Water & Wastewater Treatment-1

- Coagulation & Flocculation

- Granular Filtration

(from *MWH's Water Treatment Principles and Design* by Crittenden et al.)

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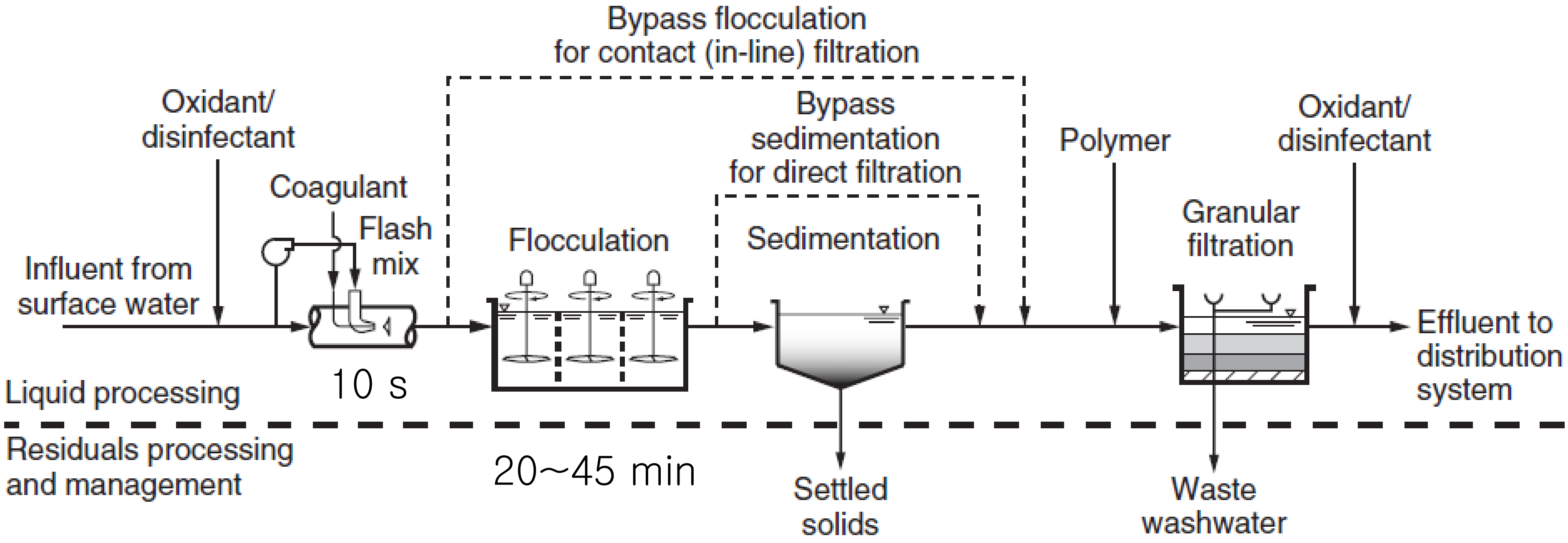
Coagulation and Flocculation

Role of Coagulation and Flocculation



Typical water treatment process flow diagram employing coagulation (chemical mixing) with conventional treatment, direct filtration, or contact filtration.

Coagulation Process

√ The coagulation process involves

-Destabilization of small suspended and colloidal particulate matter

-Adsorption and/or reaction of portions of the colloidal and dissolved NOM to particles

-Creation of flocculant particles that will sweep through the water to be treated, enmeshing small suspended, colloidal, and dissolved material as they settle

Flocculation Process

√ The purpose of flocculation

-To produce particles, by means of aggregation, that can be removed by subsequent particle separation procedures such as gravity sedimentation and/or filtration. Two general types of flocculation

√ Classifications

-Microflocculation in which particle aggregation is brought about by the random thermal motion of fluid molecules (known as Brownian motion)

-Macroflocculation in which particle aggregation is brought about by inducing velocity gradients and mixing in the fluid containing the particles to be flocculated

Practical Design Issues

√ Things to consider

-The type and concentration of coagulants and flocculant aids,
-The mixing intensity and the method used to disperse chemicals into the water for destabilization,
-The mixing intensity and time for flocculation
-The selection of the liquid–solid separation process (e.g., sedimentation, flotation, and granular filtration)

Stability of Particles in Water

Particle–Solvent Interactions

√ **Hydrophobic (water repelling) and Hydrophilic (water attracting) particles**

-Hydrophobic particles have a well defined interface between the water and solid phases and have a low affinity for water molecules.

-Hydrophobic particles are thermodynamically unstable and will aggregate irreversibly over time.

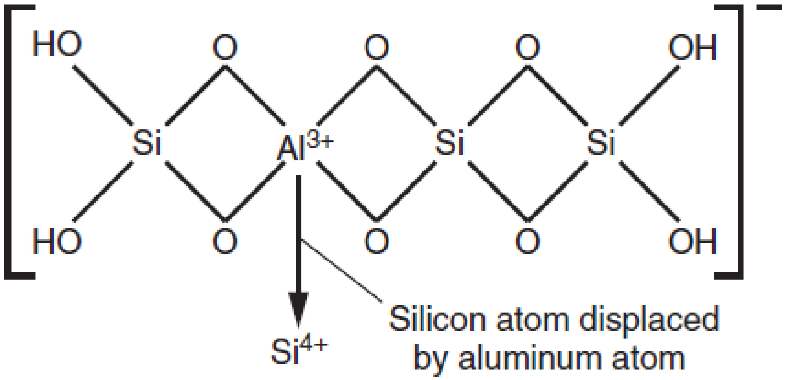
-Hydrophilic particles such as clays, metal oxides, proteins, or humic acids have polar or ionized surface functional groups.

-Water molecules will bind to the polar or ionized surface functional groups

Electrical Properties of Particles

√ ORIGIN OF PARTICLE SURFACE CHARGE

- Isomorphous replacement (crystal imperfections)



Charge acquisition through isomorphous substitution of Al for Si.

- Structural imperfections

  e.g., Broken bonds on the crystal edge

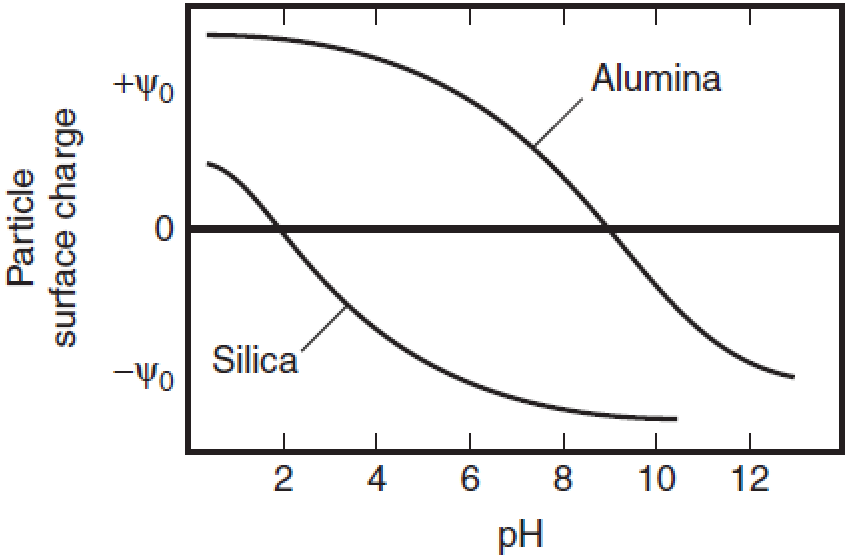
- Preferential adsorption of specific ions

  Particles adsorb NOM (e.g., fulvic acid), and these large macromolecules typically have a negative charge because they contain carboxylic acid groups

- Ionization of inorganic groups on particulate surfaces

$$\mathrm{Si-OH_2^+} \rightleftarrows \mathrm{Si-OH + H^+} \rightleftarrows \mathrm{Si-O^- + 2H^+}$$

$\mathrm{pH} \ll 2$ $\mathrm{pH} = 2$ $\mathrm{pH} \gg 2$



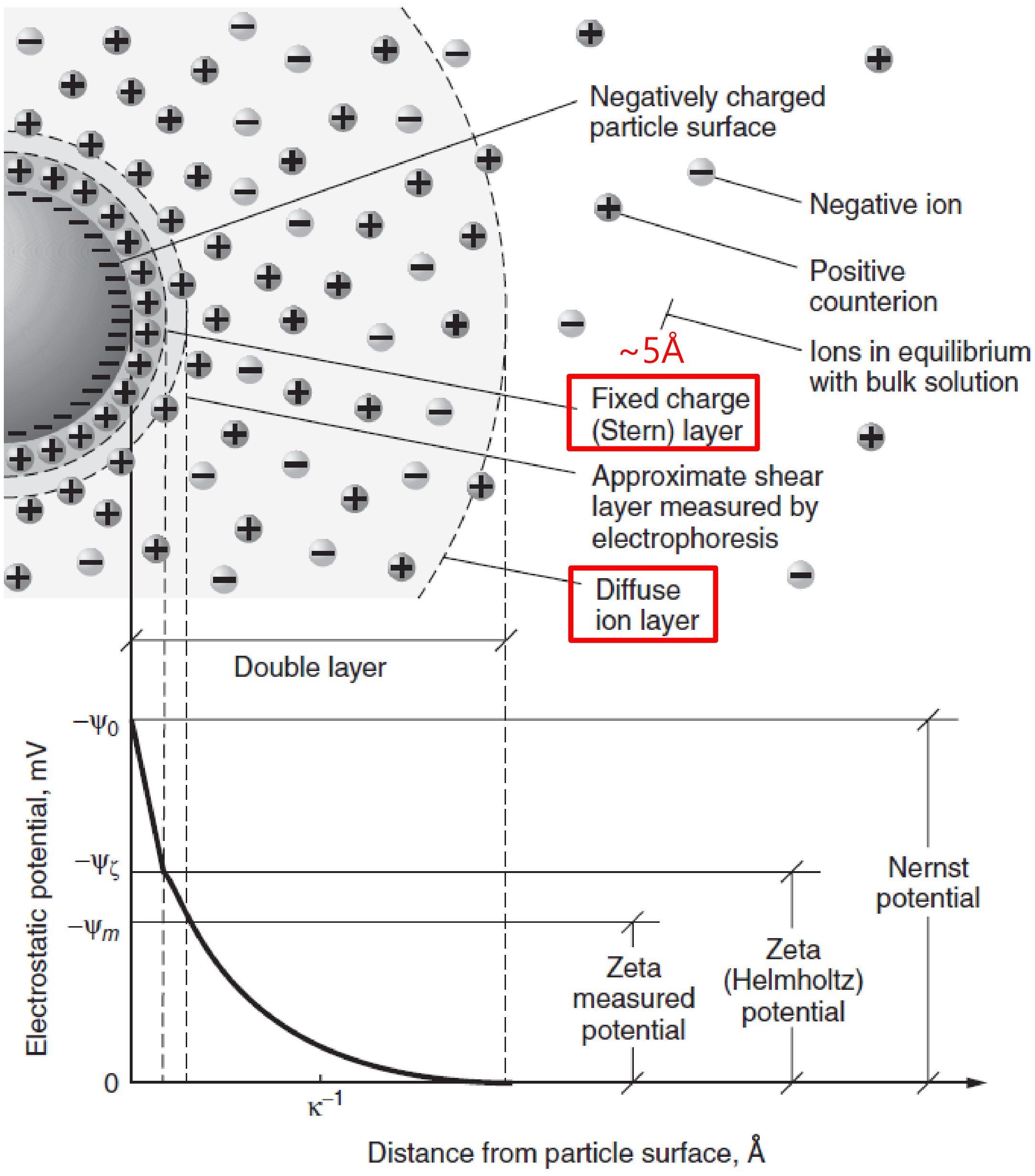
Variation in particle charge with pH.

Table
Surface characteristics of inorganic and organic particulates commonly found in natural waters

Type of Particle	Zero Point of Charge, pH_{zpc}
Inorganic	
$Al(OH)_3$ (amorphous)	7.5–8.5
Al_2O_3	9.1
CuO_3	9.5
$Fe(OH)_3$ (amorphous)	8.5
MgO	12.4
MnO_2	2–4.5
SiO_2	2–3.5
Clays	
Kaolinite	3.3–4.6
Montmorillonite	2.5
Asbestos	
Chrysotile	10–12
Crocidolite	5–6
$CaCO_3$	8–9
$Ca_5(PO_4)_3OH$	6–7
$FePO_4$	3
$AlPO_4$	4
Organic	
Algae	3–5
Bacteria	2–4
Humic acid	3
Oil droplets	2–5

Source: From Parks (1967) and Stumm and Morgan (1981).

√ ELECTRICAL DOUBLE LAYER

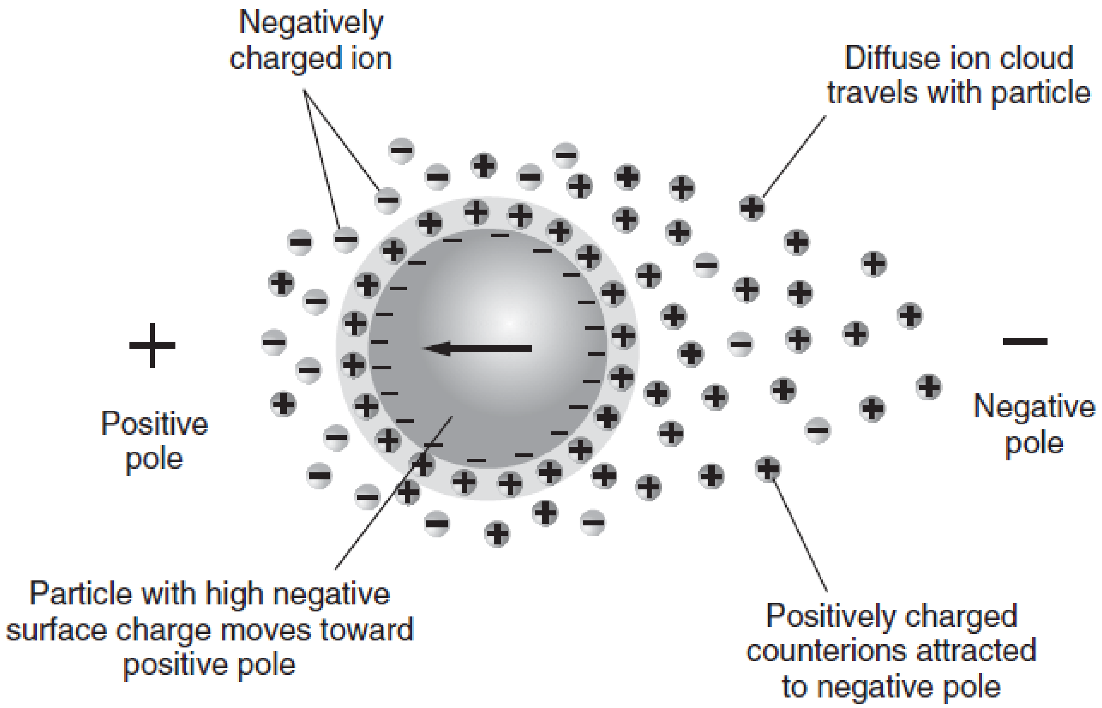


Structure of the electrical double layer. The potential measured at the shear plane is known as the zeta potential. The shear plane typically occurs in diffuse layer.

