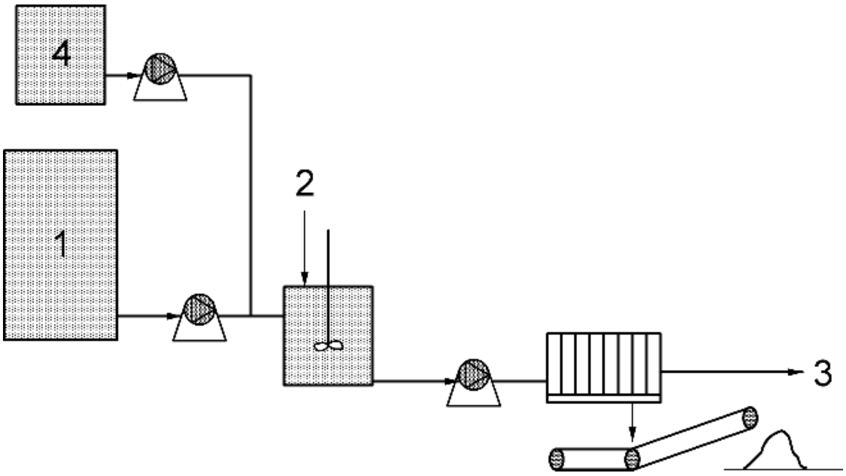


Key

1 sludge storage tank
2 milk of Lime preparation
3 lime is added as milk of lime
4 polymer preparation
5 centrate to head to plant
6 dewatering device

b) Example of continuous conditioning with milk of lime in centrifugation

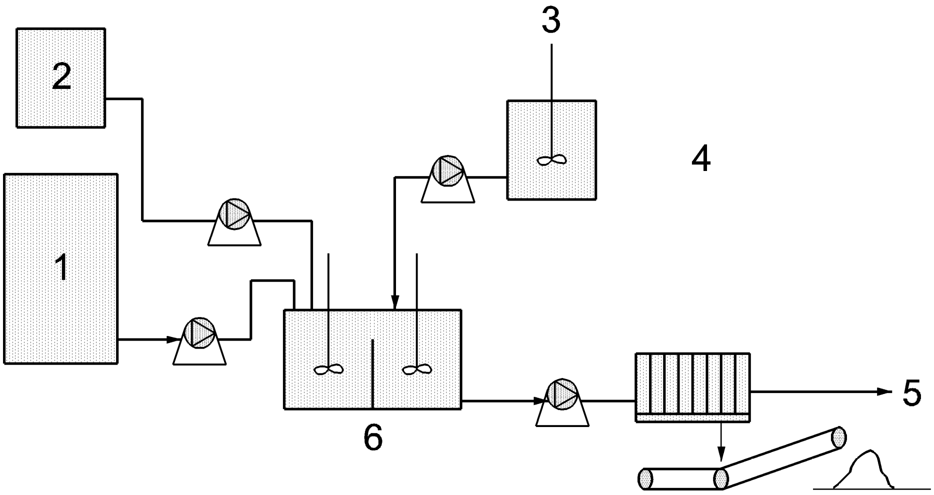
Figure 23 — Examples of continuous conditioning with powder lime and of continuous conditioning with milk of lime in centrifugation



Key

1 sludge storage tank
2 lime is added in sludge directly as delayed reactivity Lime powder
3 filtrate to head of plant
4 $FeCl_3$ storage tank

a) Example of Ferric Chloride and powder lime conditioning system in filter press



Key

1	sludge storage tank	4	lime is added as Milk of Lime
2	$FeCl_3$ storage tank	5	filtrate to head of plant
3	milk of lime preparation	6	conditioning tank

b) Example of Ferric Chloride and milk of lime conditioning system in filter press

Figure 24 — Examples of Ferric Chloride and powder lime conditioning system and of Ferric Chloride and powder lime conditioning system in filter press

5.4.5 Automation

A continuously changing feed makes it difficult to optimise the dewatering process without intensive operator involvement. Operators have to make manual adjustments to the process to compensate for the variations of sludge characteristics. Running at a not-optimal level of performance leads to lower cake solids concentration, higher polymer consumption and more solids being re-circulated with the sludge liquor.

Improvements in sensor and automation technology in recent years have made it possible to design systems controlling the key parameters in and around the dewatering process. By continuously monitoring the feed conditions and the process output, such a system can continuously and automatically make the necessary adjustments to the feed, the polymer dosage or the internal settings of the dewatering equipment, to keep the optimum overall performance. Most systems use on-line measurements of flow rate, suspended solids (in the feed) and turbidity in the sludge liquor. These operational parameters are used in combination with the operational cost structure (costs of polymer, disposal, water and power).

Examples of developments are:

- centrifuge, where a system monitors polymer dosing rate and the differential speed and conveyor torque of the decanter by controlling suspended solids content and flow rate of the incoming sludge and suspended solids content in the centrate;
- gravity thickener, where a system adjusts polymer dosage to settling velocity;
- filter-press, where developed computer supported measurement, control and monitoring systems regulate the quantities and mass flows, the pressure rise and the mixing energy; the filtration results can be optimised and, at the same time, the requirement for flocculation agent;
- can be minimised. Automatic control of polymer dosing for plate and frame presses is far more sophisticated because floc formation quality needs to be monitored, e.g. by optical means. An alternative system is based on measuring an inert tracer, that is electrostatically bound to the flocculant, in the sludge liquor. This system can measure the overdosing of flocculant.

6 Parameters / Methods for the evaluation of sludge thickenability or dewaterability

6.1 General

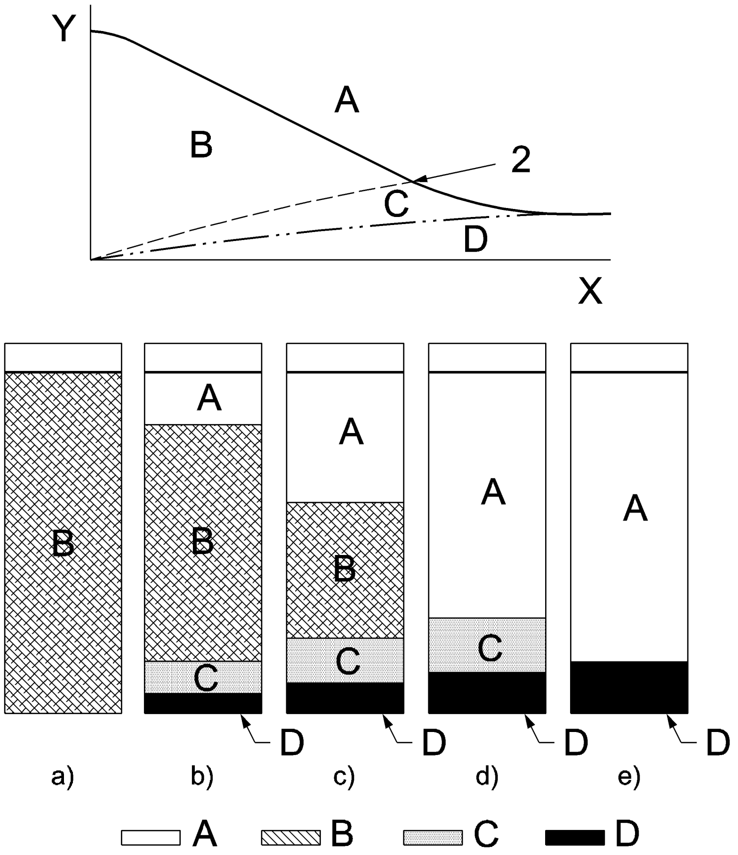
Reduction of water content in sludge suspensions, can basically be accomplished by settling, filtration or centrifugation.

6.2 Mechanisms description

6.2.1 Settling / Flotation

The general term “settling” describes all types of particles which fall through a fluid under gravitational force. It is composed of “sedimentation” where particles or aggregates are suspended by hydrodynamic or particle-particle interaction forces and “compression” where the particle aggregates are compressed by layers of aggregates lying above them.

The actual mechanism of sedimentation could be most simply described by reference to what happens in a batch settling test of slurry in a glass cylinder. Following the interface between the solid and liquid phase (Figure 25) enables the determination of the sedimentation velocity of the sludge (initial slope of the curve) and compression point (intersection of the linear compression zone and the asymptotic falling zone).



