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CV6109

Advanced Concrete Technology

Course Outline

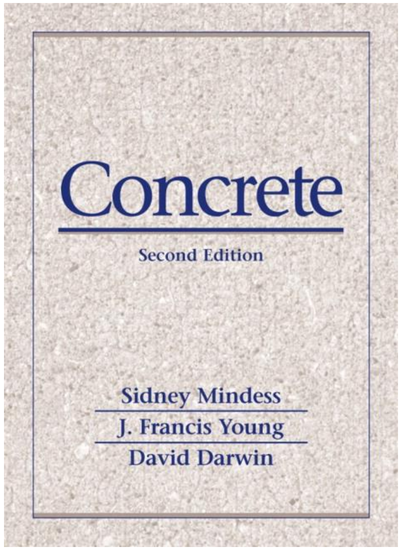
- Course content
  - 13 teaching weeks (12 lectures + 1 public holidays)
  - 4 homework assignments
  - 1 presentation
  - 1 midterm quiz
  - 1 final examination paper
- Date: **Monday** (10 Aug – 9 Nov)
- Time: **6:30pm** to 9:30pm
- Venue: **LT16**

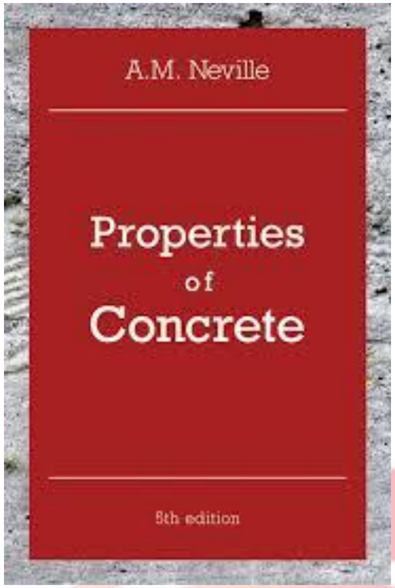
Teaching week	Date	Contents	Lecturer
1	10 Aug	• Public Holiday (No Class)	
2	17 Aug	• Introduction • Cement & Hydration	YANG EH
3	24 Aug	• Cement & Hydration	YANG EH
4	31 Aug	• Cement & Hydration • Aggregates	YANG EH
5	7 Sep	• Aggregates • **HW 1 due**	YANG EH
6	14 Sep	• Admixtures	YANG EH
7	21 Sep	• Fresh Concrete • **HW 2 due**	YANG EH
Recess (28 Sep – 2 Oct)			
8	5 Oct	• Mix Design • Mixing, Placing, Curing	C Unluer
9	12 Oct	• Properties of Hardened Concrete	C Unluer
10	19 Oct	• Properties of Hardened Concrete • **Quiz (L1.-L.8)** • **HW3 due**	C Unluer
11	26 Oct	• Testing of Hardened Concrete	C Unluer
12	2 Nov	• Durability of Concrete • **HW4 due**	C Unluer
13	9 Nov	• Special Concrete	C Unluer

References

- Mindess, S., Young, J.F., and Darwin, D. Concrete. 2nd Ed., Prentice Hall, 2002

- Neville, A.M. Properties of Concrete. 4th Ed., Pearson Education, 1995





Lecturers

Asst. Prof. Yang En-Hua
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Assignments, Examination and Grading

- Homework (20%)
  - 4 homework assignments
  - You are encouraged to discuss with others. However, …
  - **Do NOT copy others' homework**. If identified, **ZERO** mark.
  - Assignment should be submitted in class. **No late submission is accepted**.
- Presentation (5%)
  - 1 short (3-5 minutes) presentation on topics covered in the last lecture
- Midterm quiz (20%)
  - Scope: Materials covered from teaching week 1 to 8
  - Format: MCQ
  - Date/time: 19 Oct / in class
  - Venue: LT16
  - Close book
- Final exam (55%)
  - Scope: Materials covered from teaching week 1 to 13
  - Close book

INTRODUCTION

Concrete Supports Quality of Life

In 2001, transportation related activities account for over $1000 billion worth of economic activity annually or 10% of GNP
In western Europe, infrastructure represents 50% of national wealth

Concrete Applications

- Residential and commercial buildings
- Bridges, flyovers, culverts
- Dams, tunnels, water tanks
- Swimming pools
- Roads, runways, pipes
- Foundations, piles, sewers
- Offshore platforms
- Nuclear power stations, radiation shields etc.
- Fire and corrosion protection of steel structures
- Many more applications…

Concrete Facts

- The most used man-made material
- The 2nd most used material
- Total value of concrete infrastructure > 17 trillion US dollars
- Annual consumption of concrete in the world
  - 18 billion ton/year (as of 2006)
  - About 3 tons per person
  - More than 10x that of steel
- Why is concrete widely used as a construction material?

