고성능 콘크리트 공학

High Performance Concrete Engineering

<Admixture, Aggregate, Water>

문주혁 조교수
Assistant Prof. Juhyuk Moon

Chemical Admixture

Water-reducing admixture (WRA)
Set-controlling admixture (retardation and acceleration)
Air-entraining admixture (AEA)
Others

Chemical admixture

- **Definition** (ASTM C 125): a material other than water, aggregate, hydraulic cement, and fiber reinforcement that is used as an ingredient of concrete or mortar and is added to the batch immediately before or during its mixing.

- **Classification**
  - **Plasticizing admixtures (ASTM C 494 and C 1017)** – are water-soluble polymers designed to enhance workability or to reduce water requirements for a desired workability
  - **Set-controlling admixtures (ASTM C494)** – are added to control setting and to induce early hardening
  - **Air-entraining agents (ASTM C260)** – are added primarily to improve resistance to freezing/thawing cycling
  - **Miscellaneous admixtures** (e.g., Viscosity modifiers, corrosion inhibitors, shrinkage reducing admixtures, etc)

Chemical admixture

TABLE 8.1 Beneficial Effects of Chemical Admixtures on Concrete Properties

Property	*Admixture Type*	*ASTM Spec*
Workability	Water-reducing admixtures	C 494
	Plasticizers	C 1017
	Air-entraining admixtures	C 260
	Pumping aids	–
	Anti-washout admixtures	–
Set Control	Set-accelerating admixtures	C 494
	Set-retarding admixtures	C 494
	Extended-set admixtures	–
Strength	Water-reducing admixtures	C 494
Durability	Air-entraining admixtures	C 260
	Water-reducing admixtures	C 494
	Corrosion inhibitors	–

(Mindess et al 2003)

- **Precautions:**
  - Conform to standards
  - Test using job materials under job-site conditions
  - Ensure accurate batching

Chemical admixture: WRA

- **Applications of WRA and HRWRA**
  - Improve workability without increase water and cement contents – facilitate difficult placements
  - Achieve desired slump with less water (lower w/c) – improve strength, impermeability, and durability
  - Achieve desired slump with lower cement content without changing w/c
    - Technical benefit: reduce heat
    - Economic benefit: reduce coast
    - Environmental benefit: reduce cement consumption

TABLE 8.4 Typical Effects of Water-Reducing Admixtures

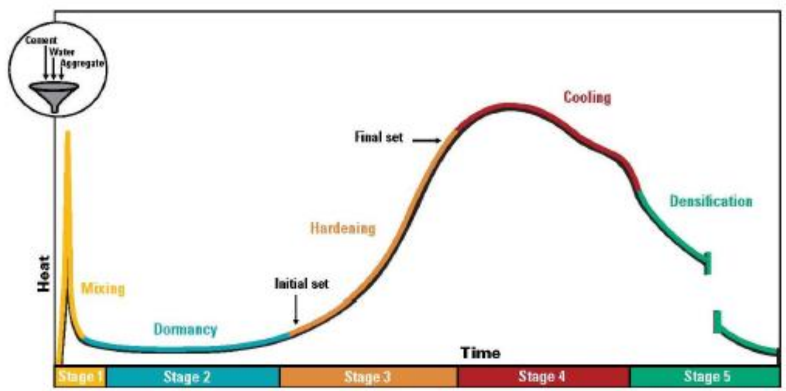
Classification	*Common Name*	*Typical Dose* (%)*	*Slump Increase (mm)*	*Water Reduction percent*	*Water Reduction w/c*	*ASTM Spec.*
Low-range	Regular	0.1%	50–85	5–10	−0.05	C 494
Mid-range	Mid-range	0.5%	50–100	10–15	−0.10	
High-range	Superplasticizer	1.0%	>100	15–30	−0.15	C 494, C 1017

*Active ingredient by weight of cement.

(Mindess et al 2003)

Chemical admixture

- **Types of WRA and HRWRA**
  - Type A* – water reducing admixture (WRA)
  - Type B – retarding
  - Type C – accelerating
  - Type D – water reducing and retarding
  - Type E – water reducing and accelerating
  - Type F – high range water reducing (superplasticizer, SP)
  - Type G – high range water reducing and retarding

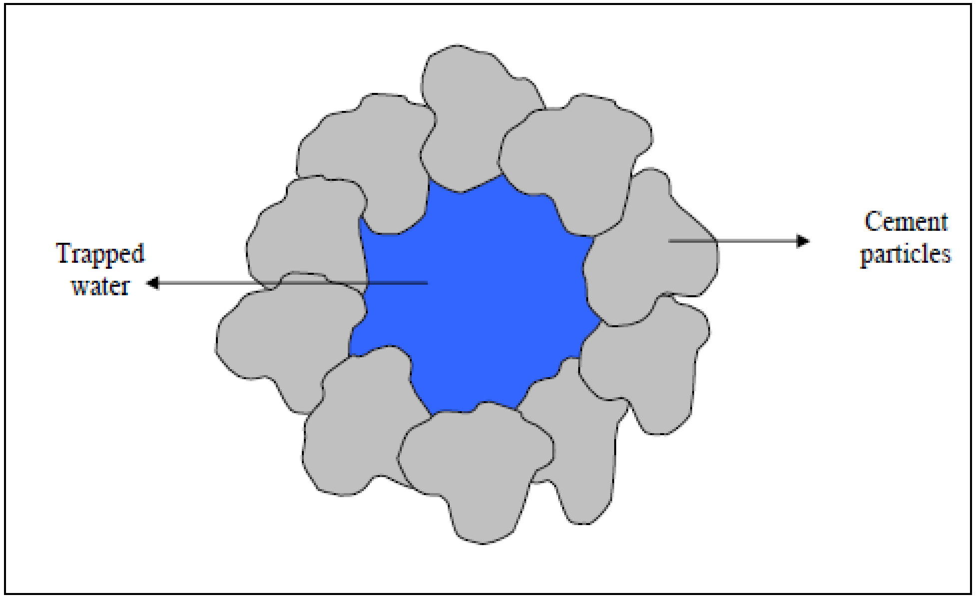


* In general, Type A WRA

- ↑ the rate of aluminate hydration (risk of flash set)
- ↓ the rate of C3S hydration (slowing strength gain)

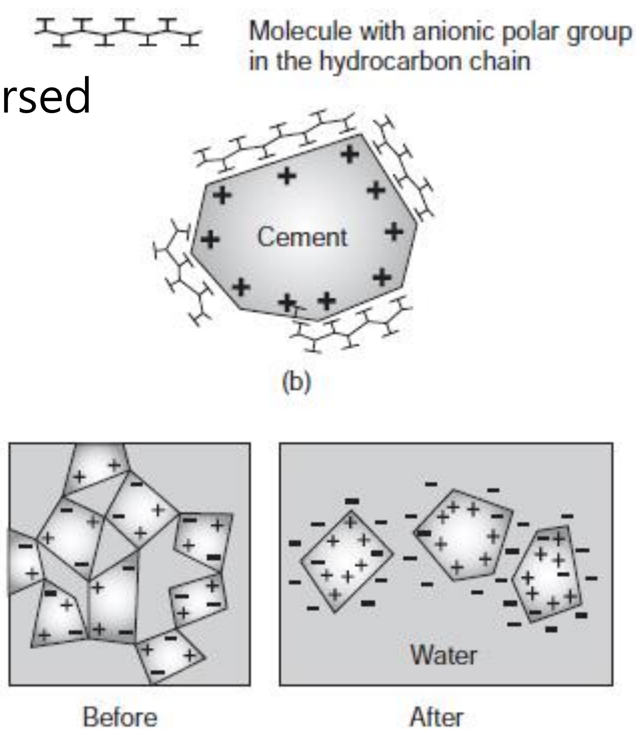
Chemical admixture (WRA)

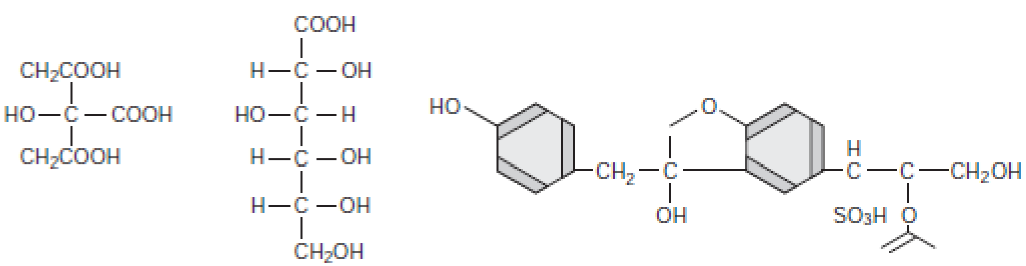
- **Mechanism of dispersion**
  - Cement particles carry charges on their surface which may be positive or negative.
  - In cement paste, opposing charges on adjacent cement particles lead to flocculation due to electrostatic attractions



Chemical admixture (WRA)

- **Mechanism of dispersion**
- **Electrostatic repulsion**
  - Negatively charged organic molecules adsorb at the solid-water interface
  - Molecules of RWA interact to neutralize surface charges on cement particles, and cause all surface to carry uniform charges of like sign
  - Particles repel each other, remain dispersed