Key

a) formation of a clear supernatant liquid at the top of a suspension
b) fall of particles with their own terminal settling velocity under hindered settling conditions
c) formation of a volume of suspension in compression
d) formation of a single distinct interface between deposit and the clear liquid
e) final compression where liquid being forced upwards through the pores of solids into the clear zone

A	clear liquid
B	uniform concentration
C	sediment compression
D	deposit
2	compression point
X	time
Y	interface height

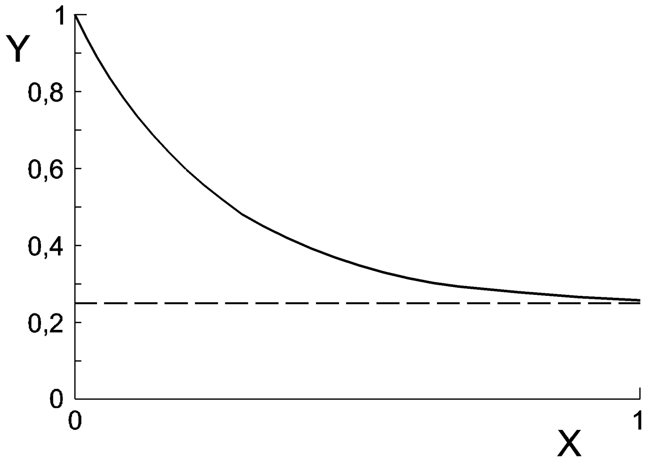
Figure 25 — Sedimentation of a flocculated suspension

Flotation is a separation process in which solids go upwards and are recovered at the free surface of fluid phase. Process details are given in 4.1.3.

6.2.2 Centrifugation

As well as settling, centrifugal sedimentation relies on the difference of density between particles and fluid. Process occurs at a centrifugal acceleration G measured in multiple's of the earth gravity g. In centrifugation two mechanisms take place usually simultaneously: compaction and desaturation.

In compaction, a rearrangement of the loosely packed solid structure from sedimentation takes place to form a much tighter packed arrangement under centrifugal force. In de-saturation, air replaces water in the pores while liquid trapped in the sediment cake is squeezed out. The cake moisture decreases with increasing centrifuge acceleration (G) or residence time (t) until reaching an asymptote (Figure 26).



Key

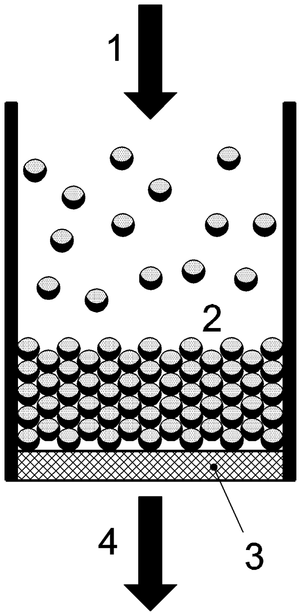
X G or t
Y cake moisture

Figure 26 — Moisture weight fraction in cake during dewatering

6.2.3 Filtration

Filtration involves passing a suspension through a filtering medium under a pressure gradient.

The cake is built by accumulation of particles on the filter medium at the same time the filtrate is removed (Figure 27).

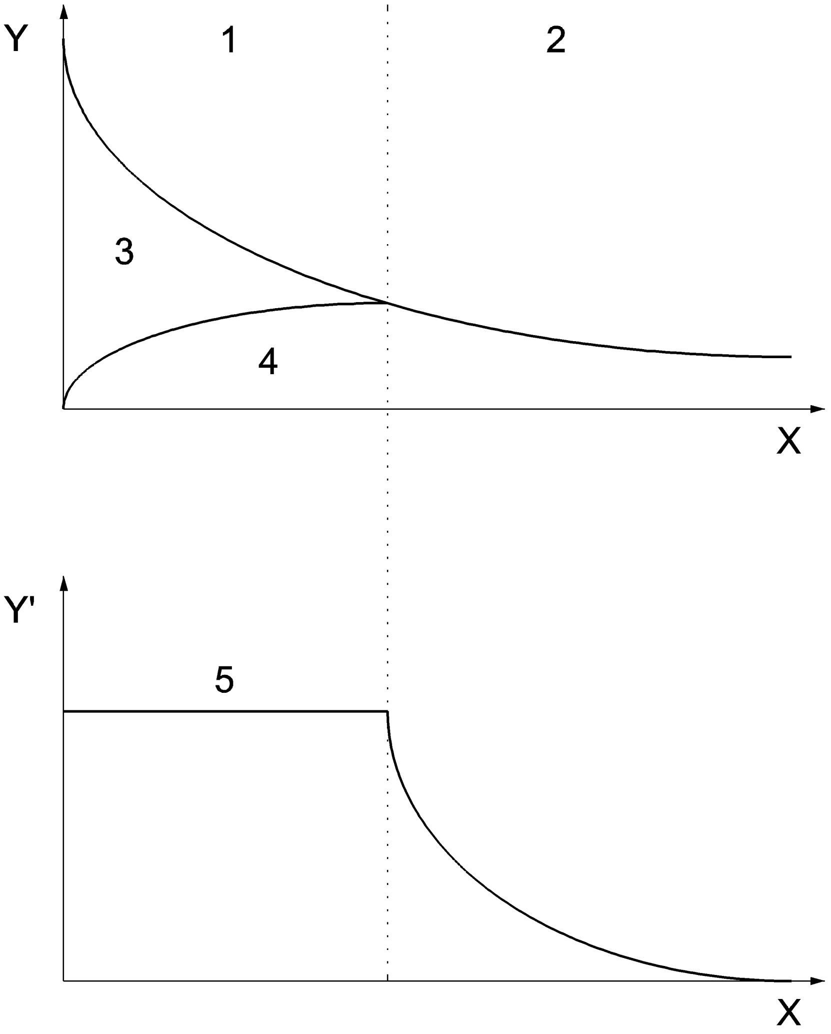


Key

1	feed
2	cake
3	filter medium
4	cleaned fluid

Figure 27 — Concept of cake filtration

At the end of filtration, cake achieves its maximal height. The moisture content of cakes is then reduced by subjecting the cake to a mechanical compressive force, thereby removing liquid by compaction. Figure 28 illustrates evolution of solid height and liquid pressure during operation.



Key

X	dewatering time	X	dewatering time
Y	height	Y'	relative liquid pressure
1	filtration	5	constant pressure Filtration
2	expression		
3	suspension		
4	cake		

Figure 28 — Evolution of solid height and liquid pressure during filtration operation

6.3 Basic theories and parameters

6.3.1 Settling / Flotation

Particle size, particle density and fluid viscosity are the primary factors to be considered in a sedimentation process according to Stoke's law given by the formula:

$$V_s = (\rho_s - \rho_l) \times g \times d^2 / (18 \times \mu)$$

where

V_s terminal settling velocity of a spherical particle (m/s);

ρ_s solid density (kg/m^3);

ρ_l fluid density (kg/m^3);

g gravity constant (9,81 m/s^2);

d particle size (m);

μ fluid viscosity (Pa.s).

The application of Stoke's law supposes a laminar flow (a Reynolds number below 1 involves particle size between 3 µm and 100 µm) and the absence of interaction between particles. That's rarely the case for sludges where particle concentration and shape have a significant influence. Suspensions with particle diameters of the order of microns settle too slowly for most practical operations. To increase their settling rate, the individual particles are aggregated or flocculated into larger collections of particles knows as flocs.

The behaviour of concentrated suspensions during sedimentation has been analysed by Kynch [7], Talmage and Fitch [8] and most practical analyses of thickener behaviour are based on their developments. Uniform particle concentration, no wall effects, no differential settling of particles as a result of differences in shape, size or composition shall be assumed.

The principle of flotation relies on Stoke's law but the particular attraction of flotation, as compared with sedimentation, is that particles generally rise at a much higher rate than they settle, so that the size of unit is smaller.

6.3.2 Centrifugation

Centrifuges operate mainly by sedimentation of particles having a higher density than the liquid in which they are suspended.

The Stoke's settling velocity at 1 g (V_s) is extended to an effective settling velocity (V_G) in centrifugation by replacing gravity g with centrifugal gravity

$$G = w^2 r$$

where

w rotation speed (rad s^{-1}) and;

r liquid ring radius (m).