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Concrete as A Construction Material - Advantages

- Ease of production from local materials and experience (cost benefit)
- Mouldability to achieve any shape and size
- A durable material in principle
- Excellent material for fire resistance
- Requires less energy to produce than other construction materials
- Aesthetic possibilities through the use of color, texture, and shape
- A material with tailorable properties

Energy Consumption for Production of Several Construction Materials

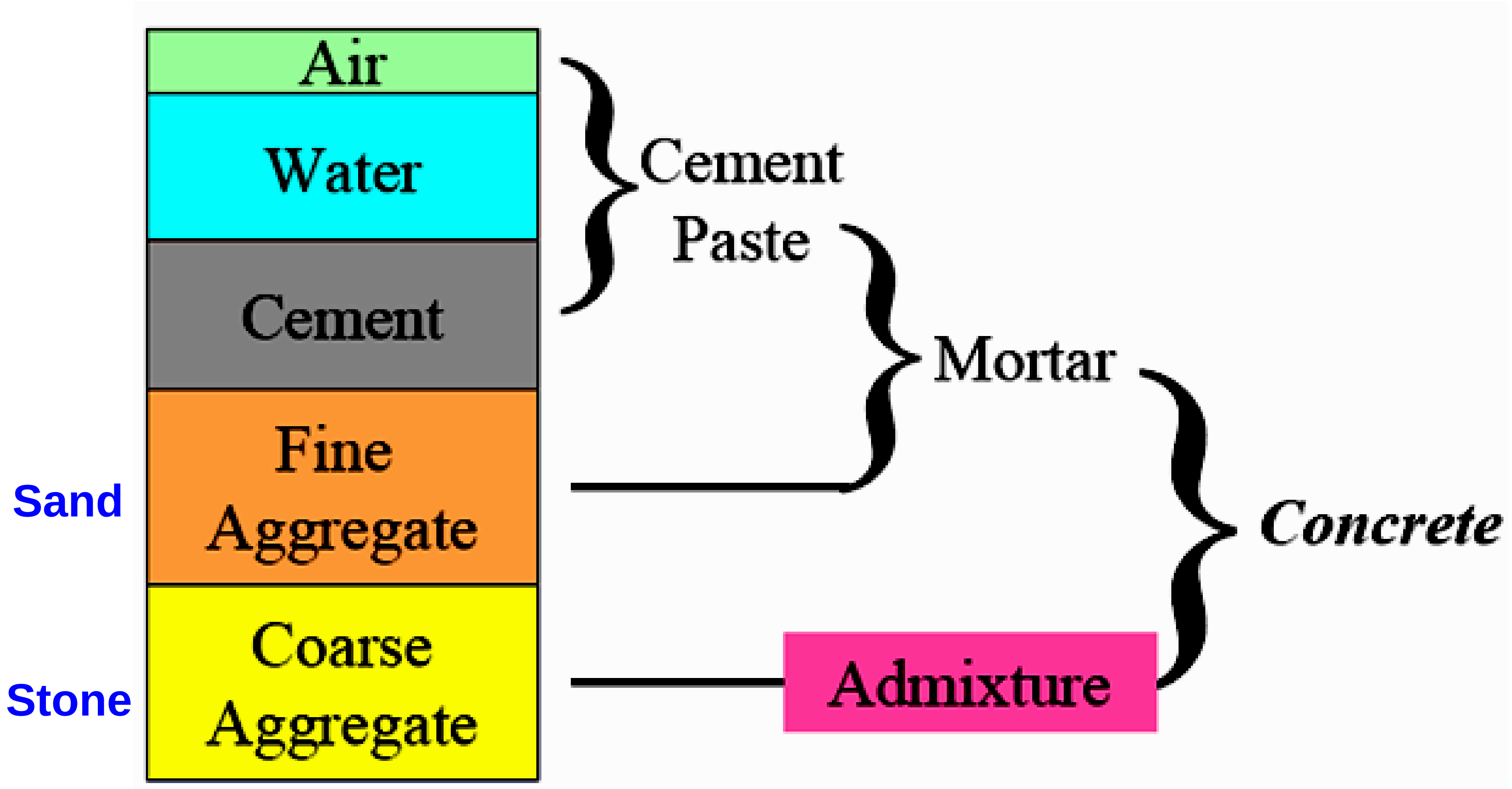
Material	Energy Requirement (GJ/m^3)
Aluminum	360
Steel	300
Glass	50
Concrete	3.4

Example Concrete Structures in Singapore

What is Concrete?