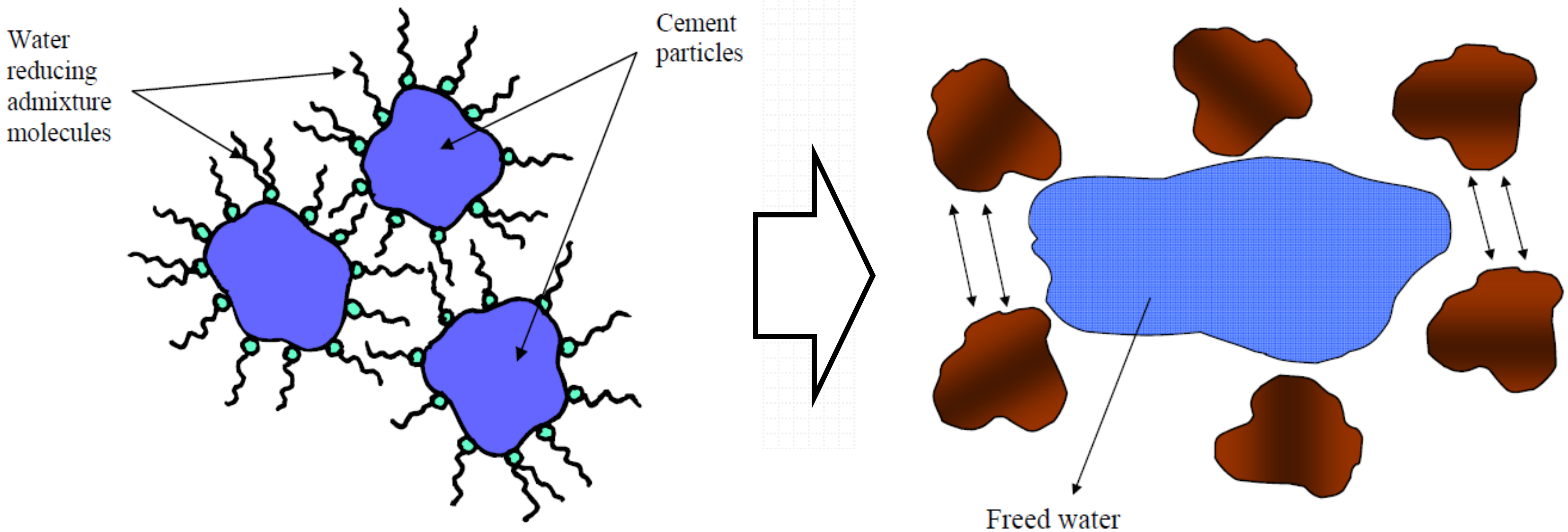


Citric acid　　Gluconic acid　　Repeating unit of a lignosulphonate polymer

(Metha and Monteiro 2006)

Chemical admixture (WRA)

- **Mechanism of dispersion**
- **Steric hindrance**
  - It is the slowing of chemical reactions due to steric bulk. Some of the newer admixtures use negatively charged polymers
  - The bulky nature of the adsorbed molecules can cause additional steric repulsion



Chemical admixture (WRA)

Electrostatic repulsion

Steric hindrance

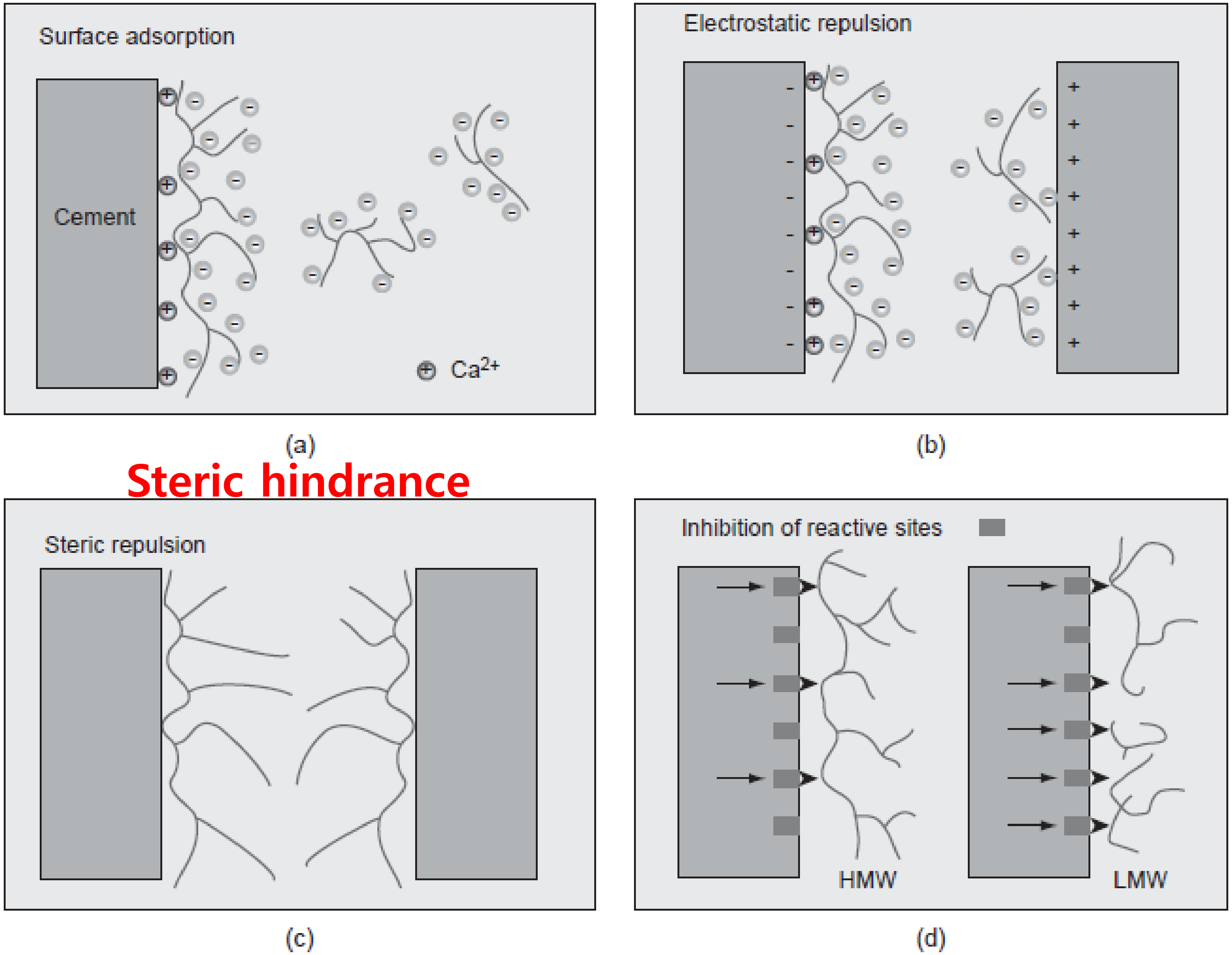


Figure 8-4 Diagrammatic illustration of mechanisms by which superplasticizers can disperse cement particles in the cement-water system (courtesy of C. Jolicoeur)

(Metha and Monteiro 2006)

Chemical admixture (WRA)

- **Water Reducing Admixture (plasticizers)**
- **Classification of water reducing admixtures**
  - ASTM Type A – water reducing admixture
  - ASTM Type D – water reducing and retarding admixtures
  - ASTM Type E – water reducing and accelerating admixture
  - ASTM Type F – High-range water reducers (superplasticizers)
  - ASTM Type G – High-range water reducing and retarding admixtures)

TABLE 8.4 Typical Effects of Water-Reducing Admixtures (Mindess et al 2003)

Classification	Common Name	Typical Dose* (%)	Slump Increase (mm)	Water Reduction percent	Water Reduction w/c	ASTM Spec.
Low-range	Regular	0.1%	50–85	5–10	−0.05	C 494
Mid-range	Mid-range	0.5%	50–100	10–15	−0.10	
High-range	Superplasticizer	1.0%	>100	15–30	−0.15	C 494, C 1017

*Active ingredient by weight of cement.