It is clear that the separation velocity is very sensitive to the speed of rotation and particle size. Complete theoretical approach is not possible owing to the difficulty of taking into consideration and quantifying all the parameters/forces and their interaction involved in the separation.

6.3.3 Filtration

Even though the fluid dynamics underlying filtration process are complex, models to interpret the processes all stem from Darcy's law with the formula:

$$u = - k / \mu \times dp / dz$$

where

dp is the dynamic (hydraulic) pressure difference across thickness (dz) of porous medium of permeability;

k and u is the superficial velocity (volume flow rate per unit cross-sectional area of the bed) of liquid with a viscosity μ flowing through the bed.

In filtration, Darcy's law enables the description of cake formation and is often used in a modified form where the specific resistance $\acute{\alpha}$ replaces the permeability k (k = 1 / (ρs x (1 - ε) x α) and the pressure gradient is replaced by the pressure loss per unit mass of solid deposited on the medium.

The relative easiness of filtration is characterised by the magnitude of the specific resistance, reported in Table 3.

Table 3 — Comparison of filtration performance with specific resistance values

Ease of separation	Specific resistance (m/kg)	Example
Easy moderate	$< 10^{11}$	Primary sludges
Difficult	10^{12}	Well conditioned biologic sludges
Very difficult	$> 10^{13}$	Biologic sludges

Generally, it is frequently considered appropriate to neglect the medium resistance but the error incurred by making this assumption should be estimated. Recent research [9] showed that filter medium resistance during filtration increases by a factor between 10 and 80 compared with clean filter medium resistance before filtration, even with little compressible solids. The filter medium resistance during filtration could increase up to 50 % of the final overall resistance (filter cake + medium).

Following Darcy's law, the relative weight of operating parameters is:

- viscosity proportional to filtration time;
- solids concentration which increase filtration time but some operations of concentration such as settling reduces volumes to be filtered;
- specific resistance function of shape and size of particles and cake formation during filtration;
- filtering medium resistance often negligible but which may increase during filtration after several cycles owing to fouling by fine particles;
- filtration area or more generally solids deposited by unit of area which corresponds to thickness of cake imposed by the filter and which contributes to an increase in filtration time;
- pressure: it's necessary to determine constitutive equation to describe the variation of specific resistance with pressure according to $\alpha = \alpha_0 * \Delta P^n$ with n representing compressibility. Table 4 illustrates value of n for different sludges.

Table 4 — Comparison of filtration performance with compressibility values

Cake behaviour	Compressibility index	Example
Very low compressibility	< 0,1	Glass beads
Low compressibility	0,1 to 0,5	Inorganic sludges
Medium compressibility	0,5 to 0,8	Physico-chemical sludges
High compressibility	0,8 to 1	Biological/Organic sludges
Very high compressibility	> 1	Flocculated biological sludges

The Terzaghi-Voigt model [10] enables the assessment of the kinetics of cake height decrease during expression.

6.4 Methods of evaluation

6.4.1 General

Many methods and laboratory procedures are available to evaluate sludge thickenability and dewaterability, and give information on the performance of processes that could be attained:

- specific parameters of interest for sludge dewaterability evaluation are those relevant to its settleability (EN 14702-1), thickenability (EN 14702-2), filterability (EN 14701-1 to 4) and centrifugability, while other parameters, such as particle size distribution, water distribution, and physical consistency (CEN/TR 15463), give more basic information on sludge properties;
- selection of chemicals and dosage depends on the mechanical stress flocs will undergo in the solid/liquid separation device. Consequently, floc characterisation tests should be related to the thickening or dewatering equipment used [11].

6.4.2 Settleability / Thickenability

Settleability and thickenability are defined as the capacity of sludge to settle and increase in solid concentration (normally by 2 times - 3 times) by gravitational/centrifugal acceleration.

The aptitude of sludges to settle can be evaluated by measuring the settling velocity; this can be obtained by plotting the height of the solid/liquid interface against time during settling tests in a graduated glass cylinder.

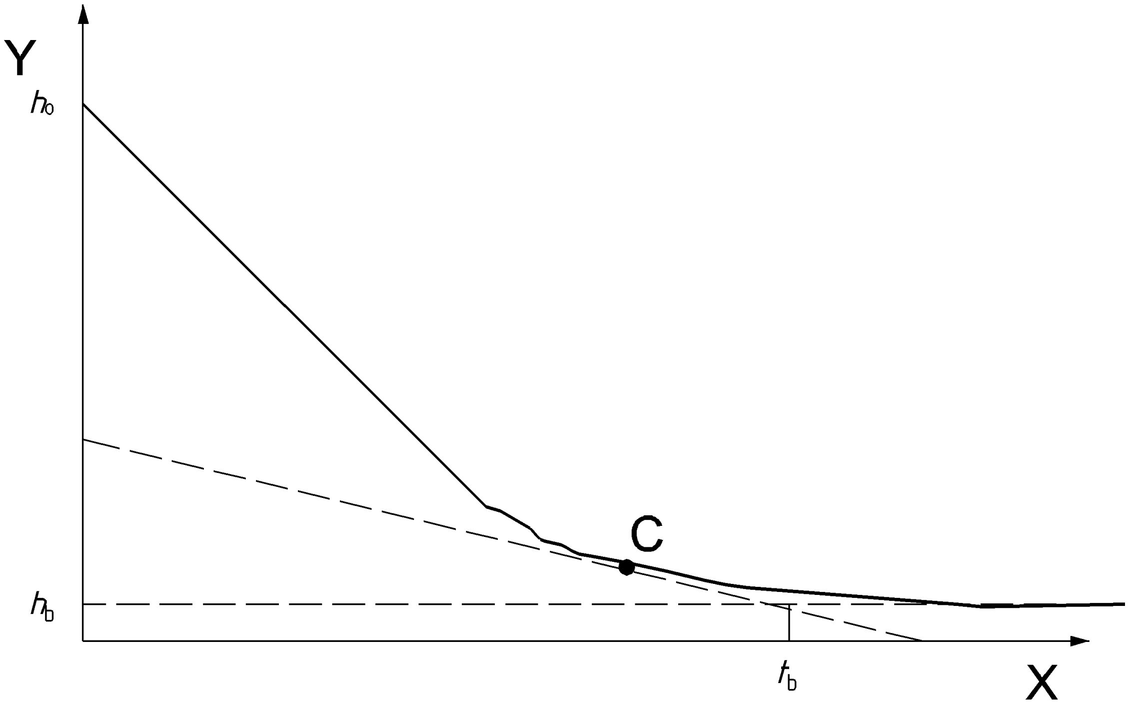
The main disadvantages of using laboratory cylinders are that the effect of high gravities cannot be evaluated and that the measurement depends on the cylinder size. In small cylinders the settling of highly concentrated suspensions is slower than in large ones due to bridging across the walls and partial support of the solids from below.

Many techniques have been proposed to overcome these problems.

EN 14702-1 specifies a method for the determination of settleability, i.e. the proportion of sludge volume and sludge volume index, of sludge suspensions in graduated cylinder, while EN 14702-2 a method for the determination of thickenability, i.e. the further concentration of suspended (undissolved) sludge solids in settling under gravity through the use of lab mechanical assisted cylinder. Good thickenability is obtained with a sludge index between 50 cm^3/g to 100 cm^3/g.

Another technique which could possibly be used for estimating the thickening behaviour, is based on the use of a low-speed stroboscopic centrifuge which allows the thickening performance, regarding both solids flow and final concentration, to be estimated [12].

Measurement of settling velocity could be done in a 2 m column that also enables information to be obtained about the compression point and sludge dryness (Figure 29). The recovered sludge can be further thickened in an Imhoff cone.



Key

X	time	h_o	sludge initial height
Y	interface height	h_b	sediment height
C	compression point	t_b	characteristic time

Figure 29 — Sedimentation curve obtained from 2 m column test

Sludge thickenability by filtration on a drainage table could be assessed by a laboratory test consisting of registering the cumulative filtrate mass over time [13] according to EN 14701-4.

6.4.3 Centrifugability

Solid liquid separation in a centrifuge is a complex dynamic process and therefore extremely difficult to simulate in a laboratory. Consequently, there's no unique test which can be used to fully assess the effectiveness of conditioning.

Centrifugability represents the aptitude of sludge to be dewatered under the action of the centrifugal force, but in full scale centrifugation the effects induced on the sludge by the screw movement (scrollability) have to be taken into account. This means that the consistency of the centrifuged sludge shall be such that it can be easily conveyed by the screw.