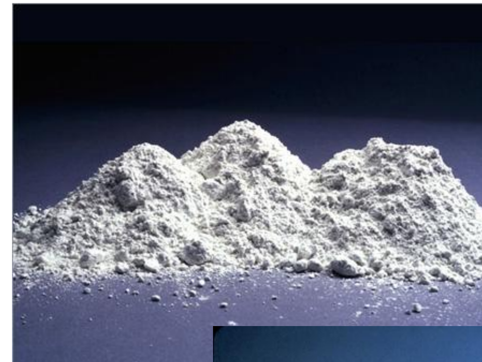
- Artificial stone produced from sand and stone together with cement paste (cement + water)
- Cement paste fills the space between stone and sand particles
- Concretus (a Latin word)
  - Compact
  - Condensed
  - To grow together

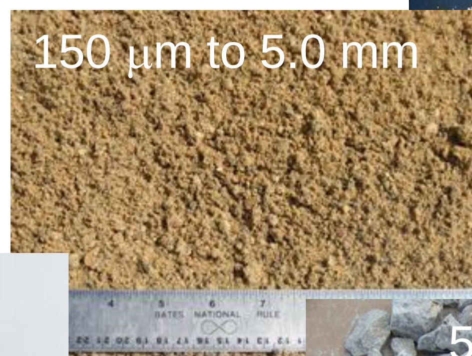
Paste, Mortar, or Concrete?



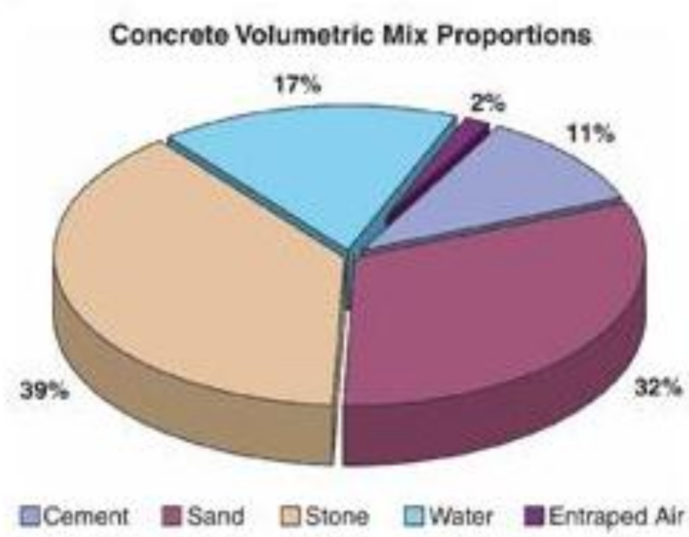
Ingredients of Modern Concrete

- Binder materials
  - Portland cements (various types)
  - Cement + supplementary cementitious materials (SCM)
- Aggregates
  - Fine aggregates < 5mm
  - Coarse aggregates > 5mm
- Water
- Admixtures
- Fiber





Proportions of Ingredients



Volumetric composition of concrete

- Cement or binder = 6 to 16 %
- Water = 12 to 20 %
- Fine aggregates = 20 to 30 %
- Coarse aggregates = 40 to 55 %
- Air content = 1 to 3 % (non air-entrained)
  = 4 to 8 % (air-entrained)

Optional components

- Admixture
- Supplementary cementitious materials
  - Silica fume
  - Fly ash
  - Slag
  - Pozzolans
- Fibers
  - Steel
  - Polypropylene
  - Glass
  - Carbon
  - Nylon
  - Natural etc.

Specifying Mix Compositions

- By relative proportions in weight

1	:	2	:	4	:	0.55
Cement		Fine Agg.		Coarse Agg.		Water

- Simple and concise
- Does not show actual quantities
- Mainly used in old days

Specifying Mix Compositions

- By quantities of ingredients to produce on cubic meter of compacted concrete

315 kg	**:**	**630 kg**	**:**	**1260 kg**	**:**	**175 kg**
Cement		Fine Agg.		Coarse Agg.		Water

  - Actual quantities needed
  - Richness of concrete

Example

- A concrete batch is produced with the following batch quantities: Cement = 10 kg; Water = 5 liters; Fine aggregate = 20 kg; and Coarse aggregate = 40 kg. Aggregates are in saturated surfaced dry condition. Given: specific gravity of cement and aggregates are 3.15 and 2.60, respectively. Assuming no entrapped air, determine the following
  - Unit weight or wet density of concrete; and
  - Mix composition of this concrete

Typical Properties of Structural Concrete

Compressive strength	35 MPa
Flexural strength	6 MPa
Tensile strength	3 MPa
Modulus of elasticity	28 GPa
Poisson's ratio	0.18
Tensile strain at failure	0.001
Coefficient of thermal expansion	$10 \times 10^{-6}/^{o}C$
Ultimate shrinkage strain	0.05-0.1%
Density	
Normal weight	2300 kg/m^3
Lightweight	1800 kg/m^3