Chemical admixture (WRA)

- **Composition**

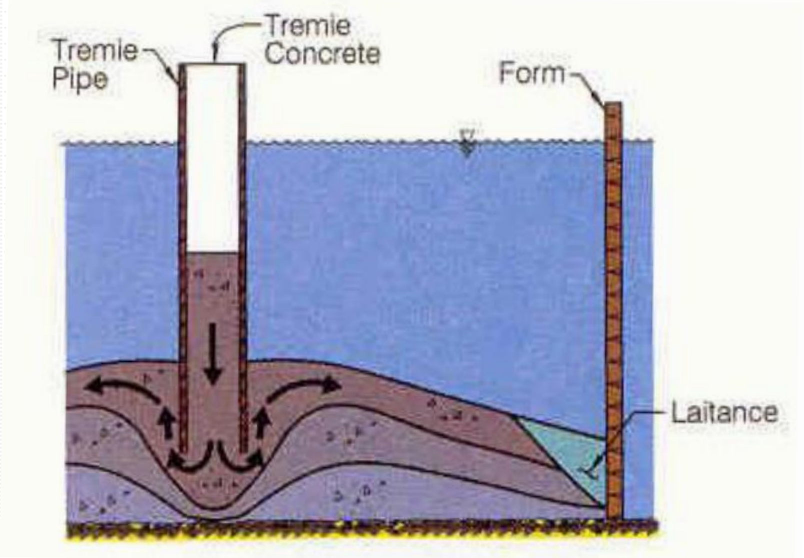
- **Regular WRA (plasticizers)**
  - Lignosulphonates
  - Hydro-carboxylic acids and their salts
  - Hydroxylated polymers derived from hydrolyzed starch

- **High-range WRA (superplasticizers)**
  - Sulphonated naphthalene-formaldehyde condensates
  - Sulphonated melamine-formaldehyde condensates
  - Modified lignosulphonates
  - Carboxylated acrylic ester copolymers (polycarboxylates)

Chemical admixture (WRA)

- **Effect on the properties of Fresh concrete**

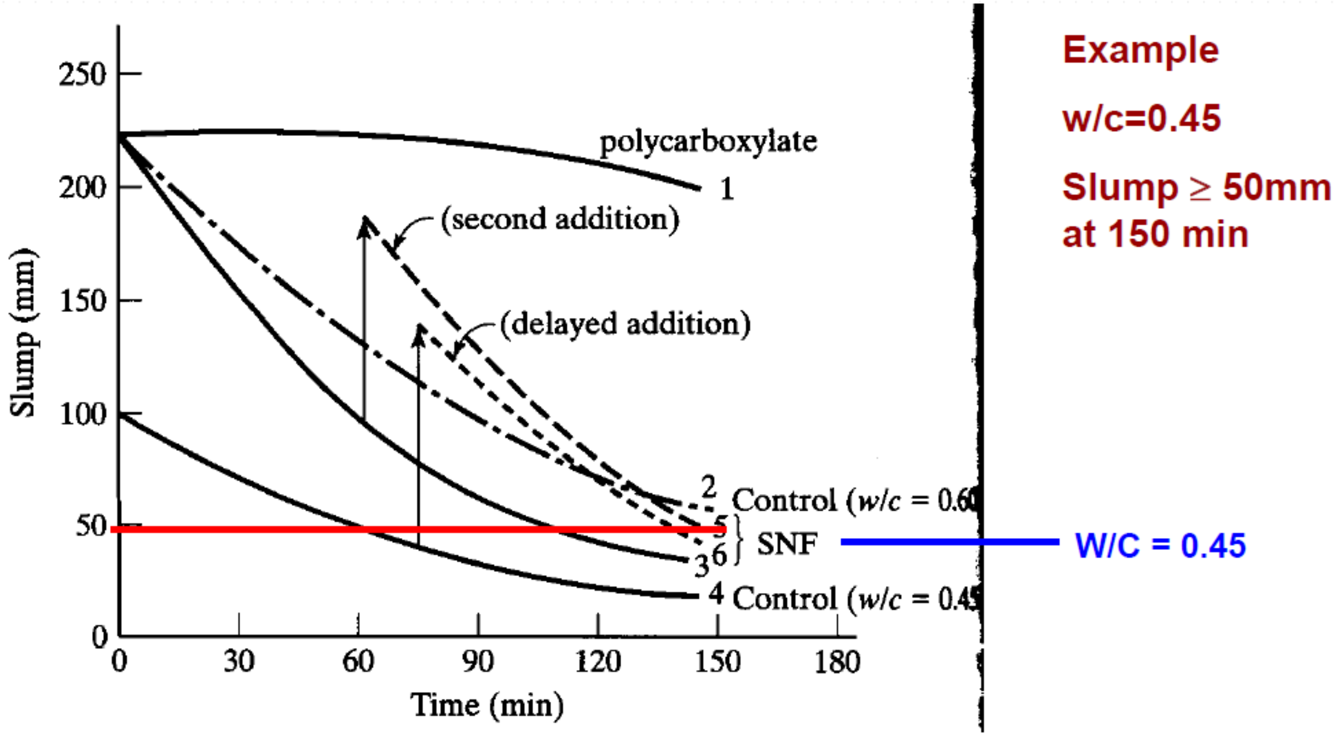
- **Flowing concrete**
  - Increase slump
    - Use of SP allows high slumps to be achieved without excessive segregation and bleeding
    - Pumping concrete, self-leveling concrete, tremie placement



Chemical admixture (WRA)

- **Effect on the properties of Fresh concrete**

- **Slump loss**
  - Adding a second dose
  - Delaying the initial addition



(Mindess et al 2003)

Chemical admixture (WRA)

- **Effect on the properties of fresh concrete**

- **Bleeding and air entrainment**
  - Bleeding
    - Overdose of superplasticizer should be avoid
  - Air entrainment
    - Regular WRA will reduce the amount of an AEA required to attain a given air content

- **Retardation of set**
  - Many regular or mid-range WRA will also act as retarding agents, some SP at high dosages have retarding effect

  - Beneficial in hot weather concreting so long as it does not affect setting and strength development significantly

Chemical admixture (WRA)

- **Effect on the properties of hardened concrete**

- **Compressive strength**
    - When WRA is used to lower water requirement, strength
    - ↑ in the compressive strength is up to 25% greater than would be anticipated from the ↓ in w/c alone, attributed to more uniform microstructure
- **High-strength concrete**
    - SPs are used in most concrete with 28-day compressive strengths of more than 80 Mpa
    - Lower w/c improve the rate of strength development at early age, can be used for precast concrete plant
- **Other properties**
    - Reduce permeability
    - ↑ in the rate of shrinkage is often observed; after 90 days of drying, little difference compared with control concrete
    - With creep, the situation is less clear, different admixtures may ↑ or ↓ the creep

Chemical admixture (Set-Retarding Admixture)

- **Type B in ASTM C 494**
- **Applications**
  - Offset the effect of high temperature
  - Prolong the plasticity of fresh concrete
  - Eliminate cold joints
  - Special effect on concrete surface with exposed aggregate

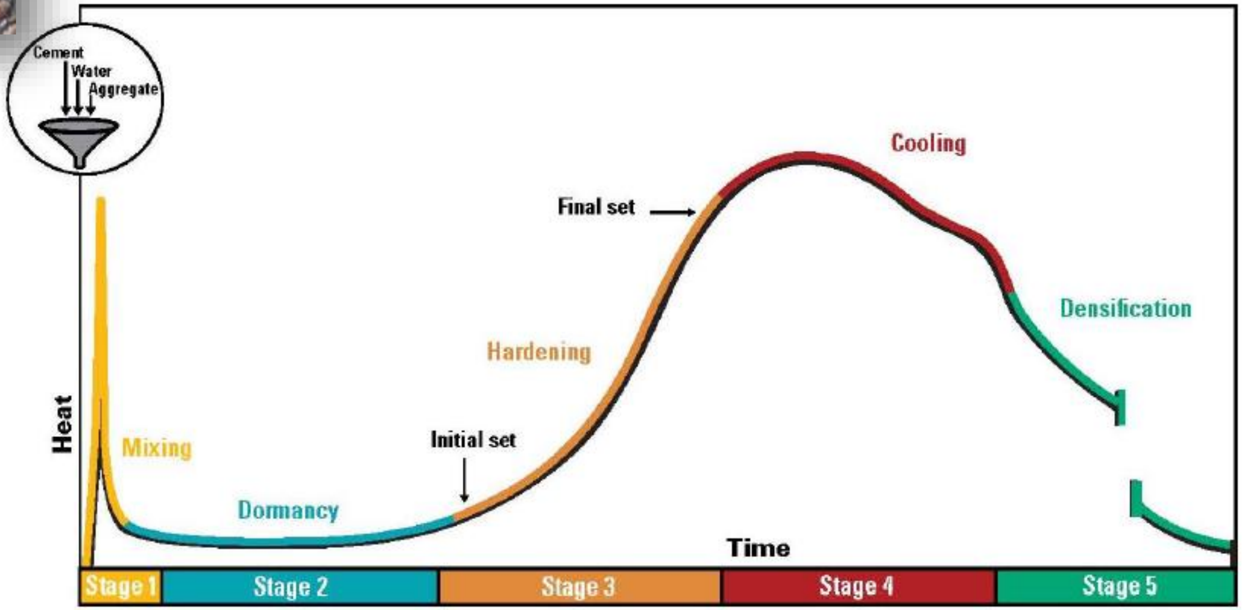
- **Composition**
  - Lignosulphonic acids and their salts
  - Hydroxycarboxylic acids and their salts
  - Sugars and their derivatives
  - Phosphates and organic phosphonate salts
  - Salts of amphoteric metals, such as zinc, lead, or tin

Water reducing, can be classified as ASTM Type D

Water-reducing & set-retarding admixtures

Chemical admixture (Set-Retarding Admixture)

- Special effect on concrete surface with exposed aggregate



Chemical admixture (Set-Retarding Admixture)