The only reliable method to evaluate all the above properties would be carrying out tests on a pilot scale, but this procedure is expensive, time consuming and not always possible, so several laboratory procedures have been proposed for the evaluation of centrifugability.

The laboratory methods currently available for evaluating this parameter are discussed in the following.

The method proposed by Vesilind [14] [15] allows both settling and scrolling (i.e. the sludge ability to be conveyed by the screw) properties to be evaluated.

It consists basically of centrifuging sludges by a lab centrifuge under various conditions of centrifugal force and centrifugation time, thus evaluating the settling properties by determining the suspended solid concentration in the centrate. Then, scrolling properties are determined by a penetration test.

However, tests carried out by a bench centrifuge at high centrifugal force allow the cake solids concentration to be evaluated alone, but not the settling velocity. For that, batch settling tests can be conducted also at high gravitational forces using a lab stroboscopic centrifuge [16].

However, the above method was only sufficiently reliable for high consistency sludges, e.g. waterworks sludges, and often provided unsatisfactory results with activated sludges because of the difficulty involved in evaluating the sludge consistency, since the penetrability value is almost zero. If the test is carried out at a single value of centrifugal force and centrifugation time, it is possible to calculate a “centrifugability index” [16], which can be utilised for comparing different sludges and/or different types and dosages of conditioners. A similar method has been proposed by Campbell et al. [17]. Alternatively, Vesilind and Zhang [18] have shown that sludge can be characterised by its compactability value (Γ) defined as:

$$\Gamma = z^{1,5} \times t$$

where

z is the number of gravities (dimensionless) and;

t the time of centrifugation in a lab centrifuge.

Centrifugation performance is also affected by the aptitude of the sludge flocs to resist the mechanical stresses they are subjected to into the machine [19] [20] [21].

This test is carried out by subjecting the sludge to stirring at 1,000 rpm for different times using a standard apparatus, and measuring the capillary suction time (CST) of the stirred sludge. The floc strength can be evaluated by plotting CST values vs. time of stirring. Good industrial centrifuging results are to be expected when:

- the pattern of CST is linear in the interval from 10 s to 100 s of stirring time, with a slight slope;
- the CST value after 10 s stirring is around 10 s to12 s (with 0,18 mm reservoir).

A similar principle is applied in the method based on rheological measurements [22]. The sludge is stirred using a properly modified rotational viscometer and the torque variation plotted vs. time. Indications similar to previous ones are obtained, but this test requires the use of a device which laboratories are not always equipped with.

Other completely empirical tests are utilised from manufacturers, including sludge spinning in a bottle centrifuge at high centrifugal acceleration (e.g. 2 000 G) from 30 s to 20 min and examination of the centrate turbidity and cake characteristics (water content, sludge volume and physical consistency).

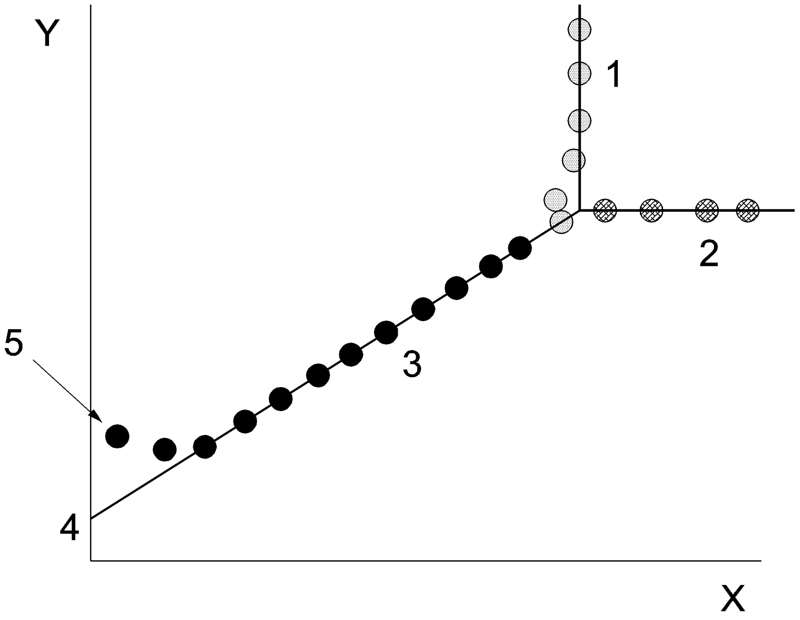
It is often recommended to carry out pilot scale experiments to help with centrifuge sizing and optimisation of operation.

6.4.4 Filterability

The classical parameter used to evaluate sludge filterability is the specific resistance to filtration (r) which represents the resistance offered to filtration by a cake deposited on the filter medium having a unit dry solids weight. This determination consists of pouring a reasonable volume of sludge into a filtering device, allowing the liquid to be filtered under vacuum or pressure, and recording the amount of filtrate with time.

Flow resistance in filtration is created by both the cake and the filtering medium resistance as deriving from the linearised Darcy's law.

It is therefore necessary that the resistance should be attributable to the cake solids alone and not the filter medium, so the initial portion of filtrate collected shall be ignored. Only the filtrate volume exceeding the initial 10 % of that of the sludge to be filtered can be used for calculations (Figure 30).



Key

1 test depleted of feed (cake deliquored)
2 permeation through a sedimented cake
3 linear part used to calculate cake resistance
4 intercept used to calculate medium resistance
5 poor experimental technique or equipment design, or prevalence of blocking over bridging

X filtrate volume
Y $\frac{\text{Filtration time}}{\text{Filtrate volume}}$

Figure 30 — Graphical interpretation of Darcy Law: characteristic plot for constant pressure filtration

EN 14701-2 specifies a method for the determination of the specific resistance to filtration of sludges.

Complementary to specific resistance to filtration is the compressibility coefficient, obtained by measuring specific resistance at different pressures.

This coefficient provides information about the most suitable operating pressure level, as values > 1,0 indicate a more than proportional increase of specific resistance with pressure and, thus, the advisability of operating at low pressures.

EN 14701-3 specifies a method for the determination of the compressibility of sludges.

The capillary suction time (CST) is also a simple, useful and rapid way to evaluate sludge filterability. The principle of the method is that dewatering is achieved by the suction applied to the sludge by the capillary action of an absorbent filter paper. Filterability is measured by the time necessary for the filtrate to cover the space between two probes detecting the advancement of the liquid front on the paper.

CST is strongly influenced by many factors, e.g. filter paper properties, temperature, suspended solids concentration, etc., so this parameter can be considered acceptable only if utilised for obtaining qualitative and comparative indications.

EN 14701-1 specifies a method for the determination of the capillary suction time.

A multi-probe CST apparatus should enable a direct estimate of specific resistance to be made with a good correlation with values determined from the conventional buchner funnel apparatus [23].

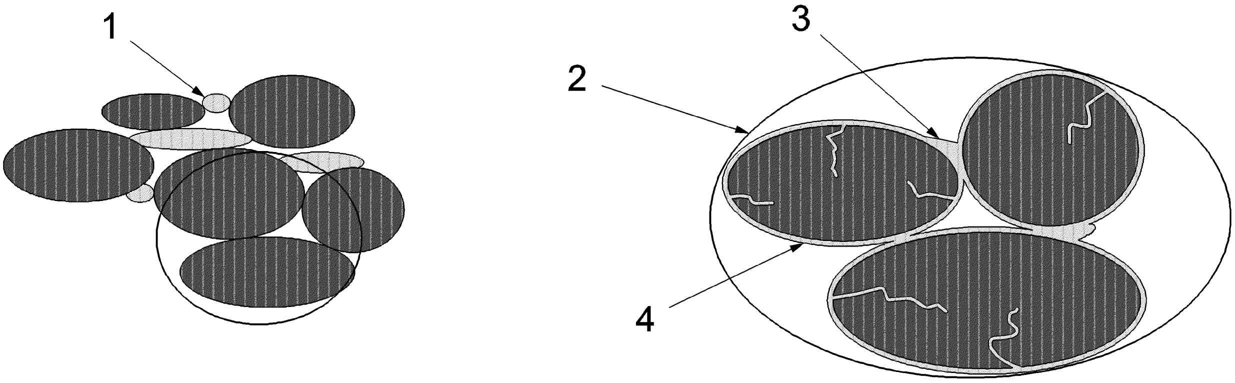
In the method described in the AFNOR documentation booklet FD T97-001-1:2011: *Characterisation Of Sludges — Tests On Sludges — Part 1: Determination Of Limiting Dryness*, the determination of the dryness is made by operating filtration-compression tests at 4 bar with a plug. Some manufacturers choose this measure as a warranty of the performances of their machines to customers.