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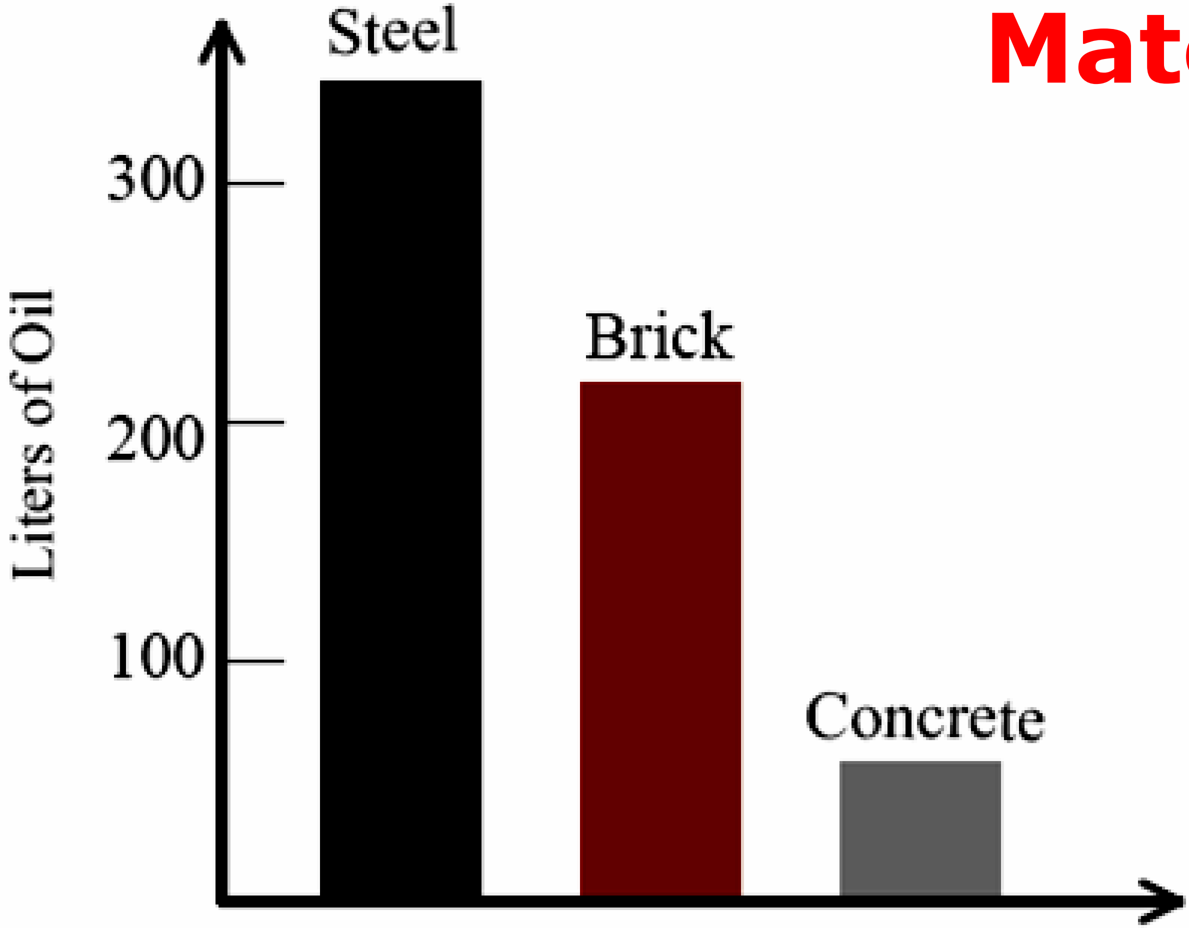
Note: Concrete properties can vary significantly from the figures given, depending on the choice of materials and proportions for a particular application

Concrete as A Construction Material - Disadvantages

- A brittle material with very low tensile strength and tensile ductility. Should generally not be loaded or designed in tension
- Even in compression, concrete has a relatively low strength-to-weight ratio, i.e. high load capacity requires large masses
- Concrete undergoes considerable irreversible shrinkage due to moisture loss and also creeps significantly under an applied load

Energy Consumption of One Meter High Column Resisting a 1000-ton Load and Constructed of Various Materials



(From O. Beijer, translated by A. E. Fiorato, *J. ACI*, Proc., Vol. 72, No. 11 p.599, 1975.)

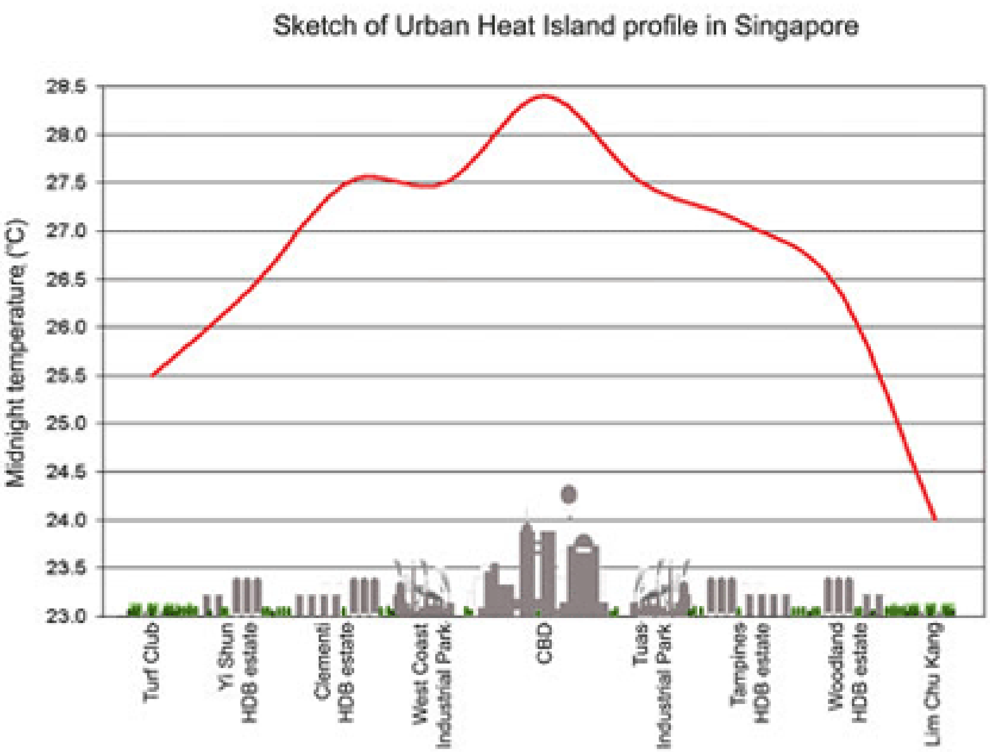
Advantages and Disadvantages of Concrete as A Construction Material