√ ZETA POTENTIAL

$$Z = \frac{v^0 k_z \mu}{\varepsilon\varepsilon_0}$$

Z = zeta potential, V
v^0 = electrophoretic mobility, $(\mu\text{m/s})/(\text{V/cm})$
$= \nu_E/E$
ν_E = electrophoretic velocity of migrating particle, μm/s (also reported as nm/s and mm/s)
E = electrical field at particle, V/cm
k_z = constant that is 4π or 6π
μ = dynamic viscosity of water, $\text{N} \cdot \text{s/m}^2$
ε = permitivity relative to a vacuum (ε for water is 78.54, unitless)
ε_0 = permitivity in a vacuum, $8.854188 \times 10^{-12}\ \text{C}^2/\text{J} \cdot \text{m}$ (note that $\text{C}^2/\text{J} \cdot \text{m}$ is equivalent to N/V^2)



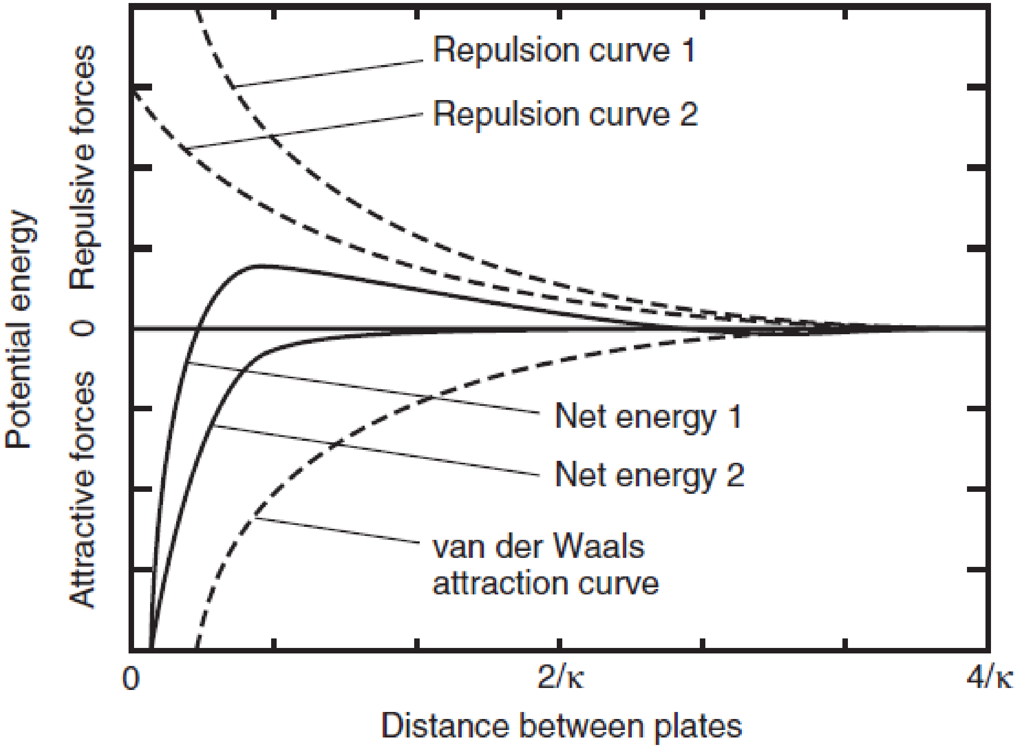
Schematic illustration of electrophoresis in which a charged particle moves in an electrical field, dragging with it a cloud of ions.

Particle Stability

√ **REPULSIVE ELECTROSTATIC FORCES**

√ **VAN DER WAALS ATTRACTIVE FORCE**

√ **PARTICLE–PARTICLE INTERACTIONS (DLVO Model)**



Attractive and repulsive potential energy that result when two particles are brought together.

Compression of the Electrical Double Layer

√ DOUBLE-LAYER THICKNESS

$$\kappa^{-1} = 10^{10}\left[\frac{(2)\,(1000)\,e^{2}N_{A}I}{\varepsilon\varepsilon_{0}\,kT}\right]^{-1/2}$$

where κ^{-1} = double-layer thickness, Å
10^{10} = length conversion, Å /m
1000 = volume conversion, L/m^3
e = electron charge, 1.60219×10^{-19} C
N_A = Avagadro's number, 6.02205×10^{23}/mol
I = ionic strength, $\frac{1}{2}\sum z^2 M$, mol/L
z = magnitude of positive or negative charge on ion
M = molar concentration of cationic or anionic species, mol/L
ε = permittivity relative to a vacuum (ε for water is 78.54, unitless)
ε_0 = permittivity in a vacuum, 8.854188×10^{-12} C^2/J · m
k = Boltzmann constant, 1.38066×10^{-23} J/K
T = absolute temperature, K (273 + °C)

*Particles are stable in freshwater (low ionic strength but high electrical repulsive forces) and flocculate rapidly in salt water (high ionic strength but low electrical repulsive forces).

Coagulation Practice

Inorganic Metallic Coagulants

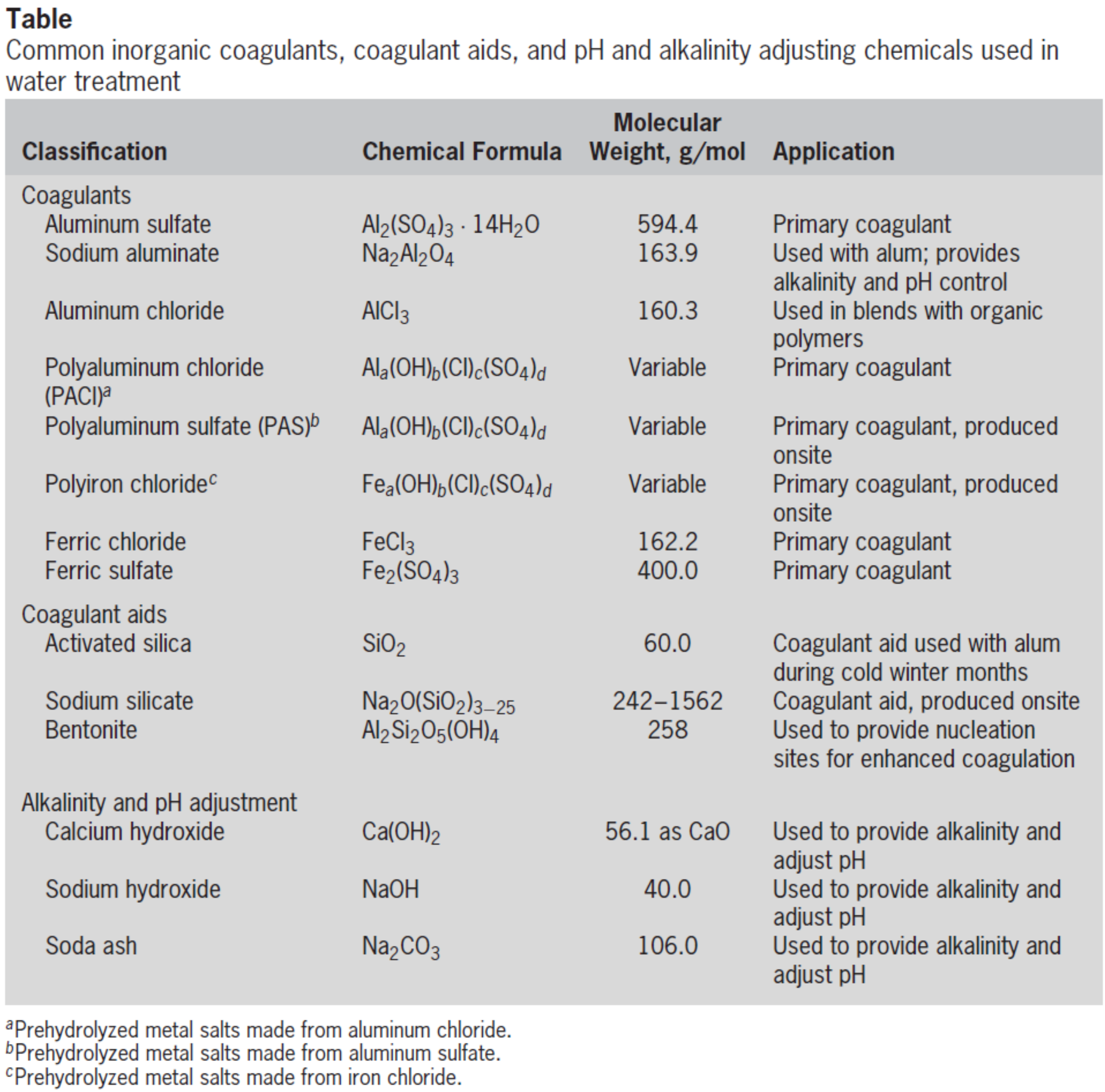
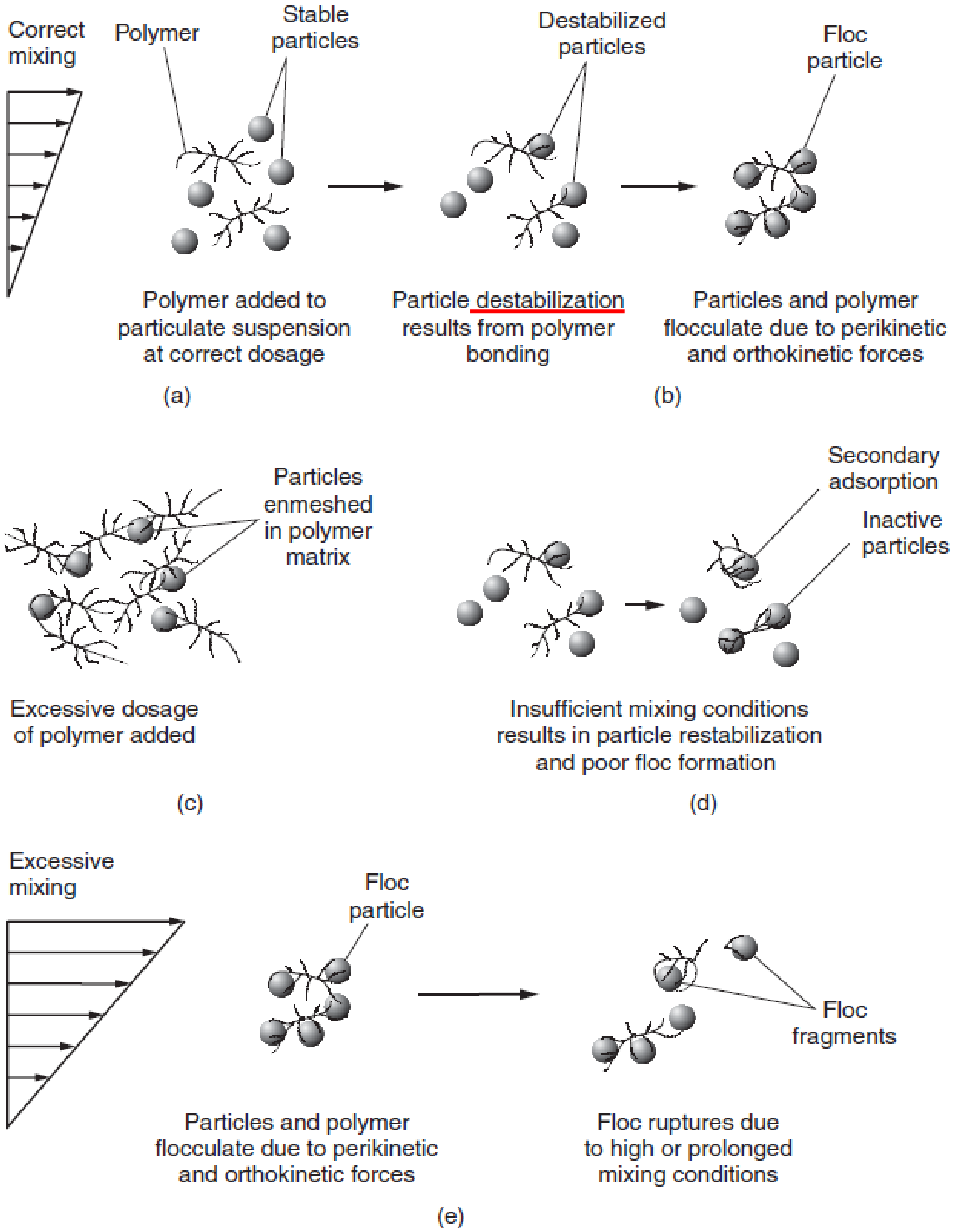


Table
Common inorganic coagulants, coagulant aids, and pH and alkalinity adjusting chemicals used in water treatment

Classification	Chemical Formula	Molecular Weight, g/mol	Application
Coagulants			
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 14H_2O$	594.4	Primary coagulant
Sodium aluminate	$Na_2Al_2O_4$	163.9	Used with alum; provides alkalinity and pH control
Aluminum chloride	$AlCl_3$	160.3	Used in blends with organic polymers
Polyaluminum chloride (PACl)[a]	$Al_a(OH)_b(Cl)_c(SO_4)_d$	Variable	Primary coagulant
Polyaluminum sulfate (PAS)[b]	$Al_a(OH)_b(Cl)_c(SO_4)_d$	Variable	Primary coagulant, produced onsite
Polyiron chloride[c]	$Fe_a(OH)_b(Cl)_c(SO_4)_d$	Variable	Primary coagulant, produced onsite
Ferric chloride	$FeCl_3$	162.2	Primary coagulant
Ferric sulfate	$Fe_2(SO_4)_3$	400.0	Primary coagulant
Coagulant aids			
Activated silica	SiO_2	60.0	Coagulant aid used with alum during cold winter months
Sodium silicate	$Na_2O(SiO_2)_{3-25}$	242–1562	Coagulant aid, produced onsite
Bentonite	$Al_2Si_2O_5(OH)_4$	258	Used to provide nucleation sites for enhanced coagulation
Alkalinity and pH adjustment			
Calcium hydroxide	$Ca(OH)_2$	56.1 as CaO	Used to provide alkalinity and adjust pH
Sodium hydroxide	NaOH	40.0	Used to provide alkalinity and adjust pH
Soda ash	Na_2CO_3	106.0	Used to provide alkalinity and adjust pH

[a] Prehydrolyzed metal salts made from aluminum chloride.
[b] Prehydrolyzed metal salts made from aluminum sulfate.
[c] Prehydrolyzed metal salts made from iron chloride.