6.4.5 Basic parameters

They include water distribution, particle size distribution and physical consistency.

a) Water distribution:

Figure 31 illustrates various water fractions existing in agglomerates of solid particles in water. The importance of this parameter is that it gives an indication of the level of forces/energy needed to break links between water and solid particles.



Key

1	interstitial water
2	internal water
3	vicinal water
4	bound water

Figure 31 — Water distribution in solid agglomerates

Classical analysis is carried out by thermogravimetry, which consists in submitting a small and thin sludge sample to drying at low temperature under standard conditions. Results are presented as drying rate curves showing three distinct stages: the constant rate period, the first falling rate period and the second one [24].

An alternative method is based on the theory that bound water does not freeze at temperatures below the freezing point of free water, so the free water can be determined by noting the expansion caused by freezing. A differential thermal analysis procedure has also been used [25].

b) **Particle size distribution:**

It is widely recognised that particle size distribution strongly affects sludge behaviour in solid-liquid separation. In particular, the higher the proportion of small particles, the higher the specific resistance to filtration.

The main problem in particle size evaluation is the difficulty of measurement [26], [27]. Three principal methods are known: direct examination, fractionation and counting, each of them requiring modifications of the sludge before and during measurements which may result in an alteration of the original distribution. A reproducibility problem is also present due to the irregular shapes of sludge flocs, so each step in sizing procedure shall be conducted carefully to preserve the original floc shape, size and structure.

The main problem of direct examination is to fix sludge in an inert medium to allow non-disruptive examination. The fractionation with a series of vibrating filters or sieves could cause the retention of smaller particles by layers where larger ones prevail. Finally, counting methods involve the use of different devices which measure signals proportional to particle size: such devices generally require mixing or pumping possibly resulting in a change of particle size distribution.

c) **Physical consistency (rheological parameters):**

The physical consistency is linked to the rheological and other mechanical properties. It is a characteristic parameter of fundamental importance in sludge characterisation, as it strongly affects almost all treatment, utilisation and disposal operations, including dewatering [28]. In addition, references to the physical consistency are often reported in European legislation on sludge as a characteristic to be evaluated for fulfilling regulation requirements.

The rheological behaviour of sewage sludge is generally described as non-Newtonian, the Ostwald pseudo-plastic and Bingham plastic models being the most recurrent ones for sludge. The Herschel Buckley model includes both previous mentioned models. Sludge has also been found to be thixotropic, which means that sludge rheology is also dependent on the shear rate history.

CEN/TR 15463 deals with the evaluation of Physical consistency and Thixotropic and Piling behaviours. The following three consistency categories have been proposed in this report:

1) liquid: sludge flowing under the effect of gravity or pressure below a certain threshold;

2) paste-like: sludge capable of continuous flow under the effect of pressure above a certain threshold and having a shear resistance below a certain threshold;

3) solid: sludge having a shear resistance above a certain threshold.

This necessarily involves setting up methods to measure values in the range of the boundary area between liquid and paste-like behaviours (limit of flowability) and that between solid and paste-like (limit of solidity) [29].

7 Critical parameters for sizing and optimisation of thickening/dewatering systems

7.1 General

Critical parameters for sizing and optimising operation of thickening/dewatering systems, and relevant design criteria, vary from system to system. In the following, for reasons of clarity, parameters and criteria are discussed only with reference to the basic systems most frequently employed and for which more experience is available, i.e. gravity thickeners, belt thickeners, filter presses, belt presses, screw presses, centrifuges.

7.2 Gravity thickeners

For gravity thickening, operation variables are:

- solid retention times;
- solid flux expressed as load of solids by unit of thickener surface.

The main operating and design parameter for this operation is the settling velocity. For a specific sludge this can be obtained by following the height of solid/liquid interface versus time (see Clause 6). The sedimentation theory then allows the volume and surface area of a gravitational settling/thickening tank to be calculated. A classical method for estimating the area requirements is the Coe and Clavenger procedure [30]; this method and others are extensively discussed in the literature [31].

Typical reference values and sizing criteria for sewage sludge include:

- solids retention times ranging from 0,5 d to 2,0 d and;
- solids loading or solids flux (expressed as kg DS/h/m^2) of 0,8 – 1,0 for activated sludge, 4, 5 – 5,1 for raw primary sludge, and 1,6 – 3,8 for raw mixed sludge.

7.3 Belt thickeners

Performances depend mainly on the following operating parameters:

- filter cloth: the higher the cloth permeability, the faster the drainage and the higher sludge dryness, but a high loss of solids would be expected in the filtrate;
- belt speed: a compromise should be chosen, depending on the input flow rate and the ability of the sludge to release water. When belt speed decreases, cake solids content and solids capture increase but the productivity of the machine could be decreased;
- cloth tension: an increase of this parameter could affect sludge dryness and solids capture ratio;
- filter area and the number and positions of ploughs.

Performances of belt thickeners can be predicted by the drainage test described in Clause 6 (EN 14701-4).

7.4 Centrifuges

Full scale sludge centrifugation is most commonly carried out in solid bowl centrifuges. The influence of the main sizing and operating variables on the separation efficiency and on the solids concentration is discussed in the following. It is assumed that the effect of each variable is evaluated by maintaining all the other variables constant. In practice, each parameter has an influence on the others.

a) Operating variables:

1) Pool depth or hydraulic level and consequent beach length:

   This is the first parameter to be adjusted when the machine is stopped. It is essential to control machine/product behaviour. Higher pool depth involves higher solid separation efficiency but may reduce cake dryness.

It is essential to find a good liquid level setting in order to maintain stable torque value and maximum cake dryness level with good separation efficiency.

2) Bowl rotational speed:

The influence of this parameter depends on the nature of the sludge to be treated and the type of conditioner. Increasing the speed improves clarification and dry matter content up to a certain limit may raise the requirement for polymer (to compensate breakage of flocs). A lower speed is used for thickening.

3) Bowl to conveyor differential speed:

A relative speed increase improves clarification to a certain point because of turbulences induced by the screw to the liquid and decreases dryness. There is a direct link between torque value and cake dryness.

Automatic torque control is possible on a centrifuge. Conveyor torque is measured permanently on a centrifuge then a simple control system adjusts differential speed in order to maintain torque value close to the set point. Differential speed ranges on modern centrifuges are usually very low (1 rpm to 10 rpm) for dewatering and higher (5 rpm to 30 rpm) for thickening.

4) Sludge flow rate:

Sludge flow rate has a direct influence on residence time so a lower sludge flow rate involves higher solid separation efficiency and increases cake solids concentration up to a certain limit.

b) Sizing variables:

Sizing variables are geometric parameters fixed by the centrifuge manufacturer.

Machines differ from each other by their length/diameter ratio cone angle as well as the geometry of their scroll.

1) Ratio length / diameter:

Internal cylindrical diameter and ratio length diameter characterise centrifuge capacity.

The larger the LT/D value is, the larger the capacity for sludge treatment will be as the centrifuge will be able to reach acceleration up to 3 000 g.

2) Conical angle:

Conical angle is between 10° to 20° on a sludge machine**, depending on the type of sludge.** A compromise should be chosen by the manufacturers between the equipment capacity and cake solids content.

3) Geometry of the scroll:

Particular scrolls are developed by the manufacturers in order to improve the cake solids concentration and the ease of extraction for specific sludges.

Design criteria are usually based on the Sigma-and-Beta theory that allows the performance of two machines of different sizes at the same centrifuge acceleration to be compared (where Sigma represents the surface of a gravity clarifier of equivalent separation performances and Beta represents the volumetric fraction of settled solids). Manufacturers can advise on the use of equivalent methods based on the same principles. This theory, however, does not take into consideration the influence of feed and extraction devices, interaction between particles, turbulences, or space occupied by solids.

7.5 Filter-presses

Main operating variables affecting the operation in a filter-press are:

- pressure during filtration and compression;

  An increase of pressure during filtration is not very useful if the cakes are highly compressible but during compression, it can enable an increase in the dryness level and a decrease in the time to achieve it.