- **Mode of Action of set-retarding admixture**

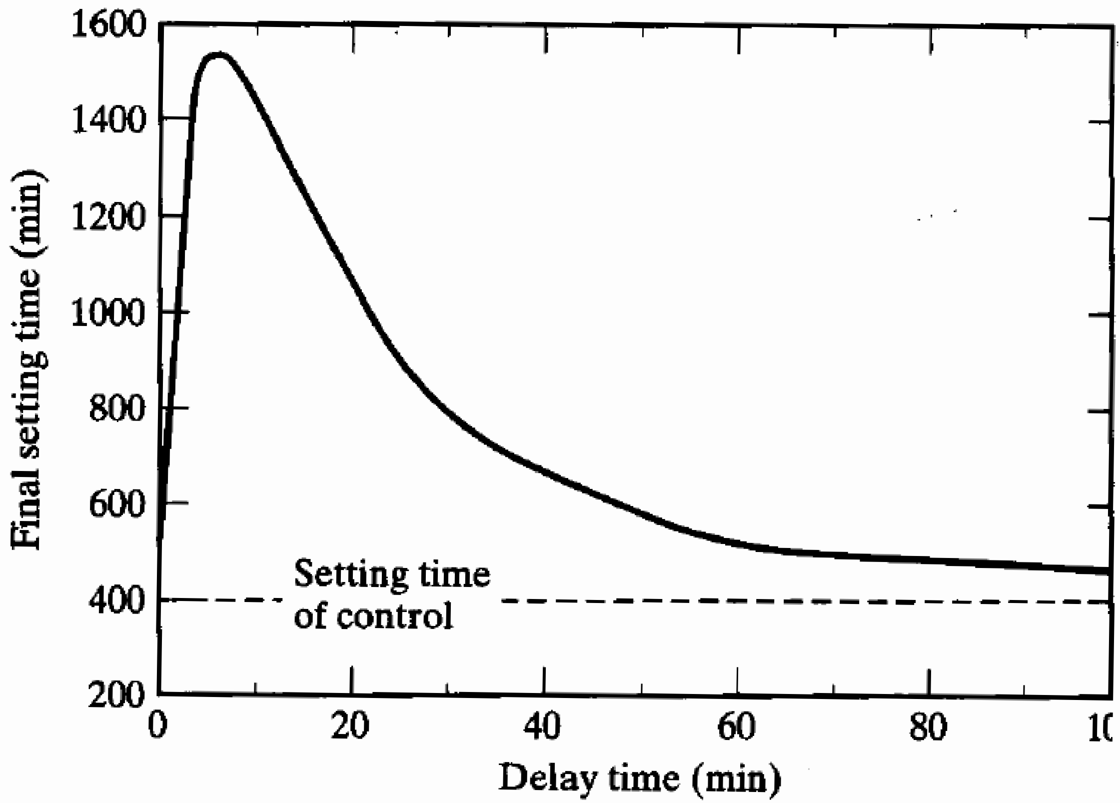
- **Effect on C3S hydration**
  - Slow down the rate of early hydration by extending the length of induction period (Stage 2), the length of induction period depends on the amount of retarders added
  - Once Stage 3 begins, hydration can proceed normally again
  - **Organic retarders**
    - Able to strongly adsorb onto the nuclei of CH and inhibit their growth into large crystals
  - **Inorganic retarders**
    - More complex, can form coating around C3S particles that severely reduce the rate of reaction

- **Extended set control**
  - Retard concrete setting in emergencies in ready-mix trucks (sugar, carbonated beverages)

Chemical admixture (Set-Retarding Admixture)

- **Effect on Concrete properties**

- Retardation increases when the addition of a retarder to concrete is delayed for a few minutes after the addition of water



Chemical admixture (Set-Retarding Admixture)

- **Effect on Concrete properties**

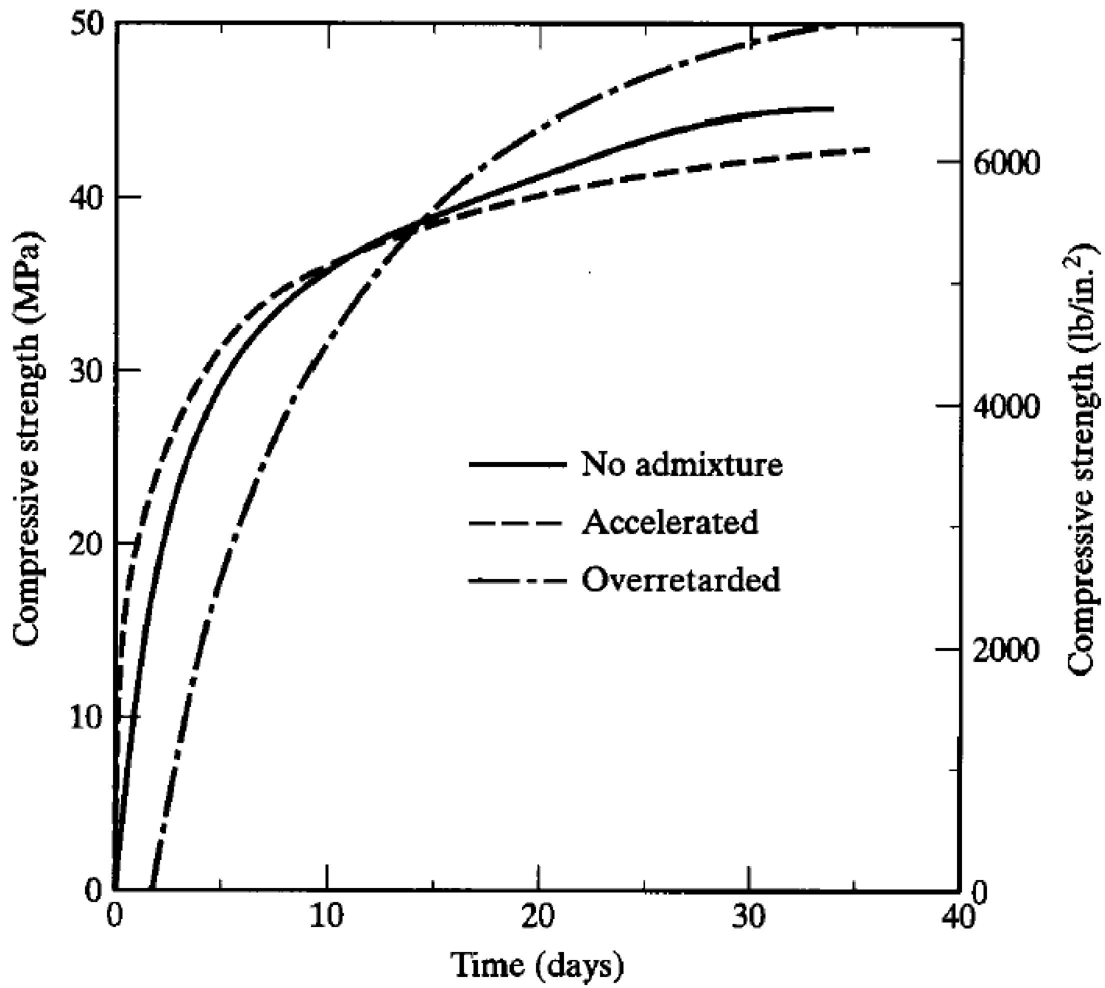
- **Strength**
  - One-day strength reduced
  - Approach the strength of control concrete within 8 days
  - Increase ultimate strength

- **Drying shrinkage and creep**
  - Lab experiments indicate that admixtures increase the rate of drying shrinkage and creep, but not the ultimate values

- Because retarders are sensitive to cement composition, admixture should be evaluated with the cement that is to be used on the job

Chemical admixture (Set-Retarding Admixture)

- Effect on Concrete properties



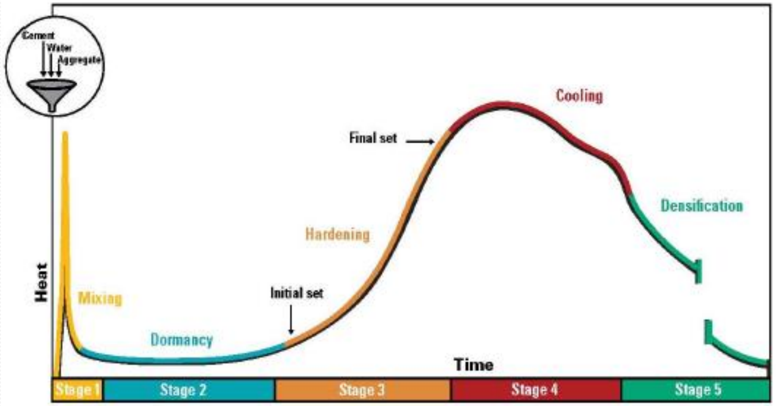
Chemical admixture (Set-Accelerating Adm.)

- **Categories**
  - Admixtures that accelerate the normal processes of setting & strength development (speed construction, for winter concreting)
  - Admixtures that provide very rapid setting not normally associated with OPC (setting in a few minutes, used for shotcrete, plugging leaks)

- **Composition**
  - **Soluble inorganic salts**
    - Accelerate setting and hardening, e.g. calcium chloride (increase reinforcement corrosion, should not be used in reinforced concrete and prestress concrete), calcium nitrite
    - Quick setting, e.g. carbonates, aluminates, and ferric salts
  - **Soluble organic compounds**
    - Calcium formate, calcium acetate

Chemical admixture (Set-Accelerating Adm.)