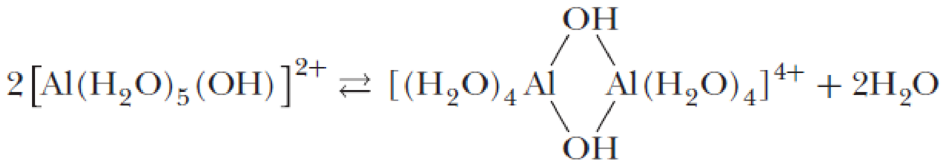
Schematic representation of the bridging model for the destabilization of particles by polymers. (Adapted from O'Melia, 1972.)

√ ACTION OF ALUM AND IRON SALTS

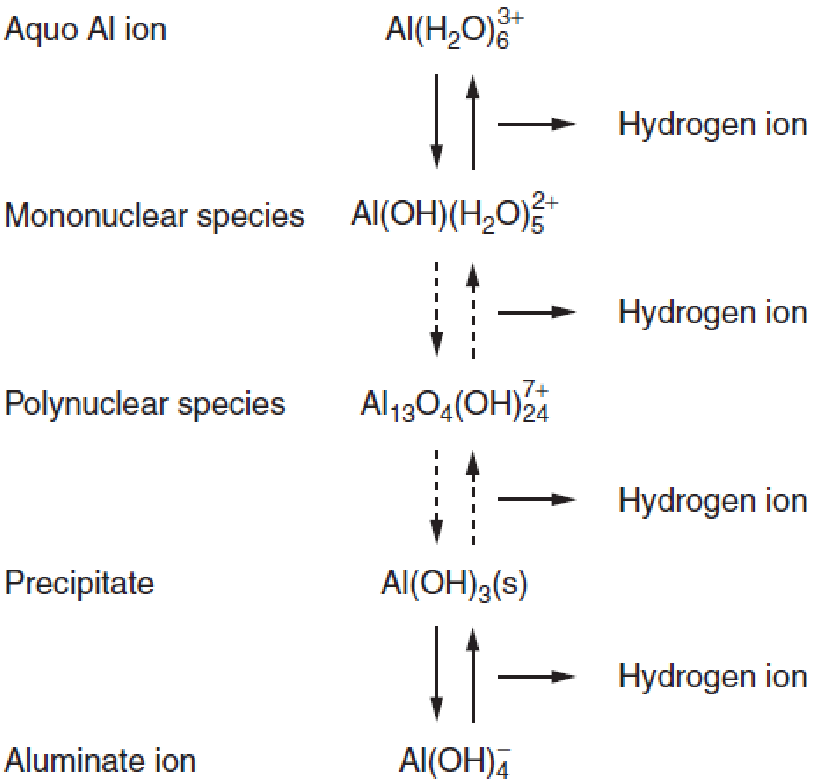
$$Al_2(SO_4)_3 \rightleftarrows 2Al^{3+} + 3SO_4^{2-}$$

$$FeCl_3 \rightleftarrows Fe^{3+} + 3Cl^-$$

$$\left[\begin{array}{ccc} H_2O & & OH_2 \\ H_2O - & Al & - OH_2 \\ H_2O & & OH_2 \end{array}\right]^{3+} \rightleftarrows \left[\begin{array}{ccc} H_2O & & OH \\ H_2O - & Al & - OH_2 \\ H_2O & & OH_2 \end{array}\right]^{2+} + H^+$$



$$2[Al(H_2O)_5(OH)]^{2+} \rightleftarrows [(H_2O)_4Al\overset{OH}{\underset{OH}{\diamond}}Al(H_2O)_4]^{4+} + 2H_2O$$



Aquo Al ion $Al(H_2O)_6^{3+}$

Hydrogen ion

Mononuclear species $Al(OH)(H_2O)_5^{2+}$

Hydrogen ion

Polynuclear species $Al_{13}O_4(OH)_{24}^{7+}$

Hydrogen ion

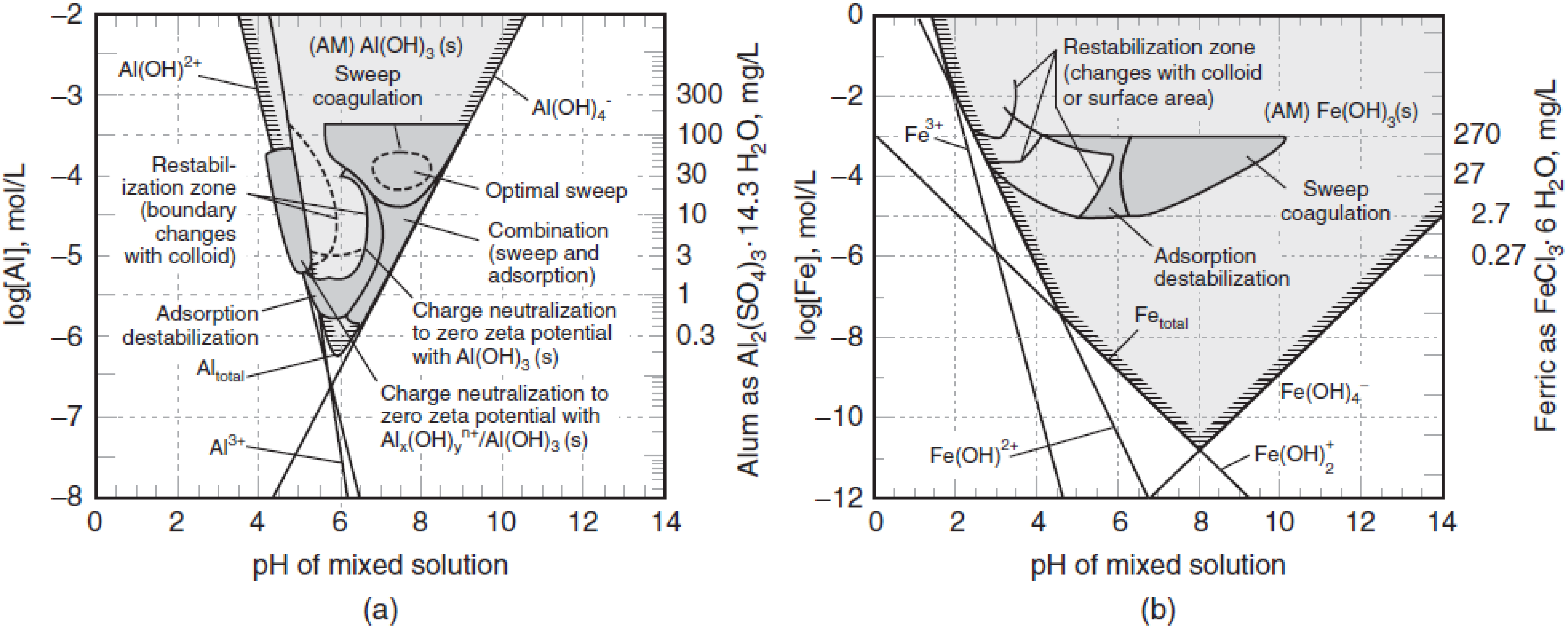
Precipitate $Al(OH)_3(s)$

Hydrogen ion

Aluminate ion $Al(OH)_4^-$

Figure
Aluminum hydrolysis products. The dashed lines are used to denote an unknown sequence of reactions. (Adapted from Letterman, 1981)

√ SOLUBILITY OF METAL SALTS



(a)

(b)

Figure

Solubility diagram for (a) Al(III) and (b) Fe(III) at 25°C. Only the mononuclear species have been plotted. The metal species are assumed to be in equilibrium with the amorphous precipitated solid phase. Typical operating ranges for coagulants: (a) alum and (b) iron. (Adapted from Amirtharajah and Mills, 1982)

√ OPERATING REGIONS FOR METAL SALTS

-Refer to the figure (on the previous slide)

The approximate regions in which the different phenomena associated with particle removal are plotted as a function of the alum dose and the pH

(e.g., optimum particle removal by sweep floc occurs in the pH range of 7 to 8 with an alum dose of 20 to 60 mg/L).

-Interactions with other constituents in water

Hydrolysis products of aluminum and iron react with various ligands (e.g., SO_4^{2-},NOM, F^-, PO_4^{3-}) forming both soluble and insoluble products that will influence the quantity or dose of the coagulant

- Typical dosages

Alum: 10 to 150 mg/L
Ferric sulfate:10 to 250 mg/L
ferric chloride: 5 to 150 mg/L, depending on raw-water quality and turbidity.
Ferric chloride is more commonly used than ferric sulfate and comes as a liquid.

- Importance of initial mixing with metal salts

The hydrolysis of aluminum and iron species (forming polymeric species) is instantaneous (It occurs within a second).
Achieving extremely low blending times in large treatment plants is often difficult.
(low blending times can be achieved by using multiple mixers).

Jar-Testing

√ JAR TEST PROCEDURE

-The jar test consists of a rapid-mix phase (blending) with simple batch addition of the coagulant or coagulants followed by a slow-mix period to simulate flocculation.

Flocs are allowed to settle and samples are taken from the supernatant.

-Parameters to be measured as part of the jar test routine:

(1) turbidity or suspended solids removal

(2) NOM removal as measured by dissolved organic carbon (DOC) or UV_{254}

(3) Residual dissolved coagulant concentrations of Fe or Al coagulants

(4) Sludge volume that is produced.

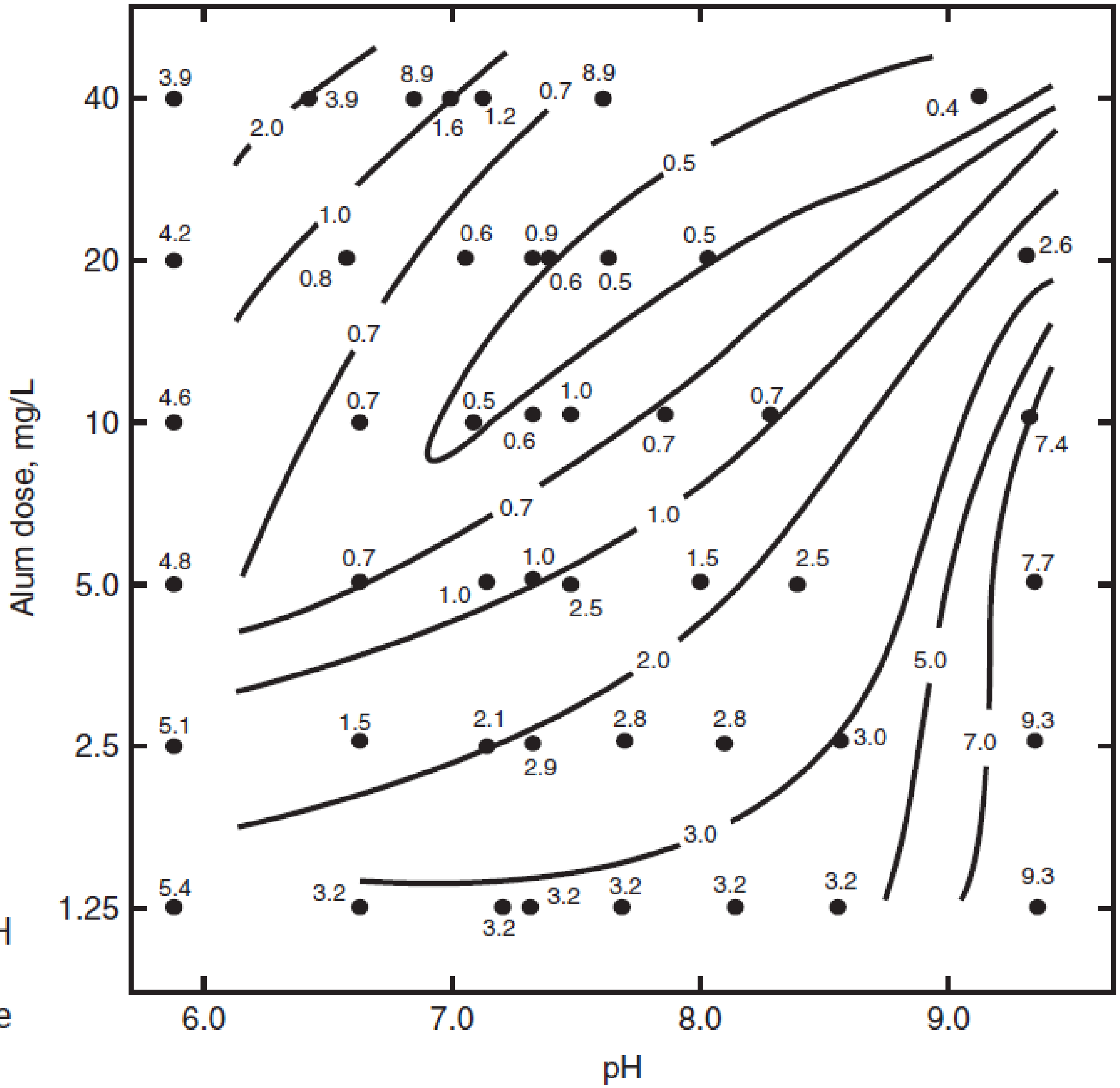


Figure
Turbidity topogram as function of pH and alum dosage. (Adapted from Trussell, 1978.) Points shown on the plot represent turbidity values and the isopleths represent constant turbidity at the value denoted on the isopleth.