- cycle time;

  Values shall be properly chosen in order to obtain a concentrated cake coupled to good productivity (as kg DS/m^2/h). Longer filtration and compression times imply higher cake solids concentration but productivity is consequently decreased.

- filter cloth characteristics.

  The filter cloth characteristics (material, weave, permeability, weight, mechanical strength) influence quality of filtrate, dryness of cake, easiness of discharge and its lifetime which can be very variable owing to the different stresses it undergoes during compression and discharge.

  Laboratory tests to estimate the performances obtainable in industrial devices consist of reproducing the operating conditions of a filter press (pressure cycle, time residence, cake height, filter cloth, etc.) in a filtration-compression test. As a matter of fact, for design purposes it is necessary to determine the chamber volume for treating a daily amount of sludge at a certain concentration.

  However, when tests on lab/pilot scale are not possible, some desk methods to predict the filterpress performance are available [33].

  Pilot tests are recommended to compare fixed chamber plates and membrane plates to check the potential use of the latter (maximal improvement of performances: productivity until 20 % to 50 %, dryness until 10 % to 15 %, better discharge of cakes).

7.6 Belt-presses

In belt presses, dewatering takes place in two stages (drainage and compression). In addition, during compression sludge also undergoes a shearing action due to the relative movement of the two belts which enables additional water to be released. In the transition zone between drainage and compression it is important to have a cake of such a consistency as to avoid its lateral leakage.

The main process variables affecting machine performance are:

- specific sludge flow rate per belt width;

  A common practical design criteria is based on the sludge flow rate per belt width. It is usually in the range 2 m^3/h/m to 8 m^3/h/m but values between 2 and 3 seem to be advisable in sizing beltpresses for dewatering sewage sludge [34].

  It shall be controlled to avoid lateral leakage of sludge.

- belt speed;

  It is usually in the range 50 m/h to 350 m/h.

  High speed of belts allows operation at higher capacity values, but a lower cake concentration is usually obtained.

- pressure exerted by the rollers.

It is increased by belt tension or decreasing the roller diameter. It varies between 1 bar (low pressure machine) to 7 bar (high pressure machine). Very high pressure machines (pressure 8 bar to 30 bar) enable cake dryness to improve (until 10 % point) but are not well adapted to sludges of high organic content and are very costly [34]. Pressure is limited by sludge leakage.

- filter cloth characteristics

  The influence is the same as for belt thickeners.

  It is not possible to develop a belt press filter scale up model from traditional pressure filtration but it is possible to evaluate the belt press filter performance by tests described in Clause 6. The difficulty of using filtration compression cells is to determine the pressure in the full scale machine [35] [36] [37] for which the hydraulic pressure used to stretch the belt is not correlated to the pressure exerted on the sludge. Specific devices (e.g. miniature pressure transducers placed between the belts) should be installed to gather the pressure exerted by the rolls.

7.7 Screw-presses

The operating variables are the speed of the scroll, the counter pressure, and the filter mesh characteristics.

Depending on the manufacturer and screw-press-type the outer diameter of the screening basket or the diameter of the screw-shaft can be varied. The slope of the screw depends on its diameter. Additionally the outlet is closed by a pneumatically closed cone. An annular gap between the cone and the outlet-housing is opened by the outpressed sludge. The pressure has to be optimised, because maximum is not always optimum.

The main operating variables are inlet pressure, rotational speed of the scroll, cone pressure and the filter mesh characteristics.

8 Operational and economic aspects of thickening/dewatering systems

8.1 General

For reasons of clarity operational and economic aspects of systems for water reduction in sludge are discussed only with reference to the basic systems most frequently employed and for which more experience is available. In all cases, high solids capture should be taken into consideration because it affects the amount of solids in return liquors and consequently the load to the waste water treatment plant.

8.2 Performances

By thickening, it is possible to achieve solids content values given in Table 5.

Table 5 — Solids content values (%) achieved after thickening [34]

Origin of sludge	Gravity thickeners	Flotator	Belt thickener	Disc, drum, screw thickener	Drainage bag, tubes	Centrifuge
Surface water treatment	0,5 - 4	2,5 - 5	NP	3 – 15	—	NP[a]
Groundwater treatment (Fe, Mn)	1 - 5	2,5 - 5	NP	2 – 10	10 - 20	NP
Softening processes	2 – 10	NP	NP	10 - 30	20 - 50	NP
Physico-chemical sludges	5 - 10	NP	8	—	—	NP
Biological sludges	2 - 3	3 - 5	5 - 7	5 - 7	—	6 - 8

[a] NP: not practiced.

EXAMPLES of mass capacity are:

- 10 – 150 m^3/h (50 to 2 250 kg DS/h) for belt thickener;
- 50 – 40 m^3/h (25 – 350 kg DS /h) for disc thickener;
- 3 – 100 m^3/h (15 – 1 500 kg DS /h) for rotating drum thickener;
- 8 – 90 m^3/h (40 – 750 kg DS /h) for screw thickener.

By dewatering, it is possible to achieve solids content values given in Table 6.

Table 6 — Dry residue values (%) achieved by dewatering systems

Origin of sludge	Filter-press	Belt press	Centrifuge	Screw press	Drying beds/ lagoons	Electro-osmosis	Others
Surface water treatment	—	NP	15 - 35	—	15 (wet climate) – 40 (dry climate)	—	—
Groundwater treatment	30 - 40	NP	20	—		—	22 - 45[e]
Softening processes	—	20 - 25	30 - 55	—		—	—
Physico-chemical sludges	35 - 46	22 - 30	26 – 38	30 – 40 25 - 40	—	—	18 - 22[a] 30[b] 32 – 40[c]
Biological sludges	24 - 37	14 - 18	17 - 22	17 – 23 16 - 23	30 - 60	25 - 45	15 - 24[b] 17 – 25[c]
Anaerobic digested sludges	31 – 43	18 - 26	23 - 35	25 – 35 22 – 35	—	35 - 50	20 - 30[c] 65[d] 90[e] 26[c]

[a] vacuum rotating drums

[b] lamellar centrifuge

[c] rotary press

[d] centrifuge dryer

[e] filter dryer

a) **Filter-press:**

Cake solids concentration of more than 30 % up to 50 % (25 % if only organic polymer is used on activated sludge) can be achieved by filter-presses. Disadvantages of fixed-plate (or chamber) machines include several factors, such as batch operation, low filter productivity, and high labour costs. The use of membrane plates, which are more expensive than chamber plates, allow labour costs to be reduced, overall length the pressing cycle (from 15 min to several hours) to be shortened up to 50 % and dryness to increase (up to 5 % percentile units). An air volume of 10 % to 50 % chamber volume is required to inflate membranes. Air consumption is 0,4 Nm^3/m^2. Mass capacity is in the range: 1 kg DS to 15 kg DS/m^2.h.

b) **Belt press:**

Belt-press dewatering machines are capable of producing cakes of quite good final solids concentration by means of continuous operation. Cake solids concentration lies between 15 % and 30 %, mainly depending on sludge quality. Positive aspects are quite low labour and power requirements, but particular sludge conditioning is needed for fast water draining in the first stage of operation. Belt washing involves high water consumption. Mass capacity is in the range: 80 kg DS to 400 kg DS / m width belt / h.

c) **Centrifuge:**

Cake solids contents of between 15 % and 35 % can be obtained by centrifuge. Bowl rotational speed involving centrifugal acceleration ranging from 2 000 g to 3 000 g are generally adopted, while higher values seem to have negligible benefits with regards to performance, and would have the drawbacks of increased power consumption, noise, maintenance needs, and in some cases of sludge floc mechanical stresses and higher dosage of conditioners. Mass capacity is usually in the range 100 kg DS/h to 3 000 kg DS/h. Devices of other capacity are available (from 15 kg DS/h to 6 000 kg DS/h).

d) Screw presses:

Screw presses are fully enclosed and need little operator attention. They work well if the sludge contains enough structural material. Depending on the sludge characteristics they achieve 15 % to 30 % cake solids, and much more with fibrous industrial sludge. With sewage sludge their performance is comparable with that of belt filter presses, but screw presses tend to need more polymer to generate sufficiently strong flocs. Solids capture is usually above 95 %. Capacity of common screw presses is limited to 10 m^3/h (non-thickened sludge) or 100 kg DS/h to 400 kg DS/h (thickened sludge).

e) Others:

The vacuum rotating drum is an old technique, less and less used in wastewater plants owing to high operating costs and low dewatering performances. The productivity of the filter is in the range: 8 DS/m^2/h to 18 kg DS/m^2/h.