- **Mode of Action**
- Conventional accelerators have exactly the opposite action that retarders have
  - ↑ the rate of C3S hydration & strength development
  - Induction period shortened, the rate of hydration during Stages 3 & 4 ↑
    - In the cases with calcium salts: increase the rate at which CH crystals nucleate and grow
    - In the cases with organic accelerators: increase the rate of C3S hydration



- Quick setting admixtures cause fast setting of C3A by promoting very rapid hydration

Chemical admixture (Set-Accelerating Adm.)

- **Effects of Accelerating Admixtures on concrete properties**
- Cut down the time during which concrete can be handled
- Increase 1-day strength
- Later strength (>28 days) are likely to be lower than the strength of concrete without accelerating admixtures
- Specifics
  - Quick setting admixtures: reduce durability of concrete if they have adverse effect on strength

Chemical admixture (Air Entraining Admixture, AEA)

- **Used to protect concrete from damage due to repeated freezing/thawing cycles**

- **Entrapped air (exist in all concrete)**
  - Irregular shape
  - Size can be up to several mm
- **Entrained air voids (introduces into concrete by using AEA)**
  - Spherical in shape
  - Size ranging from 0.05 to 1.25 mm

- Air-entrained concrete cannot be distinguished from non-air-entrained concrete with the naked eyes
- In field, only total air content is controlled

Chemical admixture (Air Entraining Admixture, AEA)

- **AEA ↑ , air content of concrete ↑**
- **Amount of air required for durability purpose**
  - Mortar: ~9% by volume of mortar
  - Concrete: 4-8% depending on the max aggregate size
- **Spacing factor ($\bar{L}$), should be < 0.2 mm**
  - The average distance from any point in the paste to the edge of the nearest void
- **Specific surface area (α)**
- **Bubble frequency (n)**

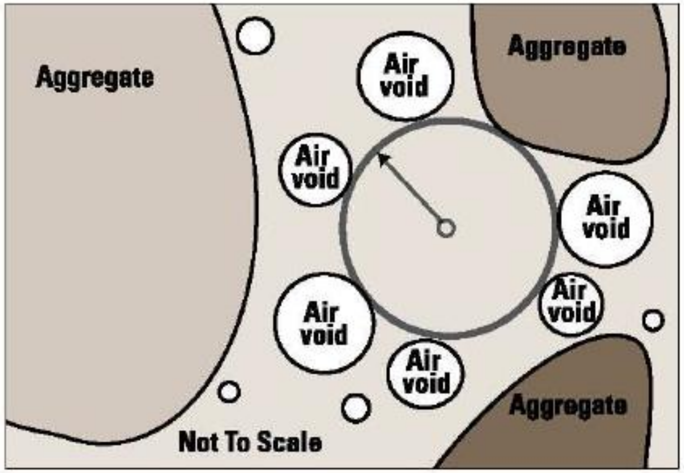


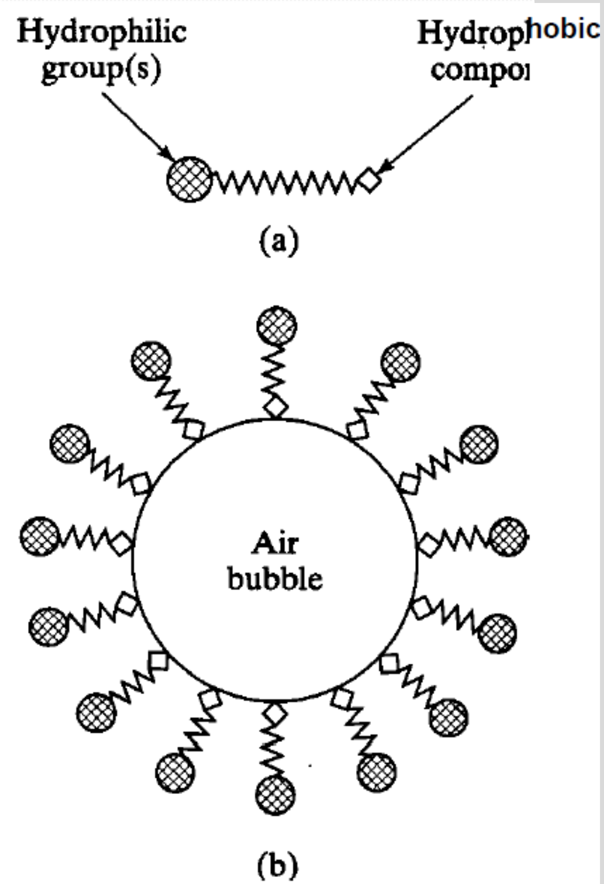
Figure 3-16. Spacing factor is the average distance from any point to the nearest air void. (Ozyildirim)

Chemical admixture (Air Entraining Admixture, AEA)

- Containing **surface-active agents** that will concentrate on air-water interface, lower the surface tension to promote the formation of stable bubbles

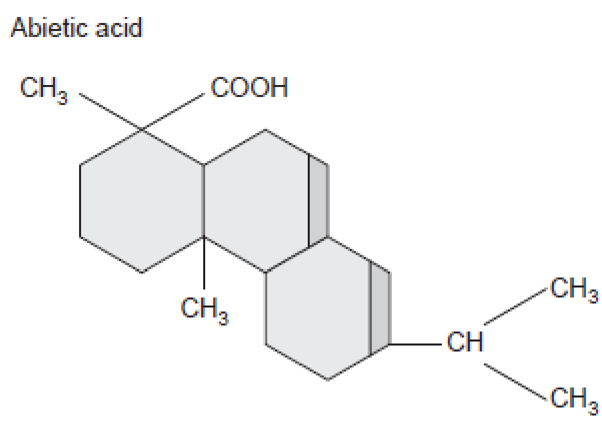
- Molecules at one end have chemical groups that tend to dissolve in water (hydrophilic), while the rest of the molecules is repelled by water (hydrophobic)

- The molecules tend to align at **the air-water interface** with their hydrophilic groups in the the water and the hydrophobic portion in air

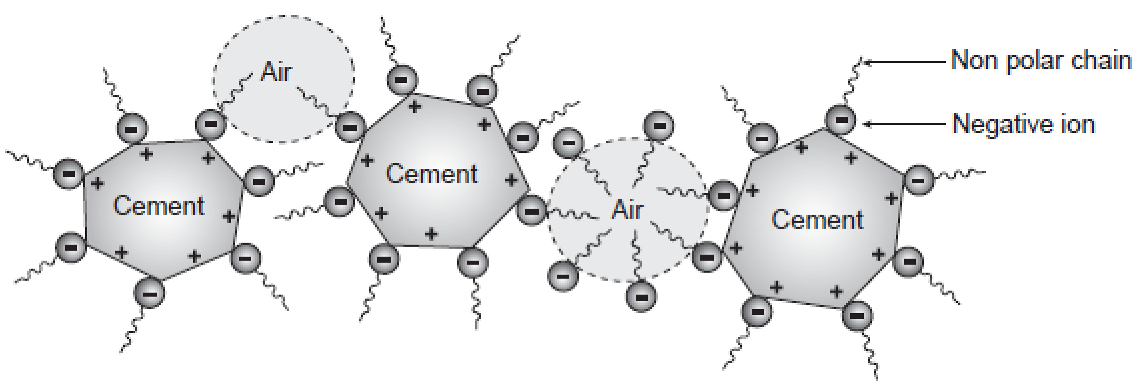


(Mindess et al 2003)

Chemical admixture (Air Entraining Admixture, AEA)



(a)



(b)

Figure 8-1 (*a*) Formula of a typical air-entraining surfactant derived from pine oil or tall oil processing; (*b*) mechanism of air entrainment when an anionic surfactant with a nonpolar hydrocarbon chain is added to the cement paste. (Adapted from Kreijger, P.C., *Admixtures*, Construction Press, Lancaster, London, 1980.)

Chemical admixture (Air Entraining Admixture, AEA)

- **Factors affecting air entrainment**

- Air entraining potential of an AEA depends on the concrete materials used and their proportions

- An air-entraining admixture should always be tested under field condition because the amount of entrained air it provides can be affected by a variety of factors

- Typical dosage
  - 0.005 – 0.05% of active ingredient by mass of cement
  - The dosage of the AEA can be adjusted to bring the air content to within the recommended limits

Chemical admixture (Air Entraining Admixture, AEA)

- **Effect on Concrete Properties**

- **Fresh concrete**
  - Improve workability
    - Tiny bubbles act as low-friction, elastic fine aggregate that reduce interaction between large aggregate particles
  - Improve cohesiveness, reduce bleeding and segregation

- **Hardened concrete**
  - Detrimental on concrete strength in general
    - Rule of thumb: each 1% entrained air will lower strength by 5%
    - However, air entrainment has much less effect or ma not affect the strength of lean concrete (cement < 300 kg/m^3
  - There is an optimum amount of air for good durability
    - Too high air content generally indicate large bubble size, will drastically reduce strength and reduce concrete resistance to stress from freezing

Chemical admixture (others)

- **Corrosion inhibitors**

- Admixtures that reduce corrosion of steel reinforcement
  - Do not inhibit the corrosion reactions completely
  - But reduce the rate of corrosion

TABLE 8.5 Types of Corrosion Inhibitors (Mindess et al. 2003)

Category	*Examples*	*Addition*[*]	*Mode of Action*
Anodic inhibitors	Calcium nitrite Sodium chromate Sodium benzoate Stannous chloride	0.5-2 2-4 6-8 2-4	Promotes formation of a protective passive film.
Cathodic inhibitors	$NaOH$ or Na_2CO_3	2-4	Increases pH and lowers solubility of Fe^{2+}.
	Aniline derivatives (Aminobenzene)		Proton acceptors that absorb on the cathode.
Mixed inhibitor	Aminobenzenethiol		Absorbs at both anodic and cathodic sites. (Amino group absorbs at cathode, thiol group at anode.)