Determination of Coagulant Dose for DOC Removal

$$\mathrm{DOC}_f = \mathrm{DOC}_{\mathrm{na}} + \mathrm{DOC}_{a,f}$$

where DOC_f = final DOC concentration, mg/L
$\mathrm{DOC}_{\mathrm{na}}$ = nonadsorbable DOC concentration, mg/L
$\mathrm{DOC}_{a,f}$ = adsorbable DOC remaining in solution after coagulation, mg/L

$$(\mathrm{SUVA})_i = (100)\left(\frac{\mathrm{UV}_{254,i}}{\mathrm{DOC}_i}\right)$$

where $(\mathrm{SUVA})_i$ = specific UV absorbance of influent water, L/mg·m
DOC_i = influent DOC concentration, mg/L
$\mathrm{UV}_{254,\mathrm{i}}$ = influent UV_{254} absorbance, cm^{-1}

The nonadsorbable DOC is determined from the expression

$$\mathrm{DOC}_{\mathrm{na}} = \mathrm{DOC}_i \times \left[K_1\,(\mathrm{SUVA})_i + K_2\right]$$

where K_1, K_2 = empirical constants

$$q = \frac{Q_M\, b\left(\mathrm{DOC}_{a,f}\right)}{1 + b\left(\mathrm{DOC}_{a,f}\right)}$$

$$Q_M = x_3\,(pH)^3 + x_2\,(pH)^2 + x_1\,(pH)$$

where q = DOC adsorbed at equilibrium, mg DOC/mmol of Al^{3+} or Fe^{3+} added (the adsorbent is the floc that forms after the coagulant is added)
Q_M = total adsorbent capacity at monolayer coverage, mg DOC/mmol of Al^{3+} or Fe^{3+} added
x_1, x_2, x_3 = empirical constants
pH = coagulation pH
b = Langmuir equilibrium constant
DOC

q x M

$$\mathrm{DOC}_i = \mathrm{DOC}_{\mathrm{na}} + \mathrm{DOC}_{a,f} + q\,(M)$$

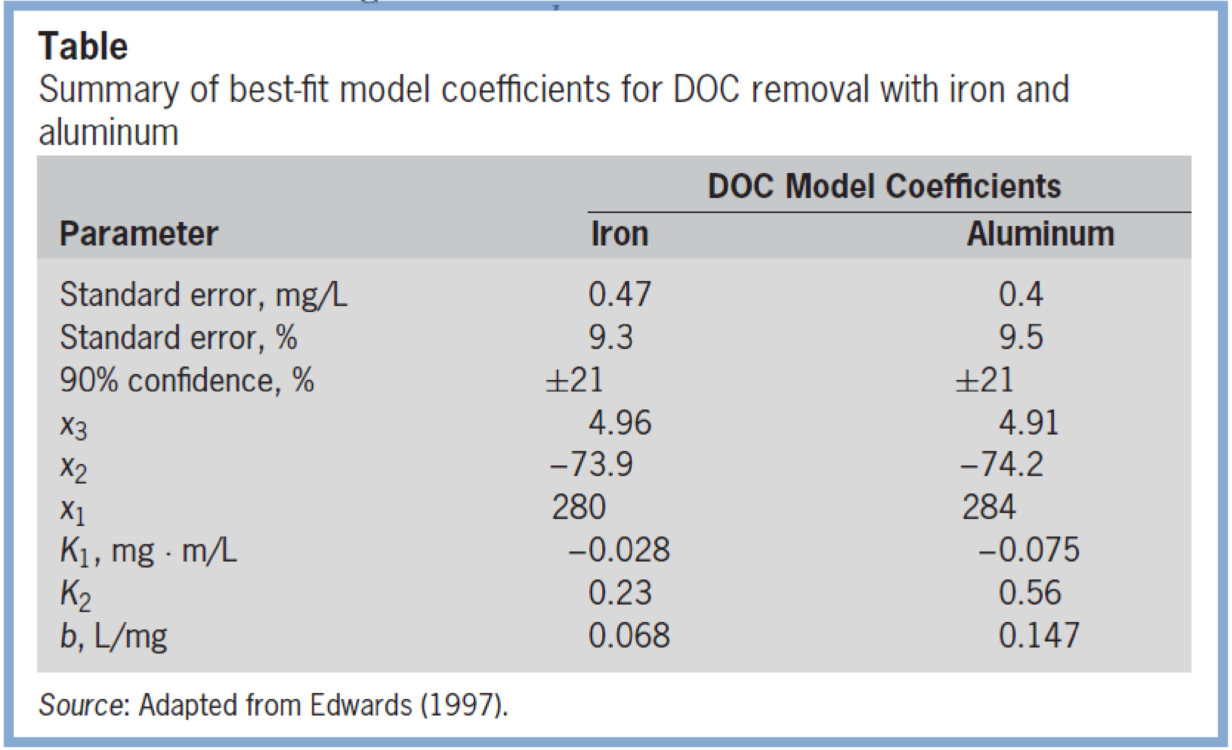
where $M = \mathrm{Al}^{3+}$ or Fe^{3+} added as coagulant, mmol/L (mM)

$$(\mathrm{DOC}_{a,f})^2 + B\,(\mathrm{DOC}_{a,f}) + C = 0$$

where B and C are defined as

$$B = Q_M M + \frac{1}{b} - \mathrm{DOC}_i + \mathrm{DOC}_{\mathrm{na}}$$

$$C = \frac{\mathrm{DOC}_{\mathrm{na}} - \mathrm{DOC}_i}{}$$



Table

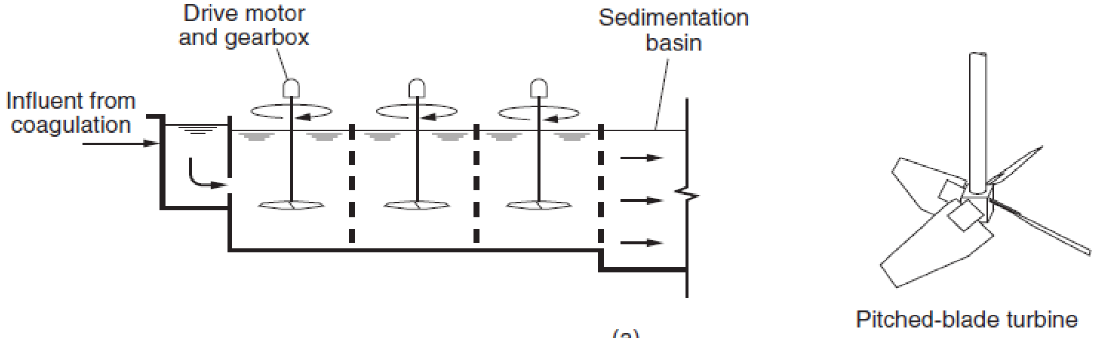
Summary of best-fit model coefficients for DOC removal with iron and aluminum

	DOC Model Coefficients	
Parameter	**Iron**	**Aluminum**
Standard error, mg/L	0.47	0.4
Standard error, %	9.3	9.5
90% confidence, %	±21	±21
x_3	4.96	4.91
x_2	−73.9	−74.2
x_1	280	284
K_1, mg · m/L	−0.028	−0.075
K_2	0.23	0.56
b, L/mg	0.068	0.147

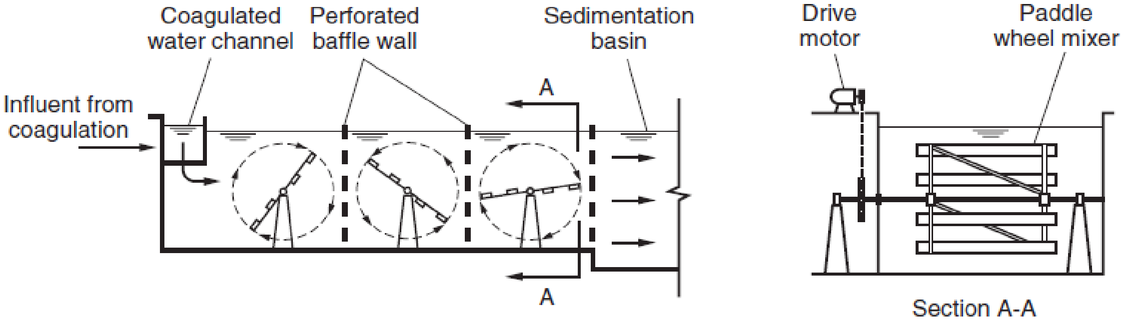
Source: Adapted from Edwards (1997).

Flocculation Practice

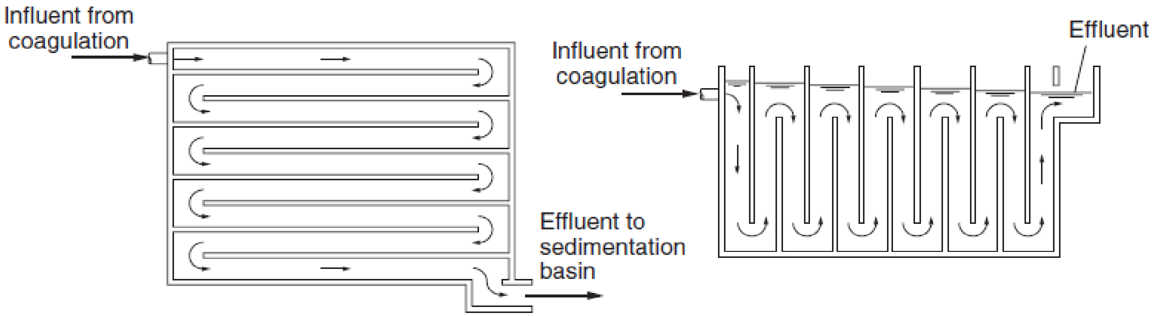
√ **Flocculation systems**



(a)



(b)



(c)

(a) Vertical-shaft turbine flocculation system

(b) Horizontal paddle wheel flocculation system

(c) Hydraulic flocculation system

Vertical Turbine Flocculators

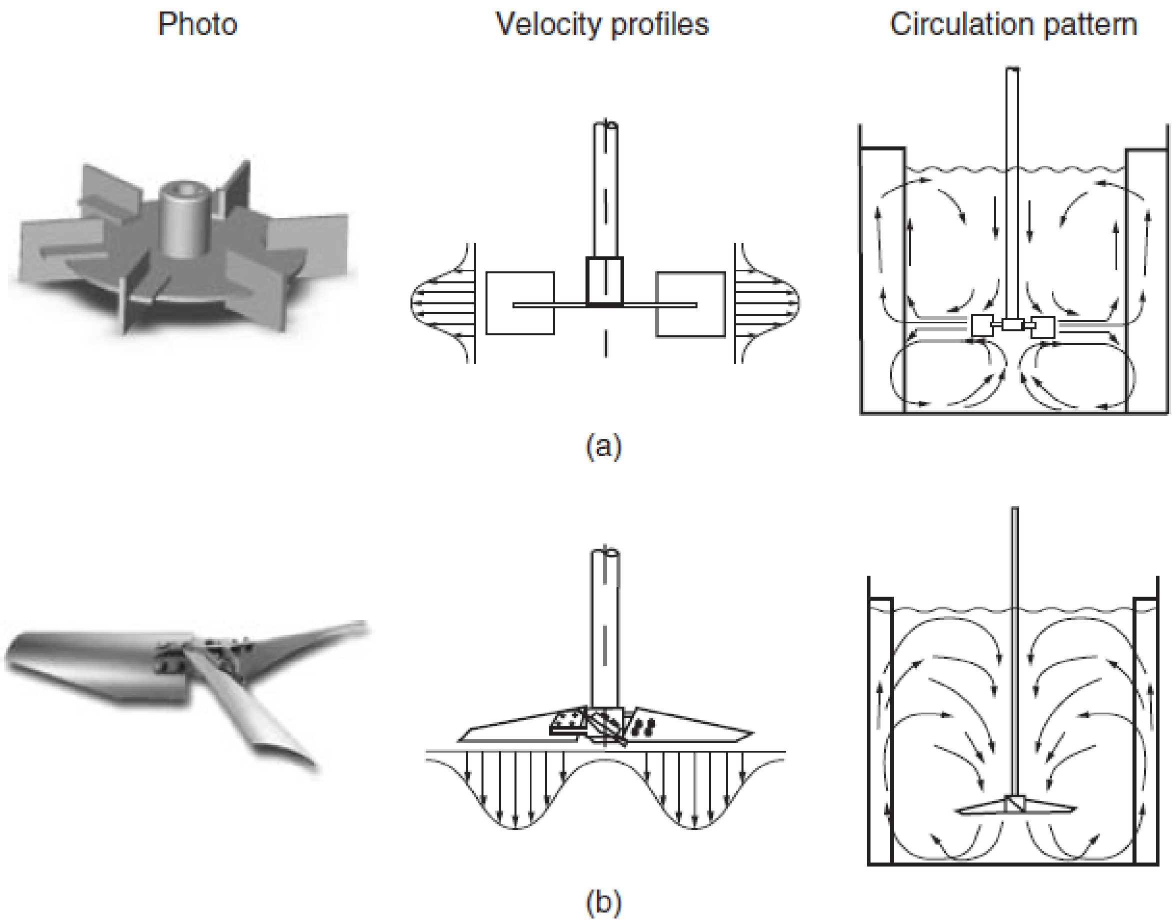
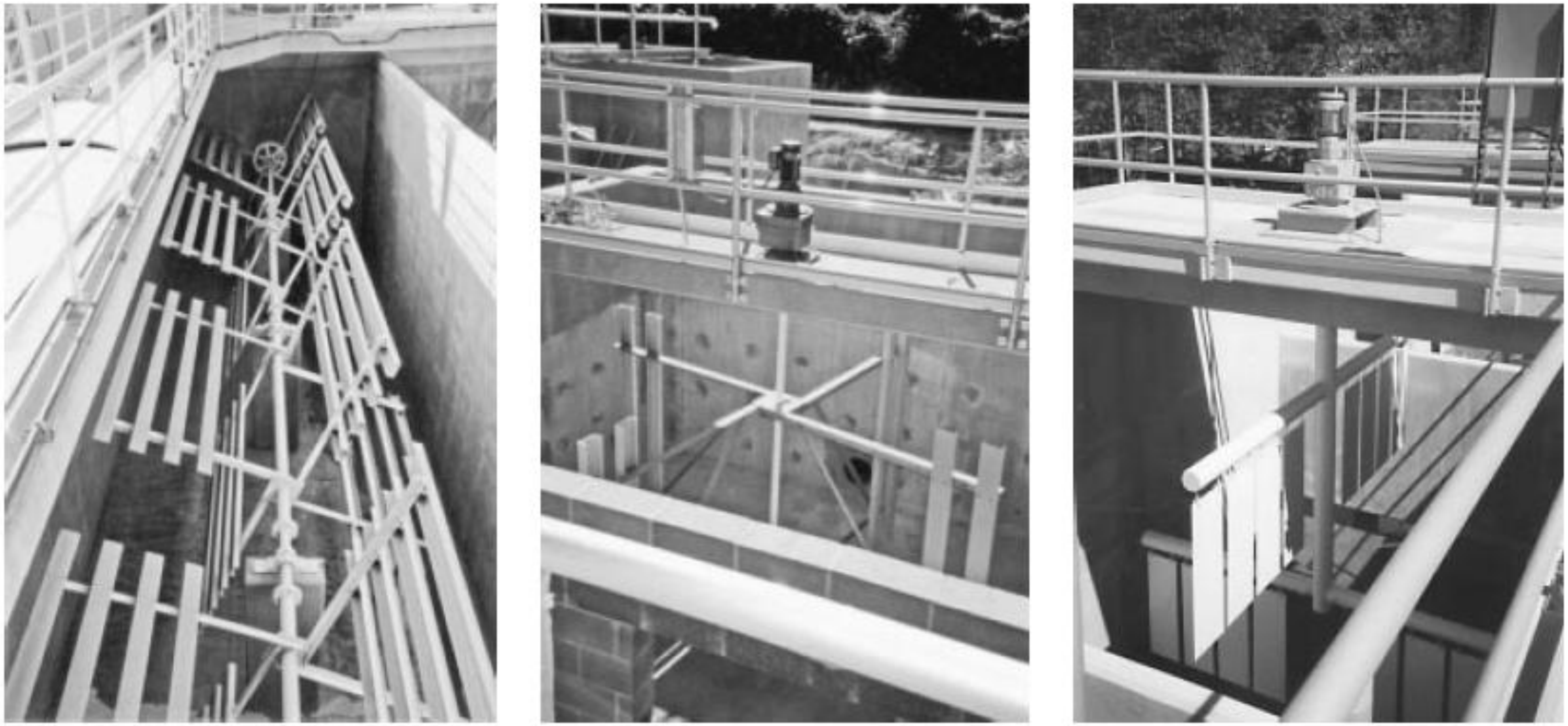


Figure
Comparison of (a) radial and (b) axial flow mixers with respect to shape, velocity profiles, and circulation patterns. (Adapted from Oldshue and Trussell, 1991.)