Electroosmosis is applied to sludge from the food industry with application of an electrical field in a filter-press but developments are in progress for wastewater sludge dewatering [38]. It's a discontinuous process and productivity is low (10 kg DS/m^2.h to 15 kg DS/m^2.h) but high cake solids content (up to 60 %) can be achieved. Unexpected r kg DS/m^2.h reactions with electrodes can contaminate filtrate and cake with heavy metals.

Centrifuge and filter dryers enable dewatering and drying in a single machine. Centrifuge dryers have a capacity of evaporation of 300 kg/h to 2 000 kg/h and produce within seconds fine grained granulate with 60 % to 90 % DS. The consumption of natural gas is 250 Nm^3/t DS to 300 Nm^3/t DS and 85 % can be recycled to ensure heat recovery. Filter dryers require a boiler for water heating at 85 °C, vacuum of 40 mBar to 50 mBar. The gas consumption is around 250 Nm^3 gas/ t DS.

Drying beds require a significant area (1 m^2 to 7 m^2 per equivalent population or 50 kg DS/m^2/y to 100 kg DS/m^2/y) and are limited to small quantities of sludge to be dewatered in a region with an appropriate climate.

8.3 Energy consumption

Table 7 gives energy consumption for thickening and dewatering systems.

Table 7 — Energy consumption for thickening (initial sludge concentration: 0,7 % to 1,2 %) and dewatering systems (initial: sludge concentration: 3 % to 8 %)

Energy consumption	Kwh / t DS	Kwh / m^3
Gravity thickener	5	< 0,1
Flottator	100 to 140	0,5 to 1,2
Belt thickener	50 2 to 5	< 0,2
Disc/drum/desk thickener	< 30	< 0,2
Screw thickener	8 to 15	< 0,2
Drainage bags / tubes	< 30	< 0,2
Centrifuge	100 to 220: thickening 80 to 200 30 to 80: dewatering 15 to 80	0,6 to 1,4 1 to 4
Filter press	20 to 40	1 to 4
Belt press	10 to 40	0,5 to 1
Screw press	10 to 20	0,2 to 0,6
Drying beds / lagoons	< 10	< 0,2
Electroosmosis	150 to 200	10 to 500
Vacuum rotating drum	80 to 200	3 to 6
Lamellar centrifuge	20 to 50	1 to 2
Rotary press	10 to 40	0,5 to 1
Centrifuge dryer	300 to 330	1 200 to 1 400

8.4 Labour requirements

From the point of view of labour requirement, centrifuges and screw presses could relatively be considered the most attractive devices for sludge dewatering.

As filter-presses work on a batch system they require operator(s) to supervise/help the cake unloading but this can be partially replaced by automation.

Beltpress is a continuous system, but an operator needs to check from time to time the operation of the machine and the discharge of solids.

8.5 Water consumption

Filtering techniques require water consumption for cloth cleaning and regeneration of its initial permeability.

For filter – presses, cloth washing is usually done at the end of each cycle.

In the case of belt presses, washing could require rinsing water flow rates of 50 % to 200 % of that of the feed sludge at a pressure of 40 kPa to 60 kPa thus negatively affecting power consumptions, contributing up to 60 % of it. The water consumption is 8 m^3/m.h, twice lower than a belt thickener. Centrifuges need 20 min to

30 min washing sequence before each stop or one washing per week is recommended if 24H/24 7 day/7 running time is in operation. That means very low wash water (industrial water quality is acceptable). Wash water flow is in the range of feed product flow.

Screw presses need little spray water because backwashing of the screen happens only periodically. Average spray water consumption is 5 % to 20 % of the sludge feed flow.

8.6 Maintenance

Skilled personnel shall be employed for maintenance of centrifuges and, to avoid additional maintenance costs, coarse or abrasive matter should be removed before the machine is used to guarantee not only a good performance but also a long machine life. For this purpose, new materials such as filled replaceable tungstene carbide tiles mounted on the scroll have been introduced on the market.

In the case of a filterpresses equipped with membrane filter elements, it shall not be forgotten that these membranes need to be replaced and do not last for ever, but require a replacement on average after 4 to 5 years if not earlier. Over a period of 10 years the replacement of filter cloth is recommended for a better cake discharge. The scrapper to remove dry solids still adhering on the filter elements after opening the filter press should be available at any time of the operation. For belt-presses, the relative shorter medium life is due to belt movement and needs frequent replacement. In addition, a damaged cloth requires hours to be replaced with consequent higher maintenance costs.

Screw presses require little maintenance because they have a strong wedge wire screen of practically unlimited life. Only brushes on the screw’s flight need to be replaced after a few years of operation.

8.7 Safety aspects

Exposition of sludge to atmosphere is an important safety aspect. Centrifuge and screw presses are machines with solid liquid separation taking place in a closed environment, contrasting with gravity thickeners, belt-presses, belt thickeners and drying beds which are opened to the atmosphere.

When inorganic chemicals are used, it’s necessary to apply handling rules such as the use of gloves, glasses and protection clothes for operators and the provision of showers near the working area.

Handling of powder polymers requires anti-dust masks to be worn. This is not necessary for microspheres and emulsions. Polymeric solutions, diluted or not, have a high viscosity and quantities spilt on wet ground could involve an additional risk for the operators.

8.8 Automation

All continuously operating dewatering machines can be complemented with a system for automatic control of operations including polymer dosage control and filtrate or centrate turbidity monitoring (see 5.4.5). But operator supervision could be required.

Nowadays, filter presses and their auxiliary equipment might incorporate automation and computer control systems, so manual input from an operator is kept to a minimum. The process variables such as sludge and polymer flow rate, filtration pressure, pump speed and time can all be monitored and incorporated in a computer system to control the filtration cycle.

Automatic torque control is possible on a centrifuge to maintain torque value close to a set point. With this feature, a centrifuge operates continuously without operator presence for start sequence, operation, washing sequence, etc.). With auto torque control system, a centrifuge is not so sensitive to sludge feed concentration variations which lead to polymer flow rate changes.

On belt presses, sludge concentration variation modifies flocculation efficiency which could have consequences on machine performance.

8.9 Cost aspects

These aspects include:

a) investment cost (cost of the machine):
   1) without automation;
   2) with automation.

b) installation cost (cost of civil engineering to install the machine including building space);

c) operational cost:
   1) conditioning;
   2) maintenance (replacement of parts, filter cloth, etc.);
   3) labour (operators);
   4) energy;
   5) water consumption;
   6) safety;
   7) solids disposal;
   8) return liquor treatment.

Table 8 presents qualitative and comparative information on cost for dewatering systems.

Table 8 — Cost aspects – comparison of dewatering solutions

	Filter press	**Belt press**	**Screw press**	**Centrifuge**
Investment cost				
Capital cost	Medium to high	Low	Medium	Medium
Installation cost				
Civil engineering	High	Medium	Low	Low
Operational costs				
Conditioning	Low to medium	Low	Low	Medium to high
Maintenance	Medium	Low	Low	Medium
Labour	High	Medium	Low	Low
Energy	Medium	Low	Low	High
Water consumption	Medium	High	Medium	Low
Safety	High	High	Medium	Medium
Cake handling	Low	High	Medium	Medium
Treatment of return liquors	Low	High	Medium	Medium

8.10 Final considerations

The selection of the most suitable equipment depends on characteristics and the amount of sludge to be treated and its final destination. It also depends on plant size, operator availability skill, and infrastructure.

Dewatering with natural processes usually demands time and aerial space. Mechanical processes need less area and time for operation, but have a higher energy consumption and require conditioning.

Filter-presses are often selected where a high solids concentration and good physical consistency is required for landfilling. Belt presses and screw presses consume less energy and are less expensive than centrifuges, but centrifuges usually achieve (but not in all cases) slightly higher cake solids concentration.

Centrifuges are prevalent at medium-size to large plants while belt filter presses and screw presses are predominantly used at small to medium-size plants. Other techniques are used for specific situations.

Tables 9 and 10 sum up advantages and drawbacks of thickening and dewatering systems.