[*] % of cement mass.

- Ability to accept electrons
- Effective only at sufficiently high concentration

  - Anodic inhibitors are the most widely used ones
    - Calcium nitrite, also used as accelerating admixture

Chemical admixture (others)

- **Alkali-aggregate reaction inhibiting admixtures**
  - **Lithium and barium salts**
  - Convert alkali-silica gels to insoluble lithium or barium salts
  - Reduce the expansion associated with the alkali-silica reaction

- **Shrinkage reducing admixtures**
  - ↓capillary tension that develops within the concrete pores as it dries
  - ↓drying shrinkage

  - ↓contact angle between fibers and pore solution
  - Improve bonding between fibers and cement paste matrix

Chemical admixture

- Comparison of ASTM and BS-EN standards

	ASTM	BS-EN
Chemical admixtures	C 494 – Spec for Chemical admixtures for concrete, Type A, B, C, D, E, F, G C 1017 – Spec for chemical admixtures for use in producing flowing concrete (slump >190 mm)	934-1: 2008- common requirements 934-2: concrete admixtures (including AEA, P, SP, accelerating, retarding adm + water retaining & water resisting adm)

Chemical admixture

- Comparison of ASTM and BS-EN standards

	ASTM	BS-EN
Chemical admixtures	C 260 – Spec for AEA for concrete	934-1: 2008- common requirements (SS EN 934-1) 934-2: concrete admixtures (including AEA, P, SP, accelerating, retarding adm + water retaining & water resisting adm) 934-3: adm. for masonry mortars 934-4: adm for grout for prestressing tendons 934-5: adm for sprayed concrete
	C 494 – Spec for Chemical admixtures for concrete, Type A, B, C, D, E, F, G C 1017 – Spec for chemical admixtures for use in producing flowing concrete (slump >190 mm)	

Aggregates

Aggregates

- **Inert, granular, inorganic materials**
- **Significance**
  - Occupies ~65-75% of concrete volume
  - Affect properties of fresh and hardened concrete, e.g.
    - Modulus of elasticity & volume stability such as shrinkage and creep
    - Abrasion resistance
  - Economic filler (if cheaper than cement+water)

Aggregates

- **Properties of Aggregates required for Mix Design**
  - Shape and surface texture
  - Maximum aggregate size and size gradation
  - Specific gravity
  - Bulk unit weight

    The above properties influence the paste requirements for workable fresh concrete
  - Moisture content and absorption

  - Properties inherent from parent rock: strength, specific gravity, absorption
  - Properties result from processing: particle shape, surface texture, size, grading

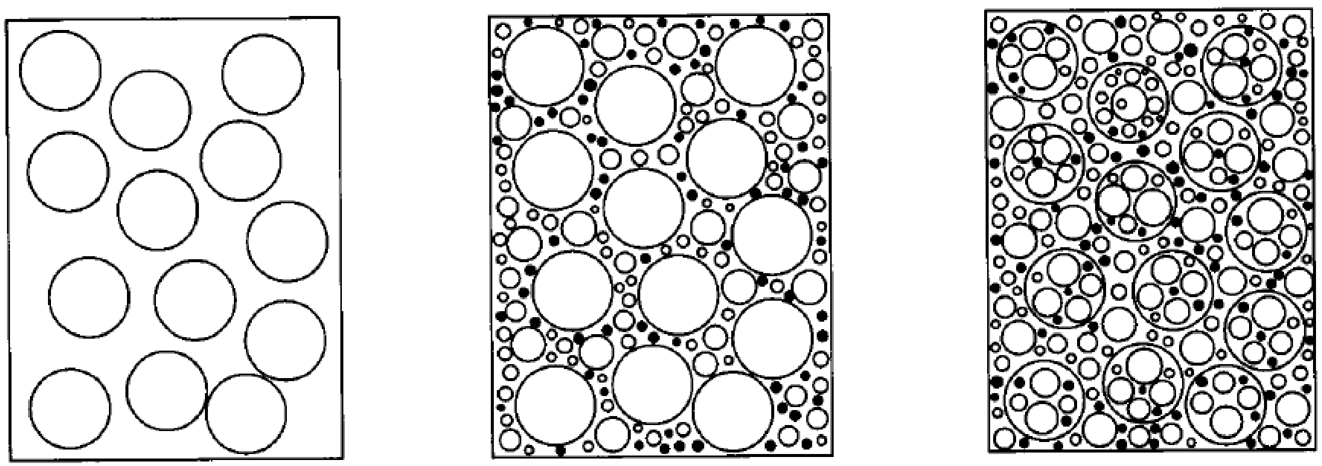
Aggregates

- **Aggregates classification**
  - Size:
    - coarse > 4.75 mm (gravel or crushed)
    - Fine < 4.74 mm (sand)
  - Bulk specific gravity:
    - Normal weight: 2.4-2.8 (granite, basalt, etc)
  - Production: crushed or uncrushed

Aggregates

- **Size gradation**
  - The particle size distribution (grading) determines the requirement of cement paste for a workable concrete

(Mindess et al 2003)



(a)

(b)

(c)

Uniform size: volume of voids is greatest

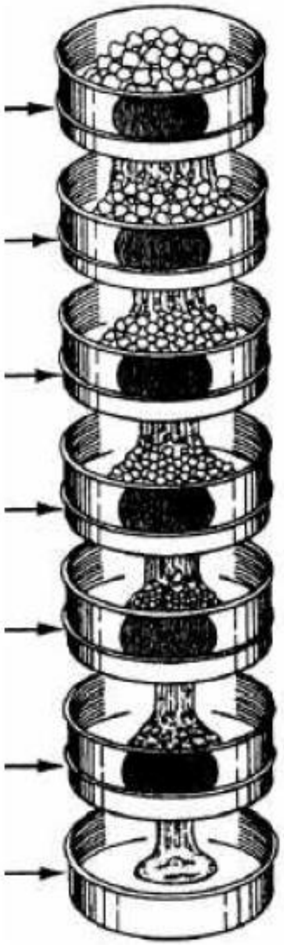
Continuous grading: volume of voids reduced

Replacement of large aggregate sizes by small ones: ↑ void space

Aggregates

- **Sieve analysis**
  - Grading of aggregate is determined by sieve analysis
    - Coarse aggregate: retained on 4.75 mm sieve
    - Find aggregate: passing 4.75 mm sieve
  - Maximum aggregate size
    - Smallest sieve opening through which the entire sample passes
      - Nominal max. aggregate size (5-10%)
    - Influence paste requirement
    - Affected by the size of element and arrangement of steel reinforcing bars
    - ↑ max. aggregate size, ↓ water/cement (w/c), ↑ strength of concrete

Size of opening
↓



Aggregates

- Sieve analysis

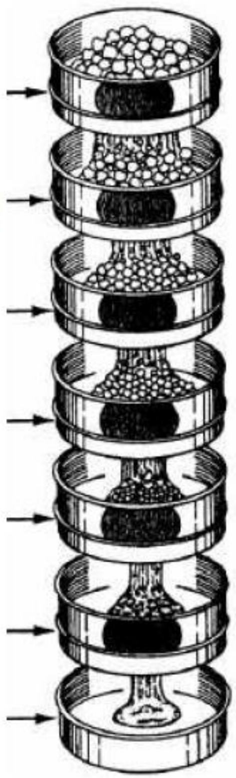
TABLE 7.3 ASTM Sieve Sizes Commonly Used for Sieve Analysis of Concrete Aggregates

	ASTM Sieve Designation	*Alternative*	*Nominal Size of Sieve Opening, in.*
Coarse aggregate	75 mm	3 in.	3
	63 mm[a]	$2\frac{1}{2}$ in.	2.5
	50 mm[a]	2 in.	2
	37.5 mm	$1\frac{1}{2}$ in.	1.5
	25 mm[a]	1 in.	1
	19 mm	$\frac{3}{4}$ in.	0.75
	12.5 mm[a]	$\frac{1}{2}$ in.	0.50
	9.5 mm	$\frac{3}{8}$ in.	0.375
Fine aggregate	4.75 mm	No. 4 ($\frac{3}{16}$ in.)	0.187
	2.36 mm	No. 8	0.0937
	1.18 mm	No. 16	0.0469
	600 μm[b]	No. 30	0.0234
	300 μm	No. 50	0.0124
	150 μm	No. 100	0.0059

[a] Half sizes.
[b] 1000 μm = 1.0 mm.