Horizontal Paddle Wheel Flocculators



(a) (b) (c)

Figure

Views of paddle flocculators: (a) horizontal paddle wheel arrangement and (b) and (c) vertical paddle arrangements. (Courtesy AMWELL A Division of McNish Corp.)

Hydraulic Flocculation

√ BAFFLED CHANNELS

-The most common form of hydraulic flocculators

√ HYDRAULIC-JET FLOCCULATORS

-The helicoidal flow flocculator

-The Alabama flocculator

-The variable-gate flocculator

√ COARSE-MEDIA FLOCCULATORS

-Energy dissipation is achieved by turbulent flow through a coarse media.

-Also called roughing filters or adsorption clarifiers because the coarse media also have excellent properties for storing coagulated solids.

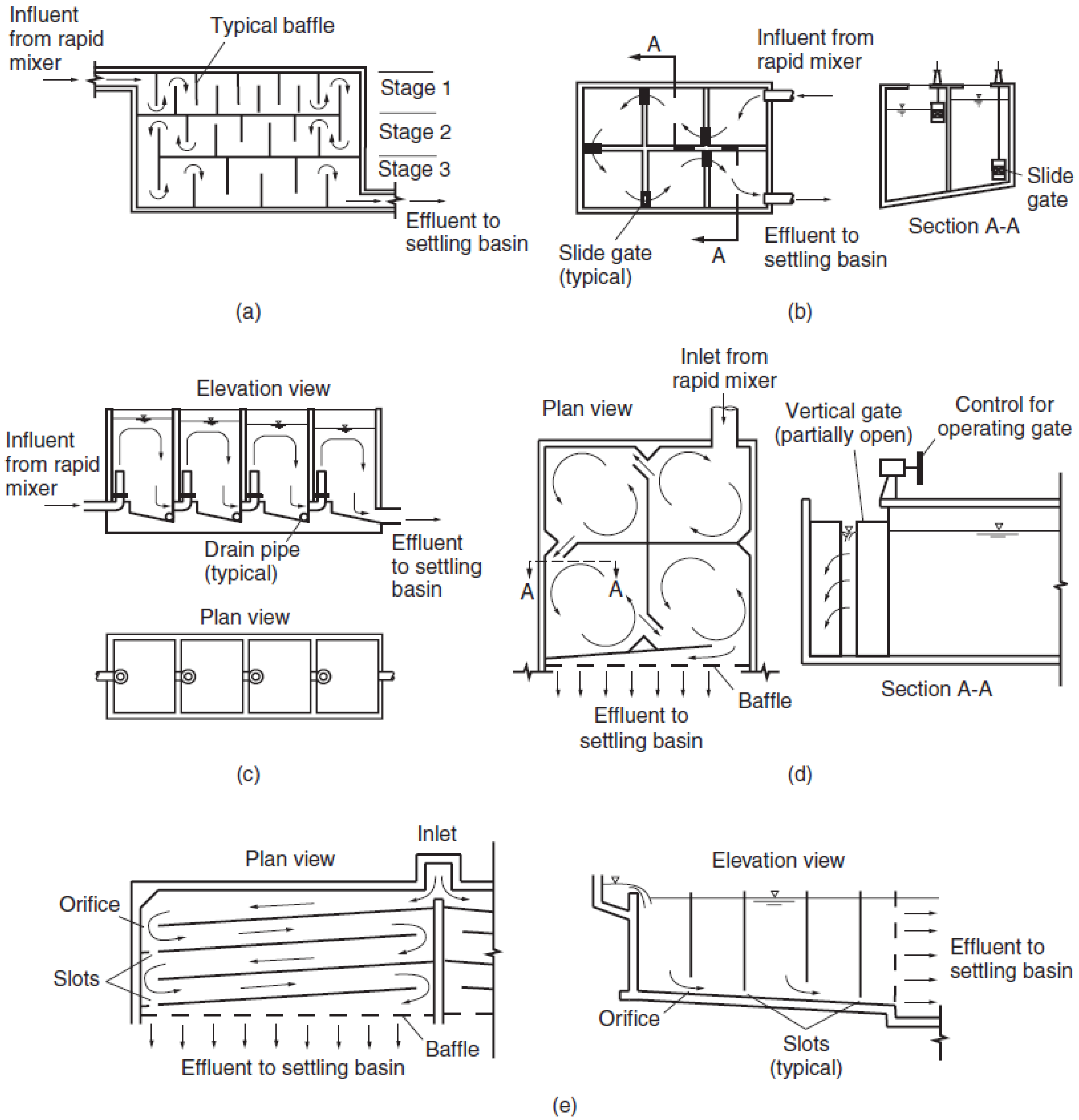


Figure
Examples of some alternative designs of hydraulic flocculators: (a) tapered horizontal baffled hydraulic flocculator, (b) helicoidal flow flocculator, (c) Alabama-type hydraulic flocculator, (d) variable-gate hydraulic flocculator, and (e) orifice and channel over and under flocculator. (Adapted from Kawamura, 2000.)

Granular Filtration

Principal Features of Rapid Filtration

***Slow sand filtration (2~6 m/day)**

The most important features of **rapid filtration (100~400 m/day)**

1) a filter bed of granular material that has been processed to a more uniform size than typically found in nature
2) the use of a coagulant to precondition the water
3) mechanical and hydraulic systems to efficiently remove collected solids from the bed **(backwashing)**

Uniformity of Filter Media

Media uniformity results in
1) a higher hydraulic loading rate
2) lower head loss
3) void spaces significantly larger than the particles being filtered
4) straining is not the dominant removal mechanism.
5) Adhesion to the filter grains is the dominant process
6) Depth filtration (a high capacity for solids retention without clogging rapidly)

Coagulation Pretreatment

- Coagulation pretreatment is required ahead of rapid filtration.

- Destabilization is needed to avoid the repulsive electrostatic forces between natural negative surface charge on the particles and filter media grains.

Basic Process Description

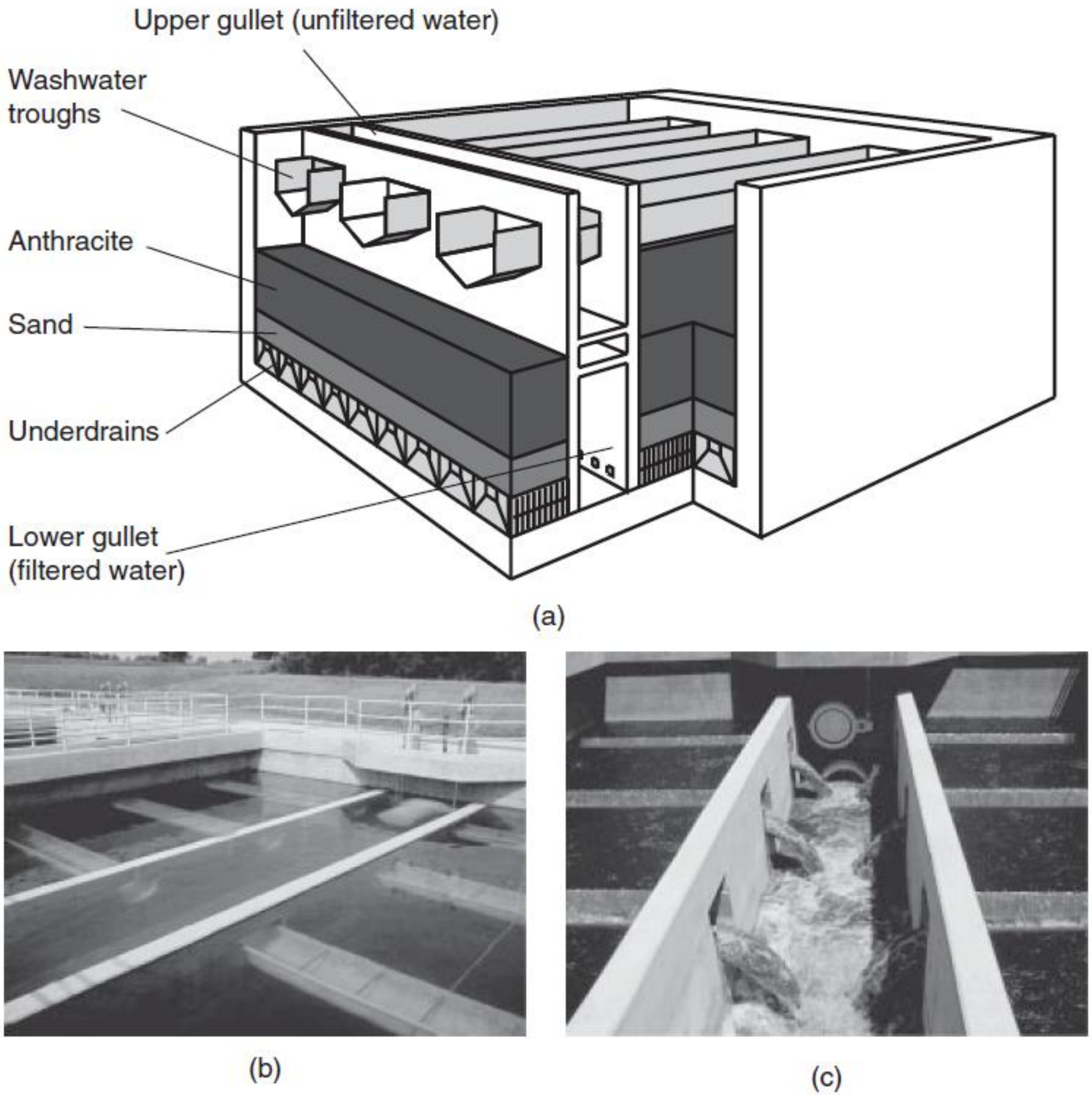


Figure
Typical dual-media rapid filter. (a) Schematic representation of dual-media filter. (b) View of an operating rapid filter. Washwater troughs are visible below the water surface. Influent water enters through the central channel, flows through the wall openings for the washwater troughs, and then down through the filter media, which is below the water surface. (c) Rapid filter during the backwash cycle. Washwater flows up through the media, pours over into the troughs, and then runs into the central channel.

Filtration stage 1~4 d

Backwash stage 15~30 min

Filtration Effectiveness During the Filtration Stage

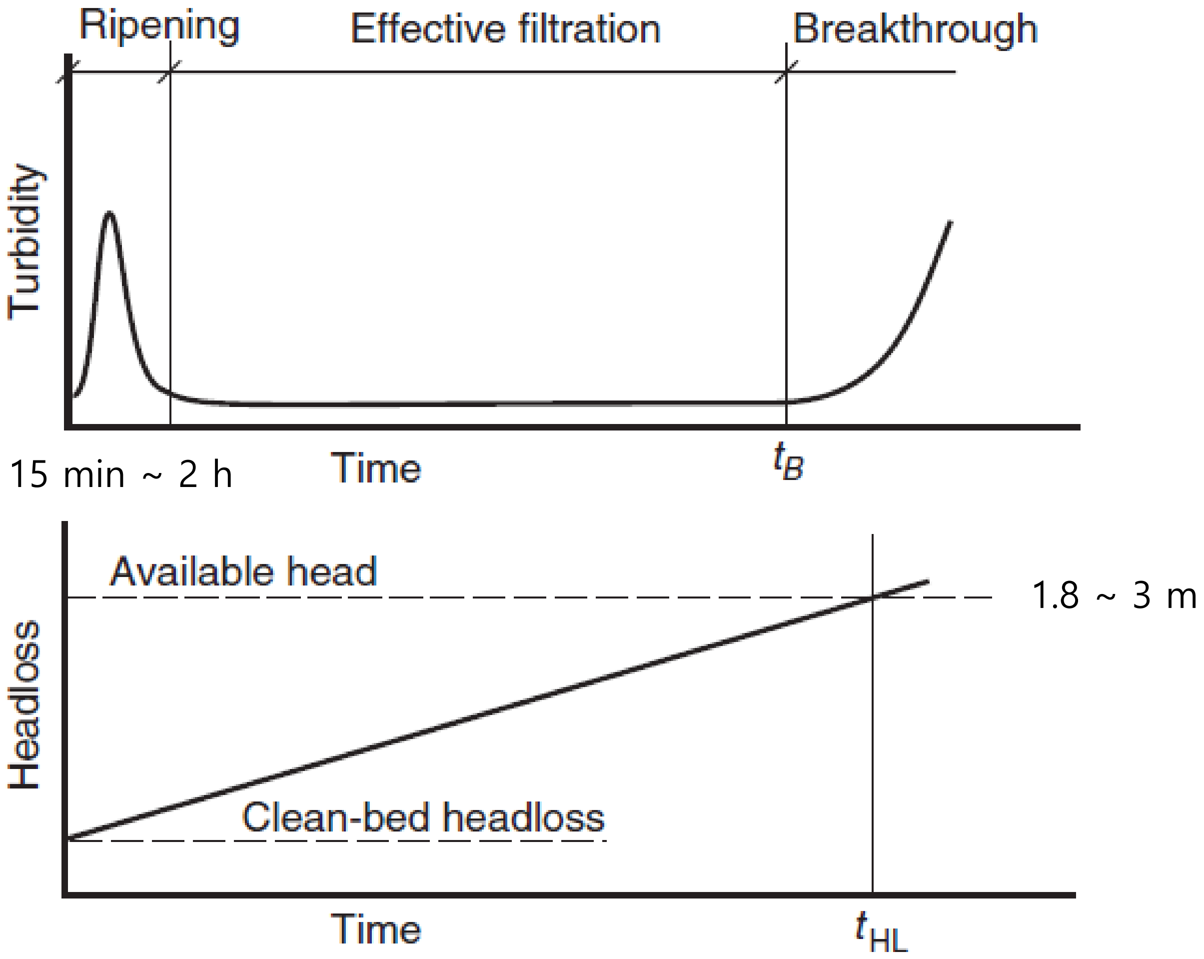
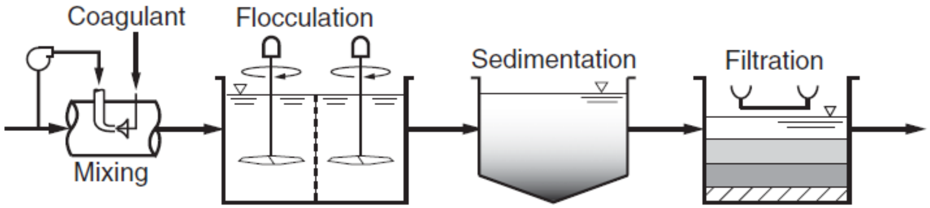


Figure
Operation of a rapid filter: (a) effluent turbidity versus time and (b) head loss development versus time.