Table 9 — Comparison of thickening devices

Process	Advantage	Disadvantage
Gravity thickeners	• Simplicity • Low operational cost and demand • Low investment • Low energy consumption	• High area demand • Odours (fermentation) • Low performances with biological sludges
Flotator	• Low polymer consumption • Less volume required than sedimentation • Low operational cost and demand	• High energy cost • Vulnerable to freezing (blocking or air jets) • Potential release of odorous substances (stripping effect)
Belt thickener	• Simple and compact process	• High water consumption
Drum / disk / desk thickener	• Compactness • Low maintenance, energy and space requirement	• High polymer consumption
Screw thickener	• Simplicity • High productivity (80-100 kg DS/h) • Auto adaptative to load variations • No noise and odour • Low operation cost	• High polymer consumption
Drainage bags/tubes	• No mechanical driven parts • Low operational demand	• Long dewatering times • Load restricted by volume of container
Centrifuge	• High solids concentration • Space requirement low • Facility of operation (low labour and water consumption) • Minimal odour problems	• Vibration and noise generation • Energy consumption • Skilled staff for maintenance • Investment cost

Table 10 — Comparison of dewatering processes

Process	Advantage	Disadvantage
Filter press	• High dewatering efficiency • Low suspended solids concentration in filtrate • High operational stability • High dryness of sludges	• High investment cost • Discontinuous process • Storage capacity necessary • Supervision during cake discharge necessary • Time required for cloth washing • Unsuitable for pasty sludges • Limited filter cloth lifetime
Belt filter press	• Continuous process • Low energy cost • High productivity • Low area demand	• Many moving parts • Higher demand for maintenance • Supervision by trained operators necessary • High demand for washing water • High demand for cleaning while operating • Limited filter cloth lifetime
Centrifuge	• Good and quick adjustment to changing sludge conditions • Continuous process • Low area demand • Low demand in operation supervision • High productivity • Enclosed compact system	• High energy demand • Skilled personnel for maintenance • Machine lifetime sensitive to abrasive materials and fibers • Noise and vibrations
Screw press	• Continuous operation • Enclosed system with integrated screen washing system • Fully automation • Low noise level • Low energy consumption • Low maintenance demand • Insensitive to abrasion and clogging	• Need sludge with structure (e.g: fibers) • Limited capacities • High polymer consumption

Table 10 — Comparison of dewatering processes *(continued)*

Process	Advantage	Disadvantage
Drying beds	• Low operational cost • Low labour requirements • Dephosphatation	• Unpredictable cake solids content depending on weather conditions • Possibly unpleasant smell • Big area demand • Long time of dewatering; • Possible contamination of groundwater.
Electro-osmosis	• Well adapted to difficult sludges (colloidal, grease, abrasive) • High quality of filtrate • Intensive automation • Low maintenance • High dryness • Low maintenance	• Control of electrical leak • Dissolution of electrodes: cake and filtrate contamination with metals • Discontinuous process • Low productivity • High investment costs
Vacuum rotating drum filter	• Continuous process • High capture ratio • Stability of performances • Adaptative system	• High power requirement • High investment cost • High operational cost • Complex equipment • High maintenance • Low dryness • Not well adapted to conditioned sludges
Lamellar centrifuge system	• Adapted to difficult sludges (colloidal, grease, abrasive) • High quality of filtrate at the start • Intensive automation • Low maintenance • No chemicals needed • Low area demand • Low noise (70 dB)	• Discontinuous process • Low productivity • Filtrate quality not constant
Rotary press	• Low labour requirement • Continuous process • Low area demand • Low operating costs • Enclosed system	• Limited production rate

Table 10 — Comparison of dewatering processes *(continued)*

Process	Advantage	Disadvantage
Centrifuge dryer	• Continuous process • Low area demand • Low demand in supervision • High dryness	• Very high energy costs • Complex operation • High maintenance and operation cost • Important safety precautions • Vibrations • Abrasion • High investment cost
Filter dryer	• High dryness • Adaptative system	• Specific plates and cloth • Complex system • Labour requirement • Very high energy cost • Discontinuous process • High investment cost

9 Conclusions

Possible solutions for sludge thickening and dewatering are illustrated in Figure 1.

For the selection of a suitable thickening / dewatering system the following aspects should be considered:

a) **Intended routes for sludge disposal or utilisation:**

The dewatering objective is, in individual cases, dependent on the subsequent management steps including transportation. The main routes for sludge management are use on land, thermal processes with recovery of energy, recovery of phosphorus, utilisation of ashes, and landfill disposal.

Post-treatment (e.g. liming) enables the deliberate changing of the characteristics of dewatered sludges in order to optimise their final utilisation.

b) **Amount and characteristics of sludge:**

The amount of sludge to be handled influences the decision about centralised, de-centralised or mobile installations.

The type of wastewater and sludge treatment processes used, including chemicals, influences the characteristics of the sludges to be thickened or dewatered. The most important characteristics of sludge affecting the selection of the thickening/dewatering system are dry solids content, and the amount of organic and inorganic matter.

In any case, the decision to use a certain dewatering system should be taken on the basis of characterisation by laboratory and pilot scale tests.

Specific problems could arise from matters such as sand, colloidal particles, grease, and fibers.

c) Specific local constraints or opportunities:

The selection of the optimal and sustainable dewatering system to be adopted for a specific situation should take into account local factors such as economic circumstances, climate, regulatory constraints, public acceptance, etc.

d) Final solids concentration and physical consistency:

The final solids concentration to be obtained influences the selection of thickening / dewatering devices. As an example in dewatering, if it is not necessary to achieve high cake solids concentration, as obtained with filter-presses, centrifuges and belt presses could be preferred.

The physical consistency influences the selection of the most suitable means of storage, transport and application on land. A low flowability and a high solidity are required for landfilling while for thermal processes a high solids concentration is necessary coupled with a level of solidity sufficient for handling.

e) Quality of filtrate/centrate:

The quality of return liquors (filtrate/centrate) especially in terms of solids, organic matter and nitrogen content is important because it becomes an additional load to the wastewater treatment plant. For this reason, dewatering systems having a higher solid/liquid separation efficiency are preferred.

f) Need for space of machinery and storage:

The building space necessary for the installation of thickening / dewatering devices is important because it affects the civil engineering cost. Dewatering with natural processes demands more space than mechanical processes.

g) Investment cost:

The investment cost i.e. the cost of the machines is another aspect to be considered. It depends on many factors, but mainly the presence or not of automation.

h) Operational costs:

The operational costs including energy consumption, conditioning, maintenance, water consumption, safety, personnel, cake handling, are important factors for the selection of the thickening / dewatering system.

i) Availability of resources:

Availability of resources like energy, materials, water, skilled operators and infrastructure, has also to be considered.

Annex A
(informative)

Environmental checklist

Document number (if available):	Title of standard: Good practice for dewatering	TC/SC/WG number: CEN/TC 308/WG 2
Work item number (if available): 00308069	Version of the environmental checklist:	Date of last modification of the environmental checklist:

Environmental Issue	**Stages of the life cycle**										**All stages**
	Acquisition		**Production**		**Use**			**End-of-Life**			
	Raw materials and energy	**Pre-manufactured materials & components**	**Production**	**Packaging**	**Use**	**Maintenance and repair**	**Use of additional products**	**Reuse/ Material and Energy Recovery**	**Incineration without energy recovery**	**Final disposal**	**Transportation**
Inputs											
Materials	X (sludge)	X (polymers, lime)	Dewatering devices / equipments								X
Water		X	X (to clean the belts etc.)								
Energy	X		X								
Land		X	X								
Outputs											
Emissions to air			X								
Discharges to water											
Discharges to soil											
Waste											
Noise, vibration, radiation, heat			X								
Other relevant aspects											
Risk to the environment from accidents or unintended use			X								
Customer information			X								

Comments: Use and end-of-life aspects are dealt with in other guides of the series
Discharges to water: through the wastewater plant
Transportation: the dewatered sludge are transported by pipes to another part of the plant

NOTE 1 The stage of packaging refers to the primary packaging of the manufactured product. Secondary or tertiary packaging for transportation, occurring at some or all stages of the life cycle, is included in the stage of transportation.

NOTE 2 Transportation can be dealt with as being a part of all stages (see checklist) or as separate sub-stage. To accommodate specific issues relating to product transportation and packaging, new columns can be included and/or comments can be added.

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