Size of opening ↓

Number of opening per inch^2



Aggregates

- **Grading curves**
- Weight of aggregate retained on each sieve is expressed as a % of the total weight of the sample
- Cumulative % retained or cumulative % passing each sieve

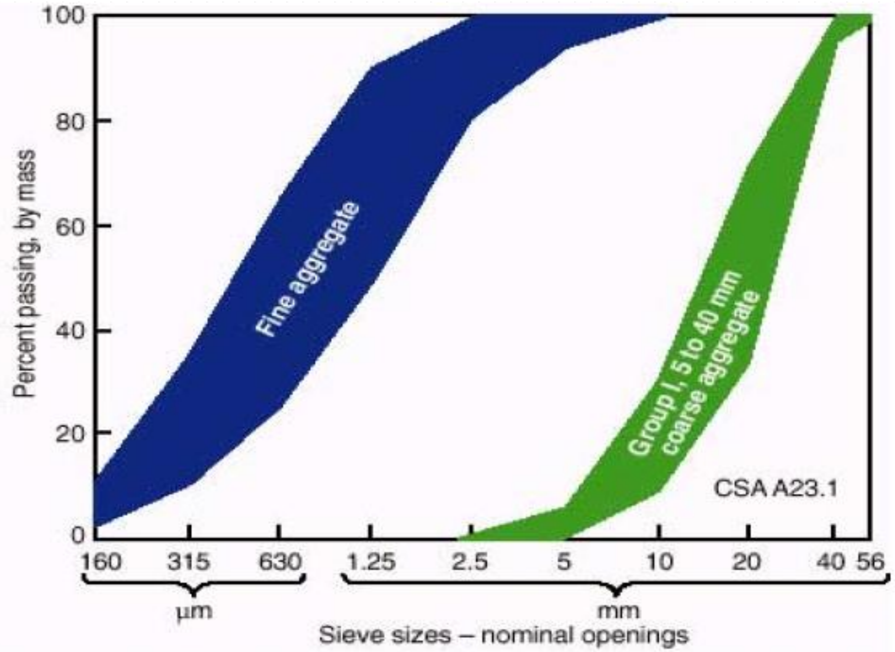


Fig. 5-6. Curves indicate the limits specified in CSA A23.1 (ASTM C 33) for fine aggregate and for one commonly used size number (grading size) of coarse aggregate.

Aggregates

- **Fineness Modulus (FM)**

FM of fine aggregate: needed for mix design, 2.3-3.1

$$\mathrm{FM} = \frac{\sum(\textit{cumulative percent retained on standard sieves})}{100}$$

- Small number indicates a fine sand
- Large number indicates a coarse sand

FM of coarse aggregate: not used for mix design

$$\mathrm{FM} = \frac{\sum\begin{pmatrix}\textit{cumulative percent retained on standard sieves,} \\ \textit{including } 2.36\textit{mm} + 400\end{pmatrix}}{100}$$

Two aggregate with the same FM can have different grading curves

Aggregates

- **Fineness Modulus (FM) calculation**

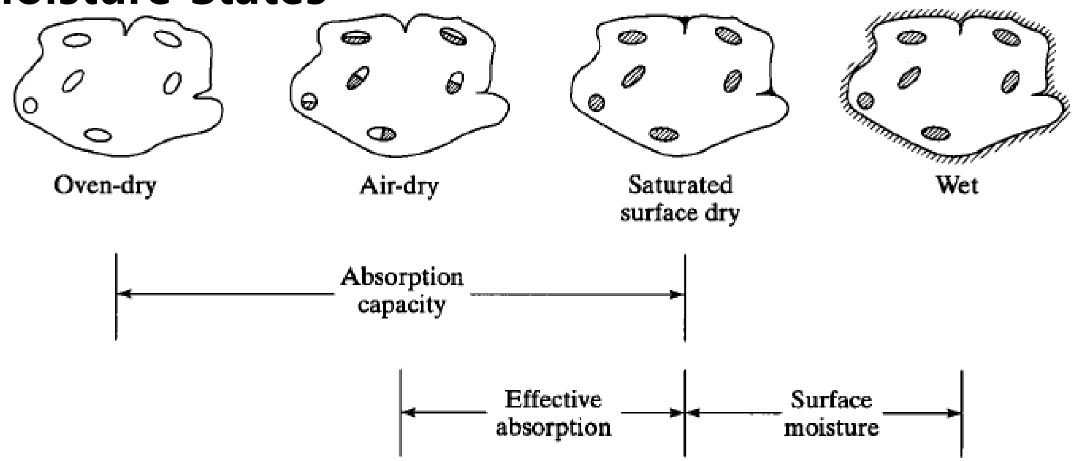
TABLE 7.6 Calculation of Fitness Modulus

	Sieve Size	*Weight Retained (g)*	*Amount Retained (wt. %)*	*Cumulative Amount Retained (%)*	*Cumulative Amount Passing (%)*
Coarse aggregate	75.0 mm (3 in.)	0	0	0	100
	37.5 mm ($1^1/_2$ in.)	42	4	4	96
	19 mm ($^3/_4$ in.)	391	39	43	57
	9.5 mm ($^3/_8$ in.)	350	35	78	22
	4.75 mm (No. 4)	180	18	96	4
	2.36 mm (No. 8)	20	2	98	2
	Sample wt.	1000g		319	
				+400 (from fine sieves 1.18 mm to 150μm)	
				$\Sigma = 719$	
	Normal maximum size = 37.5 mm ($1\ ^1/_2$ in.)				
	Fitness modulus = 719/100 = 7.19				
Fine aggregate	4.75 mm (No. 4)	9	2	2	98
	2.36 mm (No. 8)	46	9	11	89
	1.18 mm (No. 16)	97	19	30	70
	600 μm (No. 30)	99	20	50	50
	300 μm (No. 50)	120	24	74	26
	150 μm (No.100)	91	18	92	8
	Sample wt.	500 g		$\Sigma = 259$	
	Fineness modulus = 259/100 = 2.59				

(Mindess et al. 2003)

Aggregates

- **Moisture States**



(Mindess et al 2003)

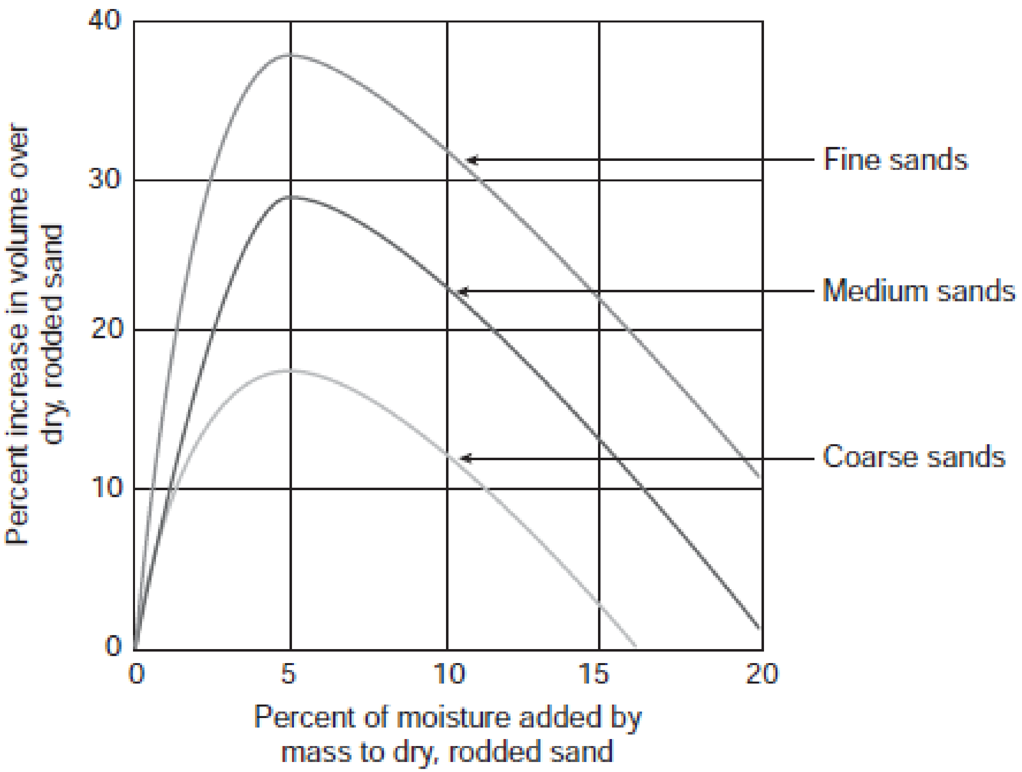
- **Oven-dry (OD):** all moisture is removed from aggregate by heating at 105°C. All pores are empty
- **Air-dry (AD):** all moisture is removed from the surface, but internal pores are partially full
- **Saturated-surface-dry (SSD):** all pores are filled with water, but no water film on the surface
- **Wet:** pores are completely filled with water with excess water on the surface

Aggregates

- **Moisture States**

State	Oven dry	Air dry	Saturated, surface dry	Damp or wet
Total moisture	None	Less than potential absorption	Equal to potential absorption	Greater than absorption

Moisture conditions of aggregates



(Metha and Monteiro 2006)