Classifications of Rapid Filtration Systems

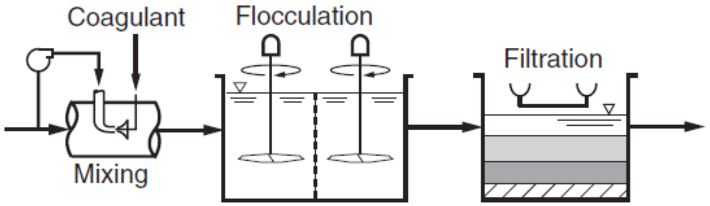
Conventional filtration.

Most common filtration system. Used with any surface water, even those with very high or variable turbidity. Responds well to rapid changes in source water quality.



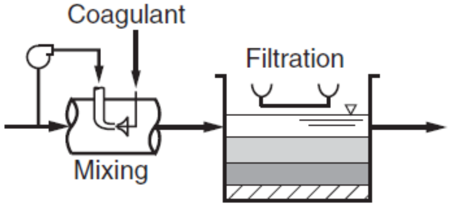
Direct filtration.

Good for surface waters without high or variable turbidity. Typical source waters are lakes and reservoirs, but usually not rivers. Raw-water turbidity < 15 NTU.



In-line filtration (also called contact filtration).

Requires high-quality surface water with very little variation and no clay or sediment particles. Raw-water turbidity < 10 NTU.



Two-stage filtration.

Preengineered systems used in small treatment plants (also called package plants). Raw-water turbidity < 100 NTU.

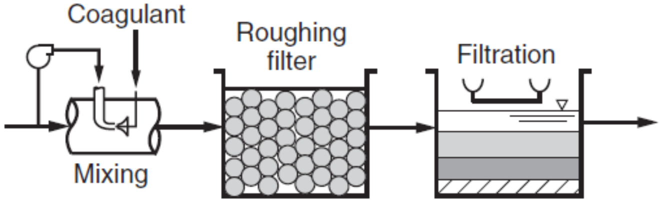
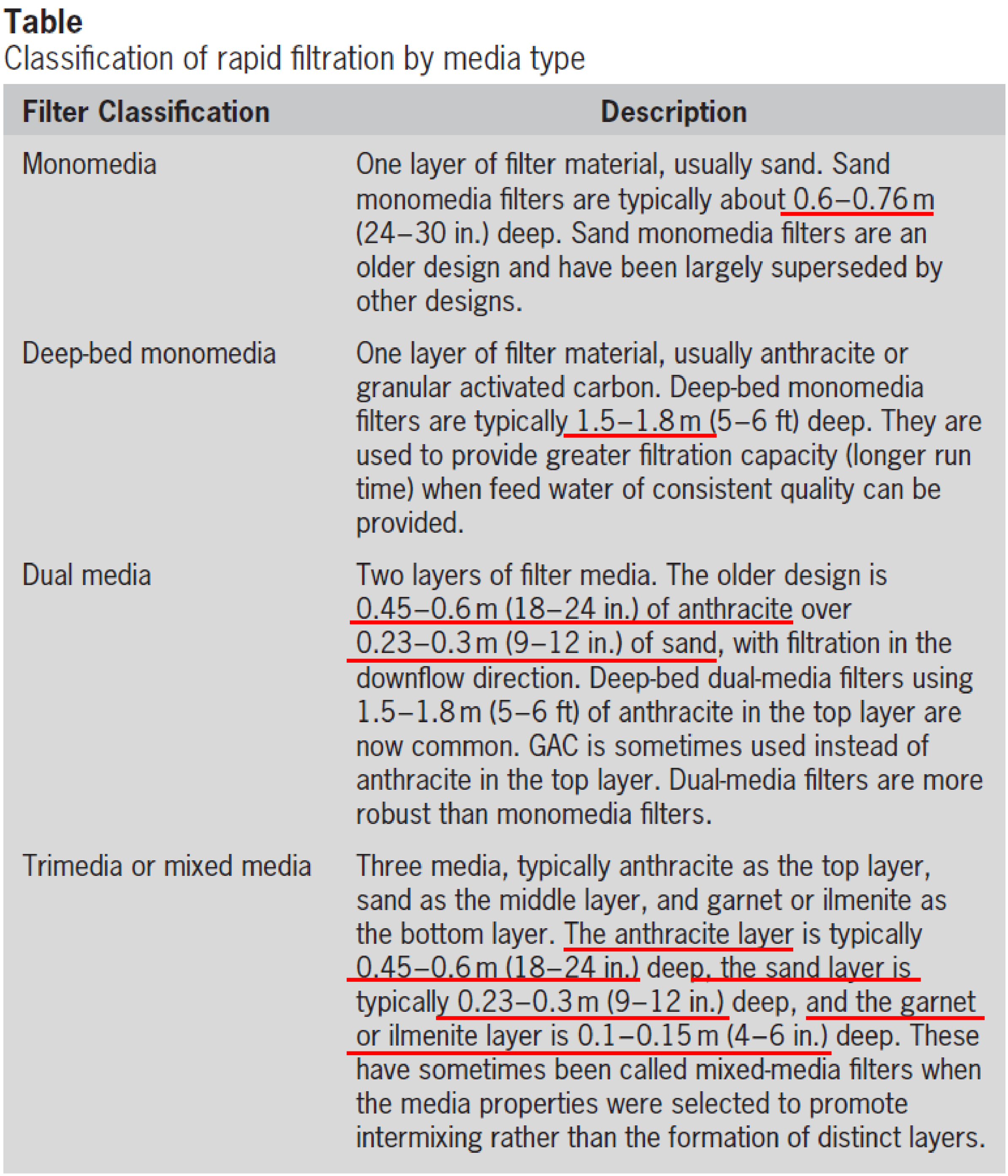


Figure
Classification of rapid filtration by pretreatment level.



Table

Classification of rapid filtration by media type

Filter Classification	Description
Monomedia	One layer of filter material, usually sand. Sand monomedia filters are typically about 0.6–0.76 m (24–30 in.) deep. Sand monomedia filters are an older design and have been largely superseded by other designs.
Deep-bed monomedia	One layer of filter material, usually anthracite or granular activated carbon. Deep-bed monomedia filters are typically 1.5–1.8 m (5–6 ft) deep. They are used to provide greater filtration capacity (longer run time) when feed water of consistent quality can be provided.
Dual media	Two layers of filter media. The older design is 0.45–0.6 m (18–24 in.) of anthracite over 0.23–0.3 m (9–12 in.) of sand, with filtration in the downflow direction. Deep-bed dual-media filters using 1.5–1.8 m (5–6 ft) of anthracite in the top layer are now common. GAC is sometimes used instead of anthracite in the top layer. Dual-media filters are more robust than monomedia filters.
Trimedia or mixed media	Three media, typically anthracite as the top layer, sand as the middle layer, and garnet or ilmenite as the bottom layer. The anthracite layer is typically 0.45–0.6 m (18–24 in.) deep, the sand layer is typically 0.23–0.3 m (9–12 in.) deep, and the garnet or ilmenite layer is 0.1–0.15 m (4–6 in.) deep. These have sometimes been called mixed-media filters when the media properties were selected to promote intermixing rather than the formation of distinct layers.

석류석
or 티탄철석

Properties of Granular Filter Media

Materials Used for Rapid Filtration Media

- ✓ Sand, Anthracite coal, Garnet, Ilmenite and GAC

Effective Size and Uniformity Coefficient

$$\mathrm{UC} = \frac{d_{60}}{d_{10}}$$

where UC = uniformity coefficient, dimensionless
d_{10} = 10th percentile media grain diameter, mm (= ES: effective size)
d_{60} = 60th percentile media grain diameter, mm

UC = 0.75/0.55 ≈ 1.4

UC = 1/0.35 ≈ 2.9

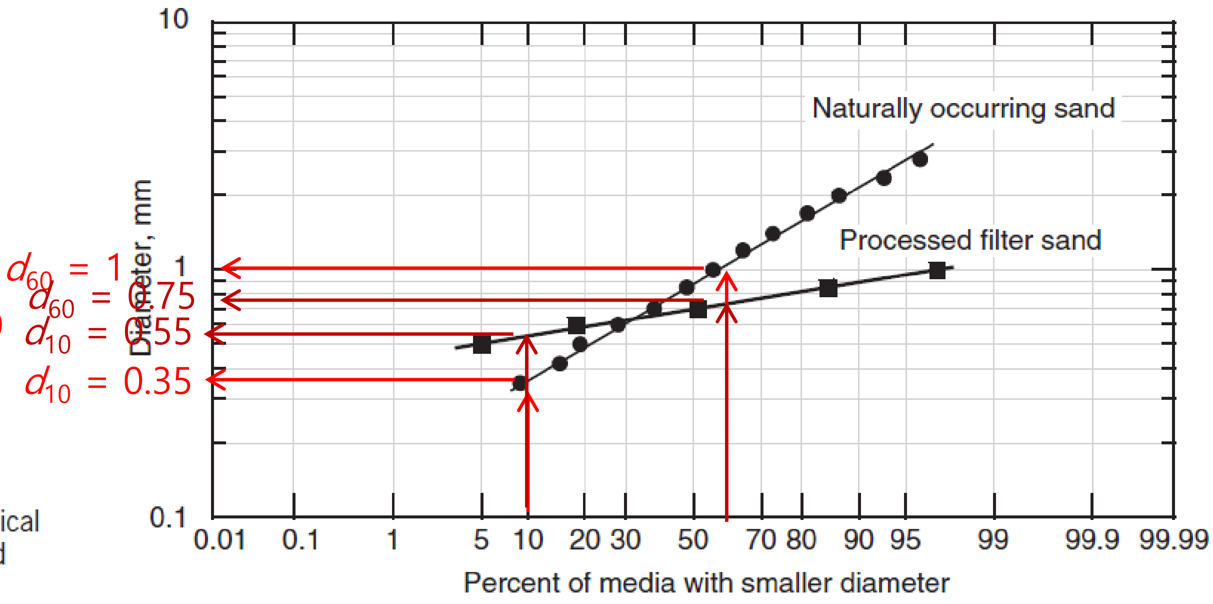


Figure
Size distribution of typical naturally occurring and processed filter sand.

Table

Typical properties of filter media used in rapid filters[a]

Property	Unit	Garnet	Ilmenite	Sand	Anthracite	GAC
(= d_{10}) Effective size, ES	mm	0.2–0.4	0.2–0.4	0.4–0.8	0.8–2.0	0.8–2.0
Uniformity coefficient, UC	UC	1.3–1.7	1.3–1.7	1.3–1.7	1.3–1.7	1.3–2.4
Density, ρ_p	g/mL	3.6–4.2	4.5–5.0	2.65	1.4–1.8	1.3–1.7
Porosity, ε	%	45–58	N/A	40–43	47–52	N/A
Hardness	Moh	6.5–7.5	5–6	7	2–3	Low

[a] N/A = not available.

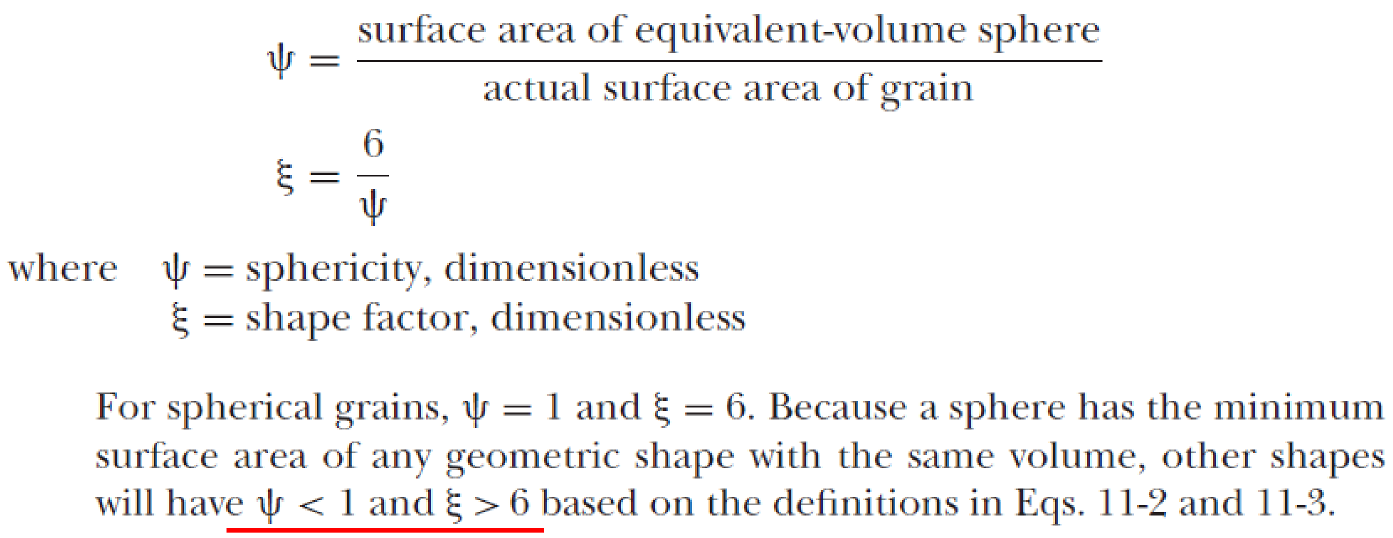
(a) (b) (c)

Figure

Typical filter media: (a) anthracite coal, (b) sand, and (c) garnet. The sand shown is a worn river sand; suppliers may provide worn or crushed sand, depending on the source, which would change the shape factor.