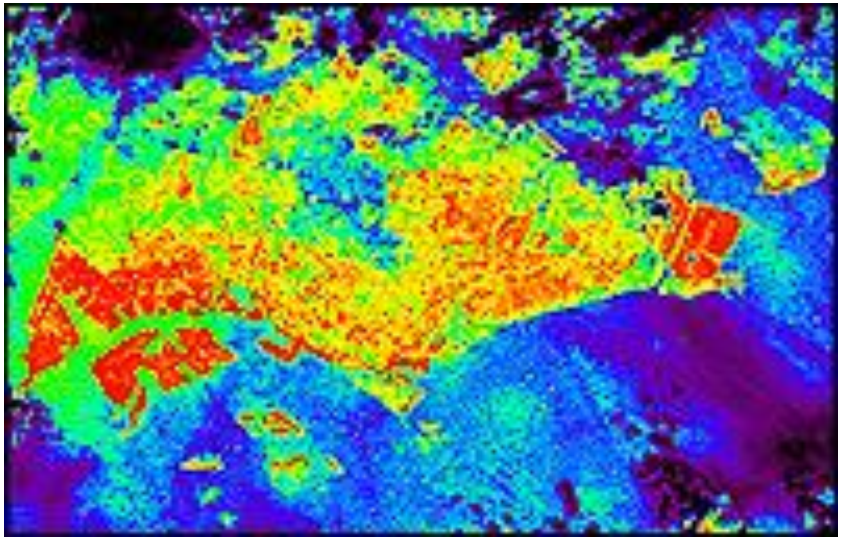
Advantage	Disadvantage
Ability to be cast	Low tensile strength
Economical	Low ductility
Durable	Volume instability
Fire resistant	Low strength-to-weight ratio
Energy efficient	
On-site fabrication	
Aesthetic properties	

Environmental Impact of Concrete

- Enormous raw material and energy consumption
  - Global concrete demand > 18 billion tons annually as of 2006
  - 1 ton of cement clinker requires 1.7 tons of non-fuel raw materials
  - Cement production is 10x more energy intensive than general economy and is account for 2% of global primary energy use (4000-7500 MJ per tonne of cement)
  - Land scarring
- CO_2 emission and climate change
  - Production of 1 ton of cement clinker generates equal amount of greenhouse gas
  - Cement production accounts for 5-10% of global CO_2 emissions
- Impermeable surface to cause surface runoff
- Urban heat island

Urban Heat Island





Source: Dr. Wong Nyuk Hien, National University of Singapore

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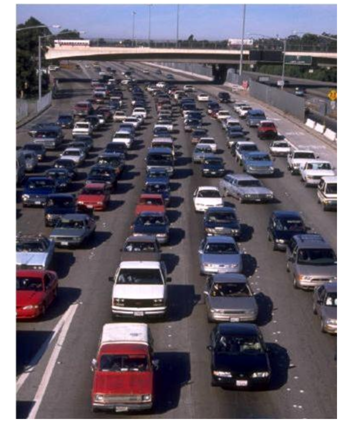
Next Great Challenge for Civil Engineers: Co-existence Between the Natural and Built Environment

Greenhouse gas emissions



Energy consumption

Land scarring

Or a battle?