Aggregates

- **Absorption and Surface Moisture**

  - **Absorption capacity (A)**
    - Maximum amount of water the aggregate can absorb
    - For normal weight aggregate (fine & coarse), 1-2%

$$A = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100\%$$

  - **Effective absorption (EA)**
    - The amount of water required to bring an aggregate from AD state to SSD state

$$EA = \frac{W_{SSD} - W_{AD}}{W_{SSD}} \times 100\%$$

Aggregates

- **Absorption and Surface Moisture**

  - **Surface moisture (SM)**
    - Water in excess of the SSD state

$$SM = \frac{W_{wet} - W_{SSD}}{W_{SSD}} \times 100\%$$

  - **Moisture content (MC)**
    - Total moisture associated with the aggregate

$$MC = \frac{W_{stock} - W_{SSD}}{W_{SSD}} \times 100\%$$

    - MC > 0, aggregate is in wet state
    - MC < 0, aggregate is in AD state

Aggregates

- **Specific Gravity**
  - A dimensionless ratio relating the density of the aggregate to that of water

$$SG = \frac{density\ of\ solid}{density\ of\ water}$$

  - **Apparent specific gravity**
    - Refers only to "solid" material excluding pores

$$ASG = \frac{weight\ of\ aggregate\ (solid\ only)}{volume\ of\ aggregate\ (solid\ only)} \cdot \frac{1}{\rho_{water}}$$

  - **Bulk specific gravity** (2.5-2.8 for most rock)
    - Includes the volume of pores in the aggregate volume

$$BSG = \frac{weight\ of\ aggregate\ (solid + pores)}{volume\ of\ aggregate\ (solid + pores} \cdot \frac{1}{\rho_{water}}$$

$$= \frac{weight\ of\ aggregate\ (solid + pores)}{weight\ of\ water\ displaced}$$

Aggregates

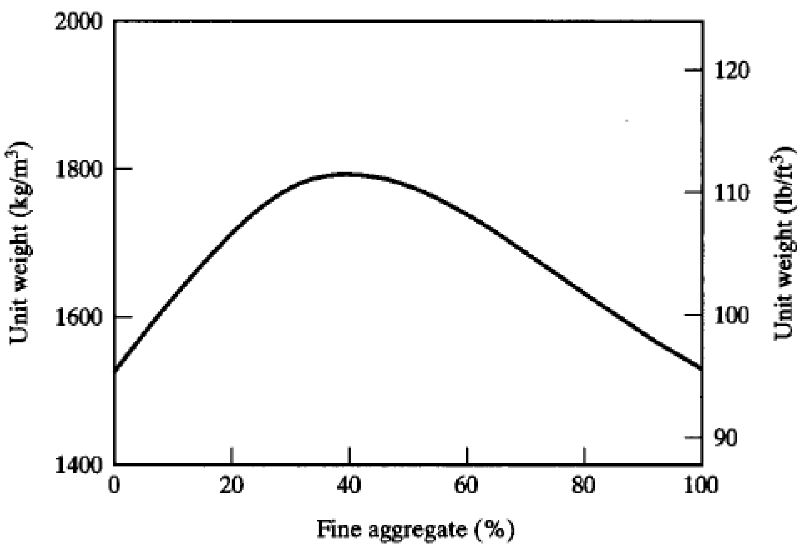
- **Specific Gravity**
  - BSG value is the realistic one to use for mix design
  - Contribution of pores to BSG depends on whether the pores are filled or empty

$$ASG > BSG_{SSD} > BSG_{OD}$$

  - For normal weight aggregate, the values of the above three SG are approximately the same since porosity of rock is usually only 1-2%

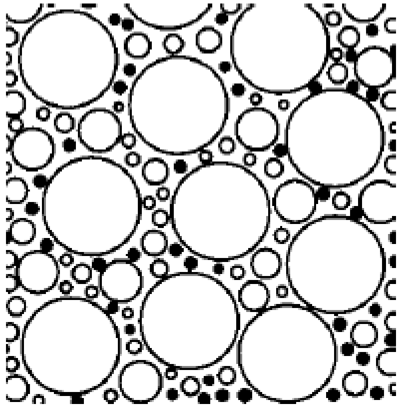
Aggregates

- **Unit Weight (Dry rodded unit weight)**



  - Defined as the weight of a given volume of graded aggregate
  - **Oven-dry** aggregate is used
  - Unit weight of coarse aggregate is required for volume method of mix proportioning

$$Total\ volume = V_a + V_V$$



  - Typical values: 1450 – 1750 kg/m^3
  - Fine aggregate content = 35-45%, maximum unit weight, minimum void space

Aggregates

- **Lightweight aggregate spectrum**

(Metha and Monteiro 2006)

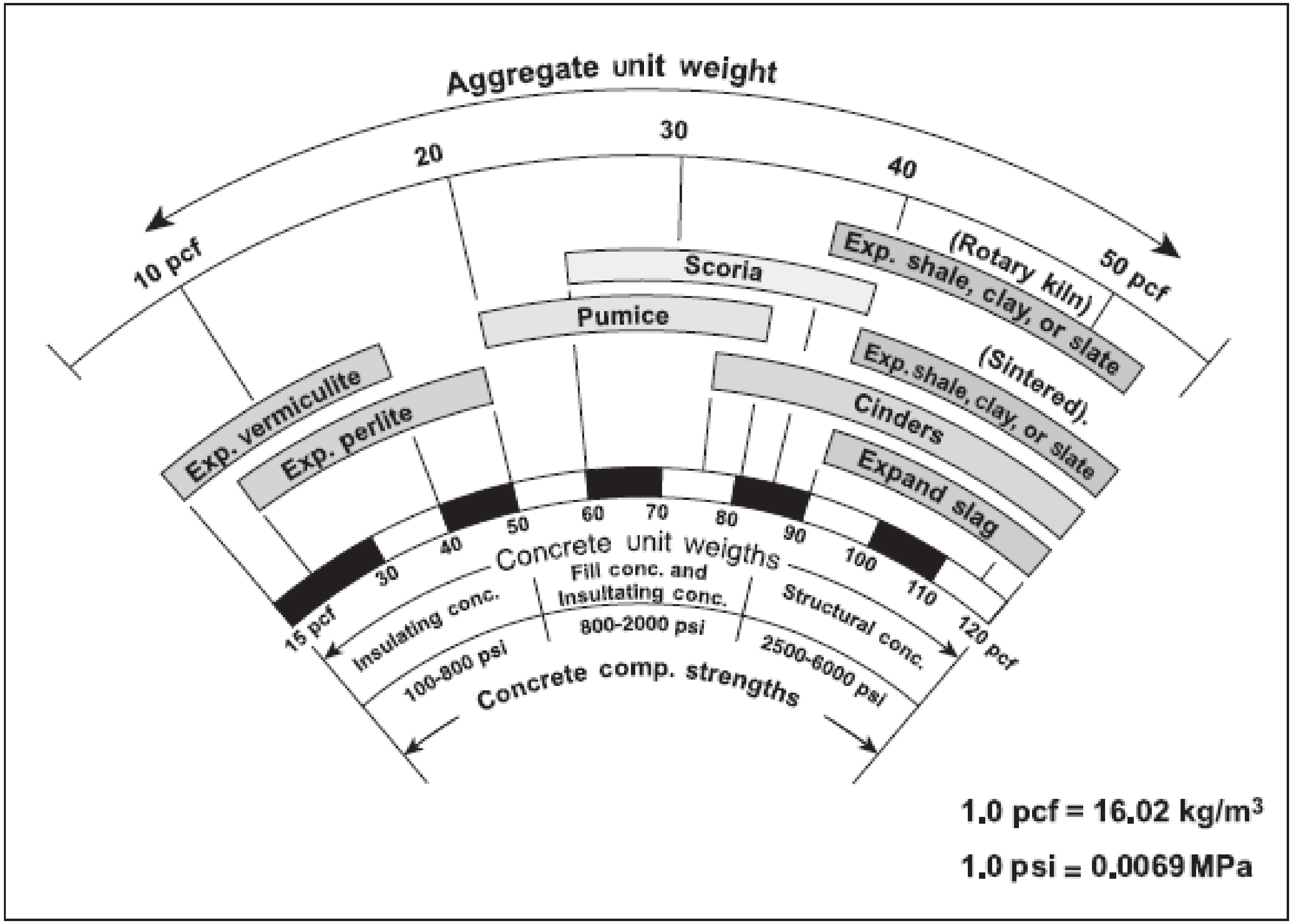


Figure 7-1 Lightweight aggregate spectrum. (Adapted from Litvin, A., and A.E. Fiorato, *Concr. Int.*, Vol. 3, No. 3, p. 49, 1981.)

Aggregates

- **Heavyweight aggregates**

TABLE 7-3 Composition and Density of Heavyweight Aggregates

Type of aggregate	Chemical composition of principal mineral	Specific gravity of pure mineral	Typical bulk density [lb/ft^3 (kg/m^3)]
Witherite	$BaCO_3$	4.29	145 (2320)
Barite	$BaSO_4$	4.50	160 (2560)
Magnetite	Fe_3O_4	5.17	170 (2720)
Hematite	Fe_2O_3	4.9–5.3	190 (3040)
Lepidocrocite	Hydrous iron ores	3.4–4.0	140 (2240)
Geothite	containing 8–12%		
Limonite	water		
Ilmenite	$FeTiO_3$	4.72	160 (2560)
Ferrophosphorus	Fe_3P, Fe_2P, FeP	5.7–6.5	230 (3680)
Steel aggregate	Fe	7.8	280 (4480)

(Metha and Monteiro 2006)