Grain Shape

- No easy way to account for the grain shape
- Sphericity (ψ) or Shape factor (ξ) are often used to characterize the grain shape



$$\psi = \frac{\text{surface area of equivalent-volume sphere}}{\text{actual surface area of grain}}$$

$$\xi = \frac{6}{\psi}$$

where ψ = sphericity, dimensionless
ξ = shape factor, dimensionless

For spherical grains, $\psi = 1$ and $\xi = 6$. Because a sphere has the minimum surface area of any geometric shape with the same volume, other shapes will have $\psi < 1$ and $\xi > 6$ based on the definitions in Eqs. 11-2 and 11-3.

Material Density

-The fluidization and settling velocities of filter media during and after backwash are influenced by material density.

-Backwash flow requirements are higher for denser materials of equal diameter.

-Denser materials are located in the bottom layers.

Material Hardness

- Hardness affects the abrasion and breakdown of filter material during the backwash.
- Hardness is ranked on the Moh table, a relative ranking of mineral hardness (talc = 1, diamond = 10). (the Mohs' scale: 모스경도계)
- Sand, garnet, and ilmenite are hard enough to be unaffected by abrasion, but anthracite and GAC are friable (design specifications must identify minimum hardness values. e.g., a minimum Moh hardness of 2.7 for anthracite)

Granular Bed Porosity

$$\varepsilon = \frac{V_V}{V_T} = \frac{V_T - V_M}{V_T} \qquad \Rightarrow \quad V_M = V_T(1-\varepsilon)$$

where ε = porosity, dimensionless
V_V = void volume in media bed, m^3
V_T = total volume of media bed, m^3
V_M = volume of media, m^3

- Filter bed porosity ranges from 40 to 60 percent

Granular Bed Specific Surface Area

$$S = \frac{(\text{number of grains})\,(\text{surface area of each grain})}{\text{bulk volume of filter bed}}$$

where S = specific surface area, m^{-1}

For a uniform bed of monodisperse spheres,

$$S = \frac{6(1-\varepsilon)}{d}$$

where d = diameter of sphere, m

$$\psi = \frac{\text{surface area of equivalent-volume sphere}}{\text{actual surface area of grain}}$$

$$\xi = \frac{6}{\psi}$$

ψ = sphericity, dimensionless

ξ = shape factor, dimensionless

For nonspherical media,

$$S = \frac{6(1-\varepsilon)}{\psi d} = \frac{\xi(1-\varepsilon)}{d}$$

where d = equivalent-volume diameter, m

Hydraulics of Flow through Granular Media

$$\mathrm{Re} = \frac{\rho_W v d}{\mu}$$

where Re = Reynolds number for flow around a sphere, dimensionless
ρ_W = fluid density, $\mathrm{kg/m^3}$
v = filtration rate (superficial velocity), m/s
d = media grain diameter, m
μ = dynamic viscosity of fluid, kg/m·s

- Flow in granular media does not experience a rapid transition from laminar to turbulent, as observed in pipes, but can be divided into four flow regimes:
  1) Darcy flow (creeping flow): $\mathrm{Re} < 1$ (influenced by viscous force)
  2) Forchheimer flow: $1 < \mathrm{Re} < 100$ (influenced by both viscous and inertial forces)
  3) Transition zone: $100 < \mathrm{Re} < 600\sim800$
  4) Full turbulence: $\mathrm{Re} > 600\sim800$

- Typical rapid filters: $0.5 < \mathrm{Re} < 5$

$\Rightarrow$ Darcy flow or Forchheimer flow

✓ DARCY FLOW REGIME

- In 1856, Henry Darcy published a report stating the relationship between velocity, head loss, and bed depth in granular media under creeping-flow conditions

$$v = k_p \frac{h_L}{L}$$

where v = superficial velocity (filtration rate), m/s

k_p = coefficient, known as hydraulic permeability, m/s

h_L = head loss across media bed, m

L = depth of granular media, m

Kozeny equation
$$\frac{h_L}{L} = \frac{\kappa_k \mu S^2 v}{\rho_W g \varepsilon^3}$$

where κ_k = Kozeny coefficient, unitless

S = specific surface area

ε = porosity

g = acceleration due to gravity, 9.81 $\mathrm{m/s^2}$

✓ FORCHHEIMER FLOW REGIME

$$\frac{h_L}{L} = \kappa_1 v + \kappa_2 v^2$$

where κ_1 = permeability coefficient for linear term, s/m
κ_2 = permeability coefficient for square term, s^2/m^2

Ergun equation

$$h_L = \kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu L \boxed{v}}{\rho_W g d^2} + \kappa_I \frac{1-\varepsilon}{\varepsilon^3} \frac{L \boxed{v^2}}{gd}$$

where κ_V = head loss coefficient due to viscous forces, unitless
κ_I = head loss coefficient due to inertial forces, unitless

Table
Recommended parameters

Medium	κ_V	κ_I	ε_I,
Sand	110–115	2.0–2.5	40–43
Anthracite	210–245	3.5–5.3	47–52

[a] When effective size as determined by sieve analysis is used for the diameter.

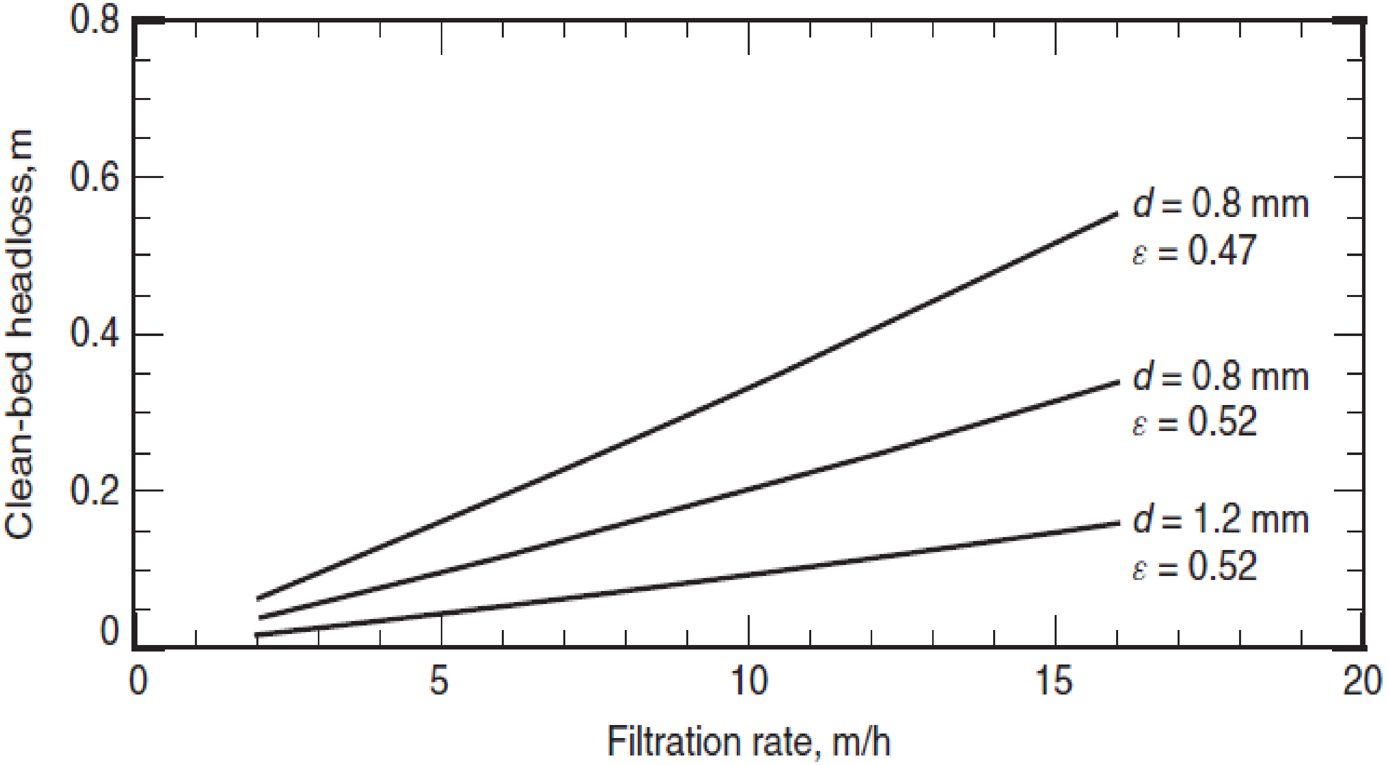


Figure
Effect of media size, bed porosity, and filtration rate on head loss through a clean granular filter bed. Calculated using Eq. 11–13 for anthracite ($L = 1$ m, $T = 15°$C, $\kappa_V = 228$, $\kappa_I = 4.4$).

$$h_L = f(v, d, \varepsilon)$$

Backwash Hydraulics

✓ FORCES ON PARTICLES

$$\sum F = F_g - F_b - F_d$$

where F_g = gravitational force on a particle, N
F_b = buoyant force on a particle, N
F_d = drag force on a particle, N

$$F_g = ma = \rho_p V_p g$$

$$F_b = ma = \rho_w V_p g$$

$$F_d = \frac{1}{2} C_d \rho_w A_p v_s^2$$

$$\sum F = \rho_P V_p g - \rho_W V_p g - C_d \rho_W A_p \frac{v_s^2}{2}$$

where ρ_P = particle density, kg/m^3
ρ_W = water density, kg/m^3
V_p = volume of particle, m^3
A_p = projected area of particle in direction of flow, m^3
C_D = drag coefficient, unitless
g = acceleration due to gravity, 9.81 m/s^2
v_s = settling velocity of the particle, m/s
the velocity of the object relative to the fluid (=backwashing rate)

✓ BED EXPANSION AND POROSITY

$$\frac{L_E}{L_F} = \frac{1 - \varepsilon_F}{1 - \varepsilon_E}$$

where L_E = depth of expanded bed, m
L_F = depth of bed at rest (fixed bed), m
ε_E = porosity of expanded bed, dimensionless
ε_F = porosity of bed at rest (fixed bed), dimensionless

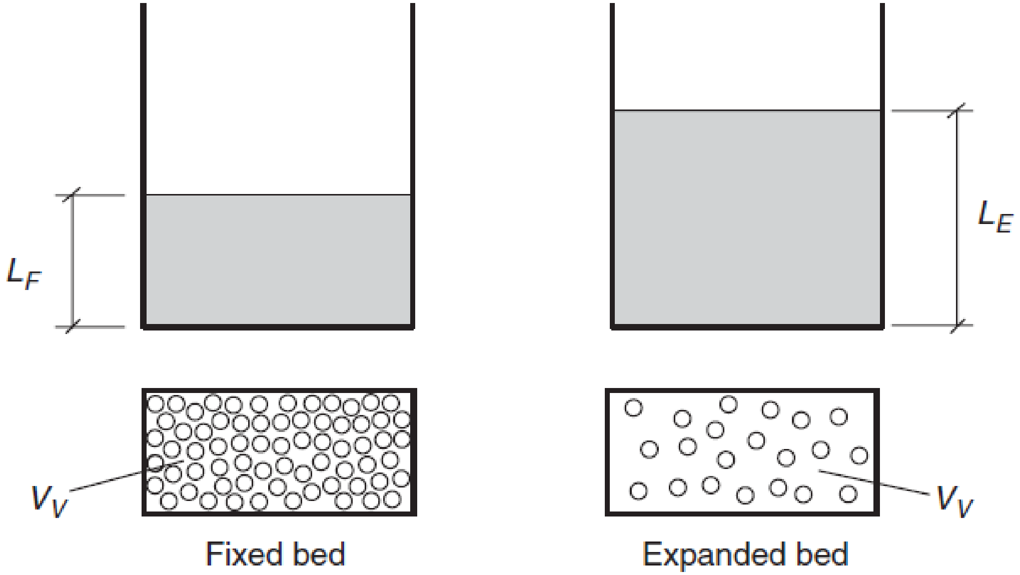


Figure
Fixed and expanded beds during backwashing of rapid filters. During filtration, the media grains are touching each other, but when media are fluidized during backwashing, the void volume increases, causing an overall expansion of the bed.

✓ The relationship between the porosity and the backwashing velocity

$$F_g - F_b = (\rho_p - \rho_w)(1 - \varepsilon)\, aLg$$

where F_g = weight of the entire filter bed, N
a = cross-sectional area of filter bed, m^2

$$\left.\begin{array}{l} F_d = h_L a \rho_w g \\ \\ F_d = F_g - F_b \end{array}\right\}$$

$$h_L = \frac{F_g - F_b}{a\rho_w g} = \frac{(\rho_p - \rho_w)(1 - \varepsilon) L}{\rho_w}$$

$$\kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu L v}{\rho_w g d^2} + \kappa_I \frac{1-\varepsilon}{\varepsilon^3}\frac{L v^2}{g d} = \frac{(\rho_p - \rho_w)(1-\varepsilon) L}{\rho_w}$$

Ergun equation

Variable: v (Re)

$$\boxed{\mathrm{Re} = \frac{\rho_W v d}{\mu}}$$

$$\kappa_I/\mathrm{Re}^2 + \kappa_V (1-\varepsilon)\mathrm{Re} - \beta = 0$$

$$\beta = \frac{g\rho_w(\rho_p - \rho_w)\, d^3 \varepsilon^3}{\mu^2}$$

where β = backwash calculation factor, dimensionless

$$\mathrm{Re} = \frac{-\kappa_V(1-\varepsilon) + \sqrt{\kappa_V^2(1-\varepsilon)^2 + 4\kappa_I\beta}}{2\kappa_I}$$

Then, the velocity (*v*) that will maintain the bed in an expanded state corresponding to a specific porosity value can be determined (in fact, same as solving the eq. directly in terms of *v*)

- Alternatively, it is frequently necessary to determine the bed expansion that occurs for a specific backwash rate. Eq. 11-18 is a cubic equation in porosity, which was analytically solved

$$\kappa_V \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu L v}{\rho_w g d^2} + \kappa_I \frac{1-\varepsilon}{\varepsilon^3} \frac{L v^2}{g d} = \frac{(\rho_p - \rho_w)(1-\varepsilon) L}{\rho_w}$$

Variable: ε

$$\varepsilon = \sqrt[3]{X + (X^2 + Y^3)^{1/2}} + \sqrt[3]{X - (X^2 + Y^3)^{1/2}}$$

where X = backwash calculation factor, dimensionless
Y = backwash calculation factor, dimensionless

The factors X and Y are defined as

$$X = \frac{\mu v}{2g(\rho_p - \rho_w) d^2} \left(\kappa_V + \frac{\kappa_I \rho_w v d}{\mu} \right)$$

$$Y = \frac{\kappa_V \mu v}{3g(\rho_p - \rho_w) d^2}$$

Particle Removal in Rapid Filtration

Straining

- Particle size > Void space in the filter: straining is the dominant removal process.

- Particle size < Void space in the filter: adhesion is the dominant removal process.