Note: Sustainability "to meet the needs for the present without compromising the ability of future generations to meet their own needs"

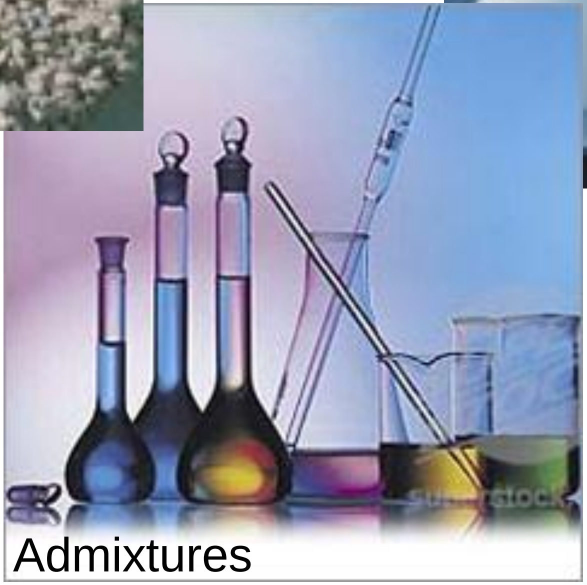
What You Will Learn From This Subject …

Cementitious Materials and Hydration

Hydrated cement paste

Photo courtesy of Mr. Jim Margeson, NRC-IRC

Properties of Other Concrete Ingredients



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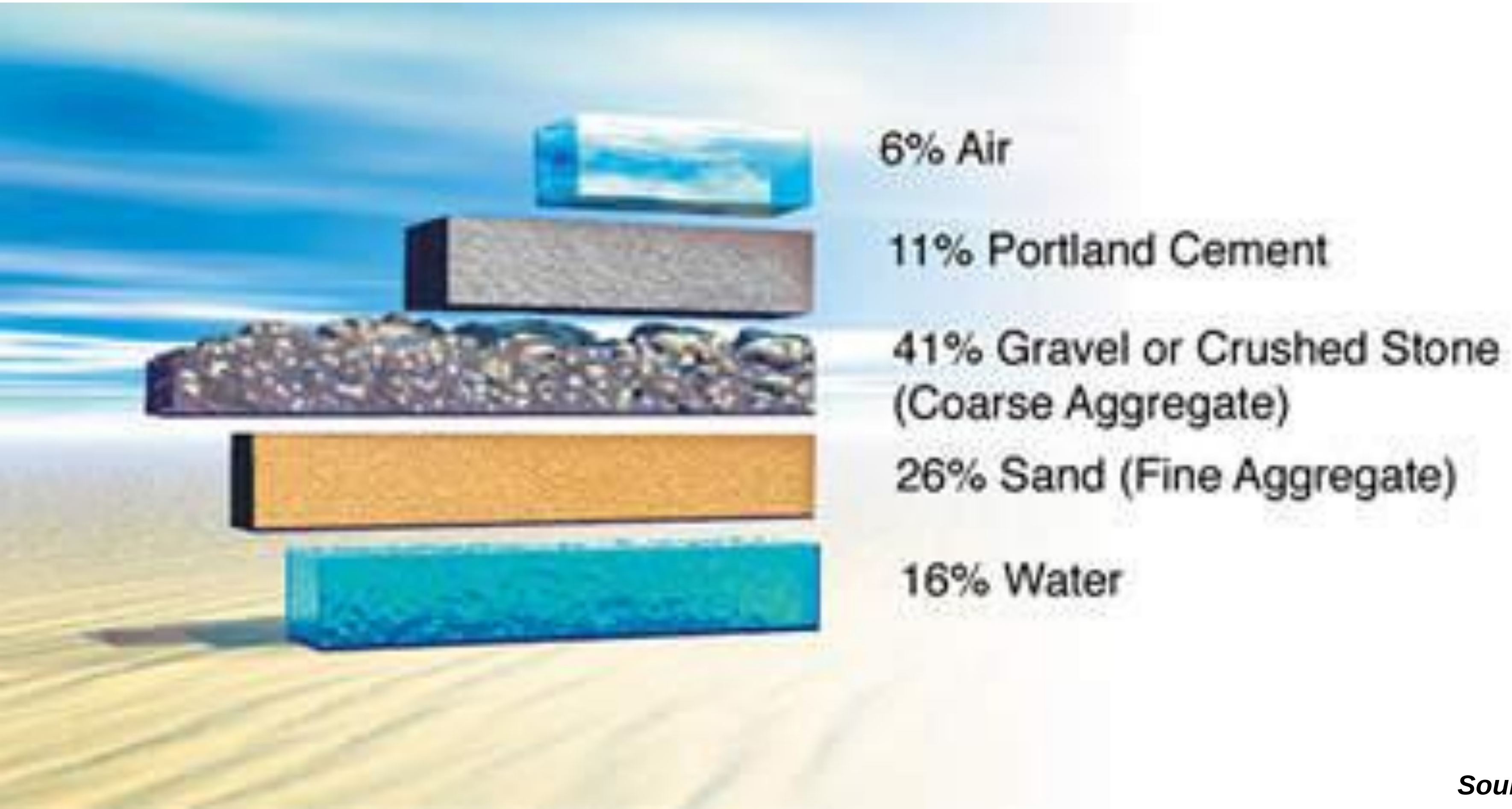
Mix Design: How to Design A Concrete Mix w.r.t. A Specified Compressive Strength?