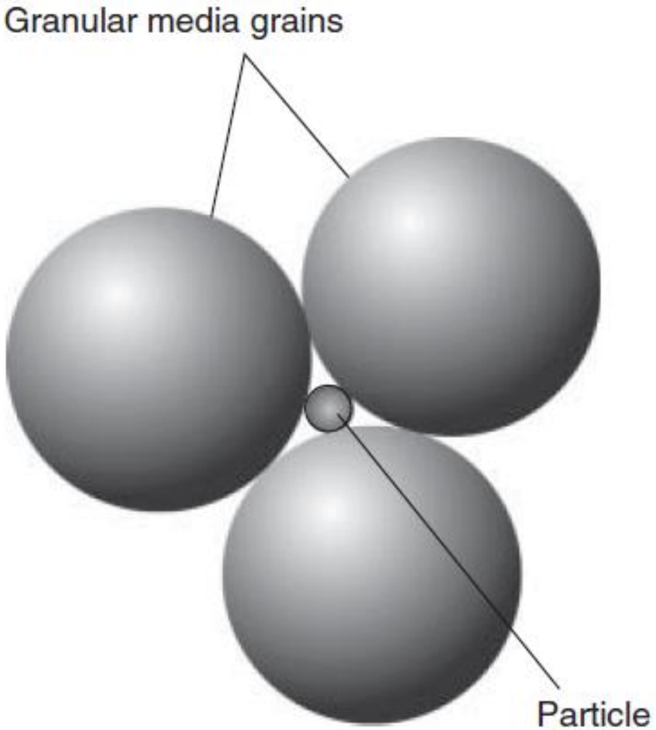


Figure
Capture of spherical particle by spherical media grains. If the ratio of particle diameter to media diameter is greater than 0.15, the particle will be strained by the media. If it is smaller, straining is not possible and particle capture must occur by other means. For typical rapid filtration, straining is limited to particles about 80 μm and larger.

Depth Filtration

Adsorption

- In depth filtration, particles are removed continuously throughout the filter through a process of transport and attachment to the filter grains.

$$\frac{\partial C}{\partial z} = -\lambda C$$

where λ = filtration coefficient, m^{-1}

C = mass or number concentration of particles, mg/L or L^{-1}

z = depth in filter, m

- If the filtration coefficient was known, it would be possible to calculate the effluent particle concentration from a filter.

Fundamental Depth Filtration Theory

- Fundamental filtration models are useful to understand how particles are removed during depth filtration and the importance of various design and operating parameters.

-However, they are not very effective at quantitatively predicting the effluent turbidity in actual full-scale filters because of the complexity of the real systems

Yao Filtration Model

-Theory is based on the accumulation of particles on a single filter grain (termed a "collector"), which is then incorporated into a mass balance on a differential slice through a filter.

$$\eta = \frac{\text{particles contacting collector}}{\text{particles approaching collector}}$$

$$\alpha = \frac{\text{particles adhering to collector}}{\text{particles contacting collector}}$$

where η = transport efficiency, dimensionless
α = attachment efficiency, dimensionless

$$\text{Mass flow to one collector} = vC\frac{\pi}{4}d_c^2$$

where v = superficial velocity, m/s
C = concentration of particles, mg/L
d_c = diameter of collector (media grain), m

$$\text{Number of collectors} = \frac{(1-\varepsilon)\,a\Delta z}{(\pi/6)\,d_c^3}$$

where ε = porosity
a = cross-sectional area of filter bed, m^2
Δz = incremental unit of depth in filter, m

$$[\text{accum}] = [\text{mass in}] - [\text{mass out}] \pm [\text{rxn}]$$

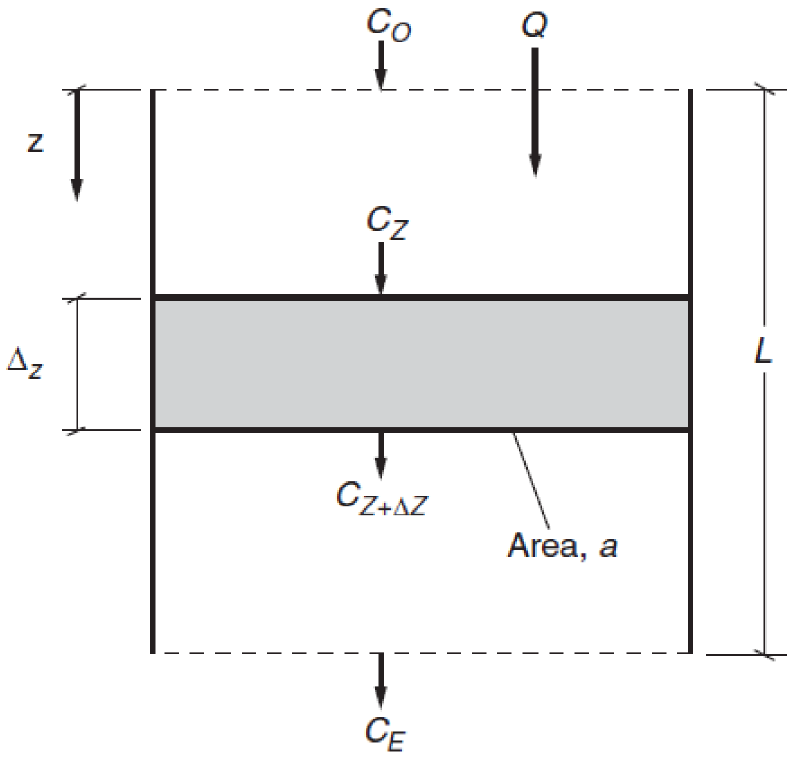


Figure
Differential element of filter bed for filtration models.

$$[\text{accum}] = [\text{mass in}] - [\text{mass out}] \pm [\text{rxn}]$$

$$\left(vC\frac{\pi}{4}d_c^2\eta\alpha\right)\left[\frac{(1-\varepsilon)\,a\Delta z}{(\pi/6)\,d_c^3}\right] = QC_Z - QC_{Z+\Delta Z} = -va\,(C_{Z+\Delta Z} - C_Z)$$

where Q = flow through filter, m³/s

Taking the limit as Δz goes to zero,

$$\frac{dC}{dz} = \frac{-3(1-\varepsilon)\eta\alpha C}{2d_c}$$

$$\frac{\partial C}{\partial z} = -\lambda C$$

and defines the filter coefficient as

$$\lambda = \frac{3(1-\varepsilon)\eta\alpha}{2d_c}$$

If the parameters (ε, η, α, and d_c) are constant with respect to depth in the filter, can be integrated to yield the expression

$$C = C_O \exp\left[\frac{-3(1-\varepsilon)\eta\alpha L}{2d_c}\right]$$

where C_O = particle concentration in filter influent, mg/L

L = depth of filter, m

Rapid Filter Design

Preliminary design of rapid filters consists of the following:

1) Setting performance criteria, such as effluent turbidity, filter run length, recovery, and unit filter run volume (UFRV)
2) Selecting process design criteria, such as required level of pretreatment; filter media type, size, and depth; filtration rate; number of filters; and available head
3) Selecting a method for flow distribution and control
4) Selecting major process components, including backwashing systems, underdrains, wash troughs, and process piping

Performance Criteria

✓ **EFFLUENT WATER QUALITY**

-Depends on the water quality standards

✓ **FILTER RUN LENGTH (running time before backwash)**

-Typically 1 ~ 4 days

✓ RECOVERY (the ratio between the net and total quantity of water filtered)

$$\mathrm{UFRV} = \frac{V_F}{a} = v_F t_F$$

$$\mathrm{UBWV} = \frac{V_{\mathrm{BW}}}{a} = v_{\mathrm{BW}} t_{\mathrm{BW}}$$

$$\mathrm{UFWV} = \frac{V_{\mathrm{FTW}}}{a} = v_F t_{\mathrm{FTW}}$$

where UFRV = unit filter run volume, $\mathrm{m^3/m^2}$
UBWV = unit backwash volume, $\mathrm{m^3/m^2}$
UFWV = unit filter-to-waste volume, $\mathrm{m^3/m^2}$
V_F = volume of water filtered during one filter run, $\mathrm{m^3}$
V_{BW} = volume of water required to backwash one filter, $\mathrm{m^3}$
V_{FTW} = volume of water discharged as filter-to-waste, $\mathrm{m^3}$
v_F = filtration rate (superficial velocity), m/h
v_{BW} = backwash rate, m/h
t_F = duration of filter run, h
t_{BW} = duration of backwash cycle, h
t_{FTW} = duration of filter-to-waste period, h
a = filter cross-sectional area, $\mathrm{m^2}$

The ratio of net to total water filtered is the recovery:

$$r = \frac{V_F - V_{\mathrm{BW}} - V_{\mathrm{FTW}}}{V_F} = \frac{\mathrm{UFRV} - \mathrm{UBWV} - \mathrm{UFWV}}{\mathrm{UFRV}}$$

where r = recovery, expressed as a fraction

Example Calculation of parameters for net water production

A filter is operated at a rate of 12.5 m/h for 72 h, of which 30 min was discharged as filter-to-waste volume. After filtration, it is backwashed at a rate of 40 m/h for 15 min. Calculate the UFRV, UBWV, UFWV, and recovery.

Solution

1. Calculate UFRV using Eq. 11-66:

$$\text{UFRV} = (12.5\ \text{m/h})(72\ \text{h}) = 900\ \text{m} = 900\ \text{m}^3/\ \text{m}^2$$

2. Calculate UBWV using Eq. 11-67:

$$\text{UBWV} = (40\ \text{m/h})(0.25\ \text{h}) = 10\ \text{m} = 10\ \text{m}^3/\ \text{m}^2$$

3. Calculate UFWV using Eq. 11-68:

$$\text{UFWV} = (12.5\ \text{m/h})(0.5\ \text{h}) = 6.25\ \text{m} = 6.25\ \text{m}^3/\ \text{m}^2$$

4. Calculate recovery using Eq. 11-69:

$$r = \frac{(900 - 10 - 6.25)\ \text{m}^3/\ \text{m}^2}{900\ \text{m}^3/\ \text{m}^2} = 0.982 = 98.2\%$$

Process Design Criteria

✓ FILTER TYPE

-Conventional filtration, direct filtration, in-line filtration
-Dual media, monomedia, etc.

✓ FILTRATION RATE

-Typically, operated at 5 ~ 15 m/h

✓ NUMBER AND DIMENSIONS OF FILTERS

-A small number of filters can reduce cost by minimizing the number of components.
-A large number of filters minimizes the filtration rate change on the remaining filters when one is taken out of service for backwash.

✓ AVAILABLE HEAD

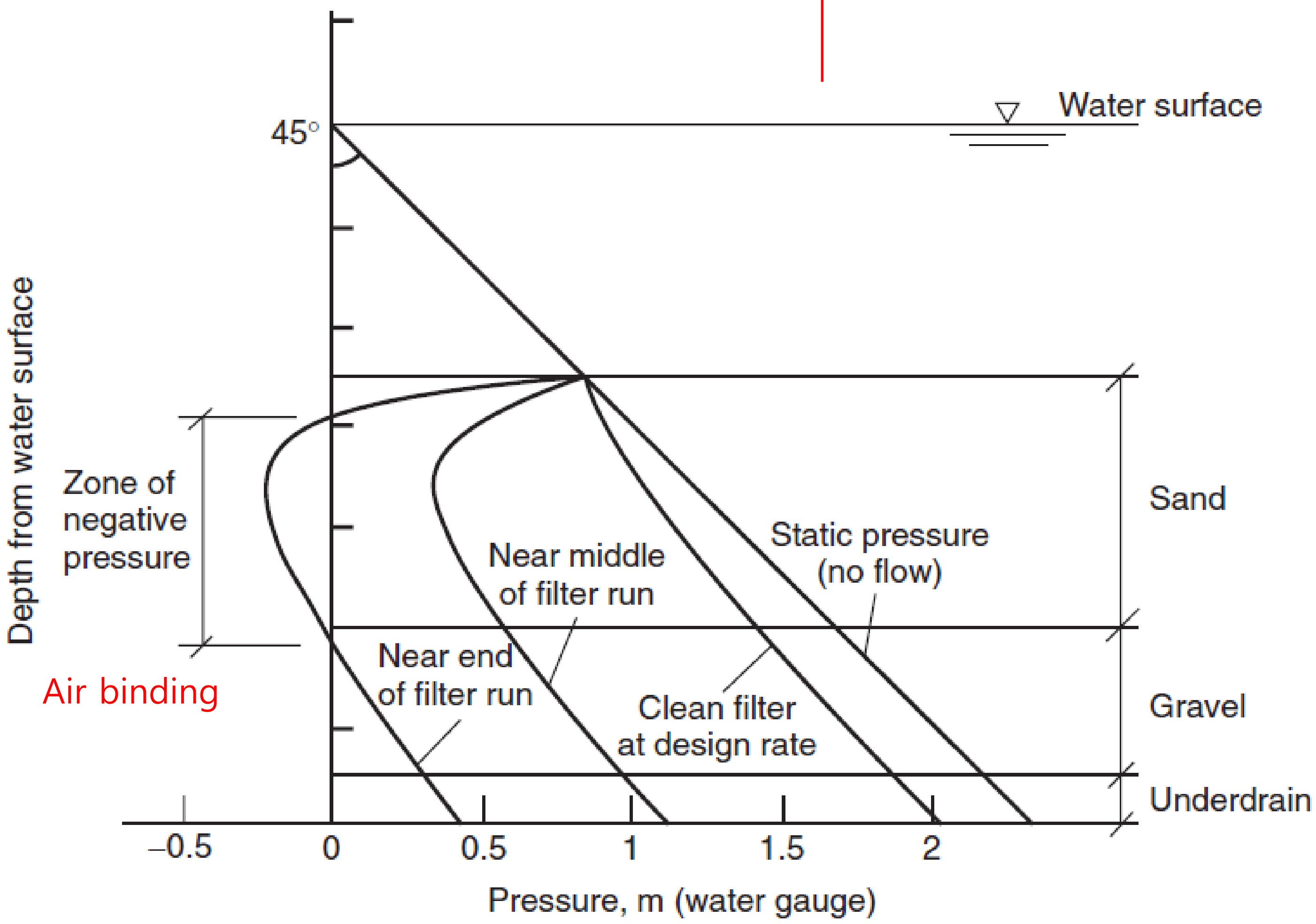
-Because rapid filters typically operate by gravity, the available head is dependent on the elevation of the filter building relative to upstream and downstream structures (sedimentation basins and clearwells).

✓ FILTER MEDIA

-Some design engineers recommend the ratio of depth to effective size (L/d ratio), to be between 1000 and 2000

Negative Pressure in Filter Beds

This problem can be avoided by maintaining sufficient Water surface level.



Air binding

Figure
Pressure development within filter bed during filtration. (Adapted from Kawamura, 2000).