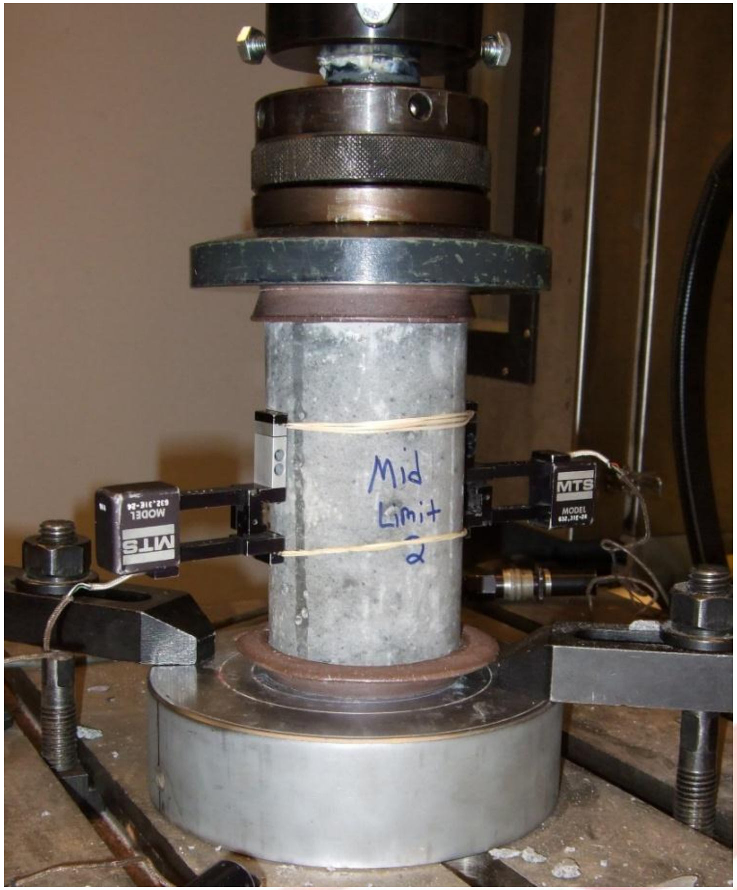


Source: PCA

Fresh and Hardened Properties of Concrete and the Tests

Compression test on hardened concrete

Slump test on fresh concrete



Concrete Durability

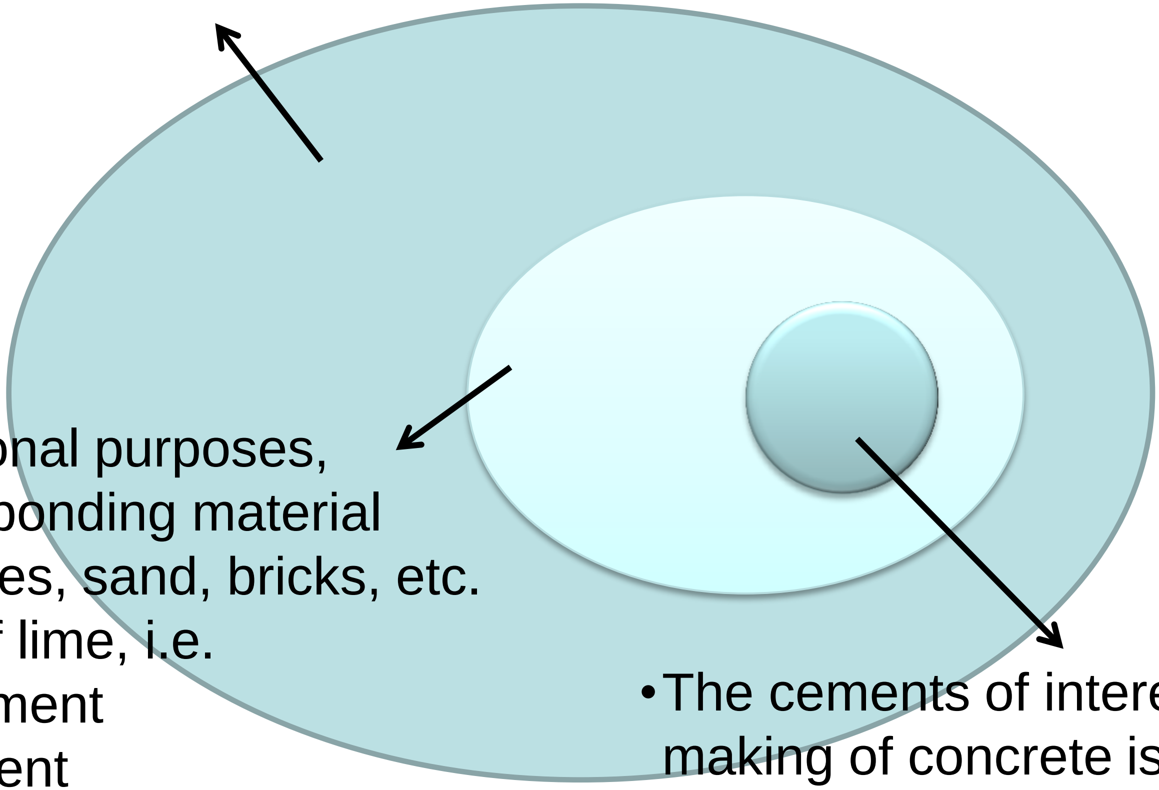
Deterioration due to alkali-aggregate reaction

Deterioration due to corrosion of steel reinforcing bars

Cement & Hydration

Cement

- Cement, in general, is the material with adhesive and cohesive properties which bonds mineral fragments into a compact whole



- For constructional purposes, cement is the bonding material used with stones, sand, bricks, etc.
- Compounds of lime, i.e. calcareous cement
- Hydraulic cement
  Non-hydraulic cement

- The cements of interest in the making of concrete is the **hydraulic cements**

Hydraulic Cements

- Cements have the property of setting and hardening under water by virtue of a chemical reaction with it
- Hydraulic cements consist mainly of silicates and aluminates of lime
- Classification
  - Natural cements
  - **Portland cements**
  - High-alumina cements

Nature of Concrete

Concrete cylinder full and sliced

Concrete - Composite Material

Aggregates (Fine & Coarse) of different sizes and shapes are randomly dispersed in cement paste (cement + water).

Aggregate: Discrete phase

Cement paste: Continuous phase

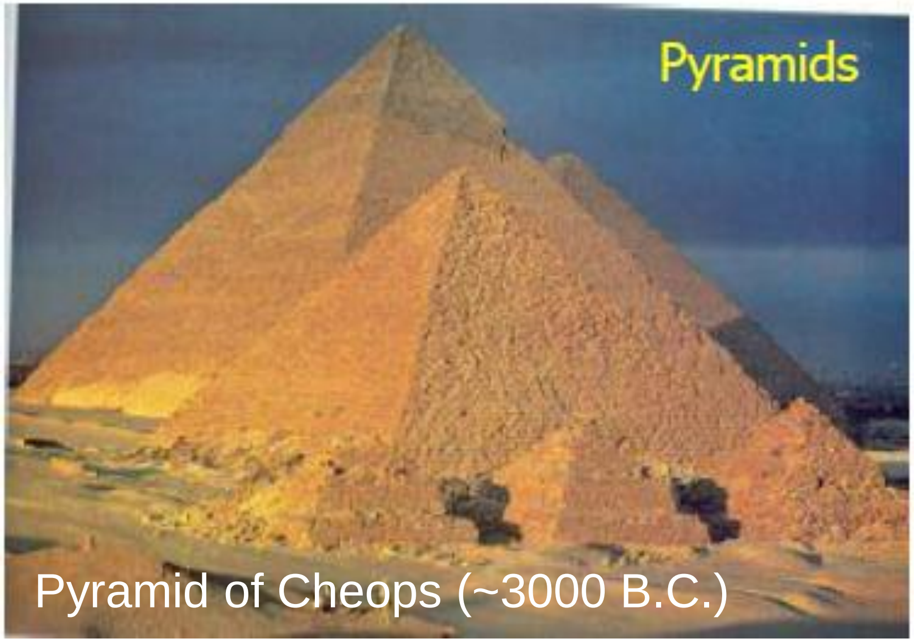
Aggregate-cement paste interfacial bond

Roles of Cement/Binder Paste

- Coats the aggregate particles
- Fills the spaces between aggregate particles
- Binds the aggregate particles
- Provides strength & stiffness to concrete
- Responsible for permeability and time-dependent deformation (shrinkage & creep)

Historical Note on Cement

- Ancient cementing materials
  - Ancient Egyptians: Calcined impure gypsum (Non-hydraulic)
  - Greeks and Romans: Calcined limestone/lime mortars (Non-hydraulic)



Historical Note on Cement

- Ancient cementing materials
  - Romans: Lime, volcanic ash or burnt clay tile ground together (hydraulic cement)

Pantheon (126 AD)

Historical Note on Cement

- Portland cement (hydraulic cement)
  - John Smeaton [1756]
    - Hydraulic lime: burning a mixture of lime and clay
    - The first to understand the chemical properties of hydraulic lime and the role of **clay**
    - Eddystone lighthouse: hydraulic lime mixed with pozzolan
  - James Parker [1976]
    - Roman cement: calcining nodules of argillaceous limestone (impure limestone containing clay)
  - Joseph Aspdin [1824]
    - Portland cement: Heating a mixture of finely-divided clay and limestone in a furnace until carbon dioxide had been driven out
  - Isaac Johnson [1845]
    - Heating a mixture of finely-divided clay and limestone until clinkering

Note: The name 'Portland cement', given originally due to the resemblance of the color and quality of the hardened cement to Portland stone – a limestone quarried in Dorset, UK.

Cement
(EN 197-1:2000)

- Cement is a **hydraulic binder**, i.e. a finely ground inorganic material which, when mixed with water, forms a paste which sets and hardens by means of hydration reactions and processes and which, after hardening, **retains its strength and stability even under water**

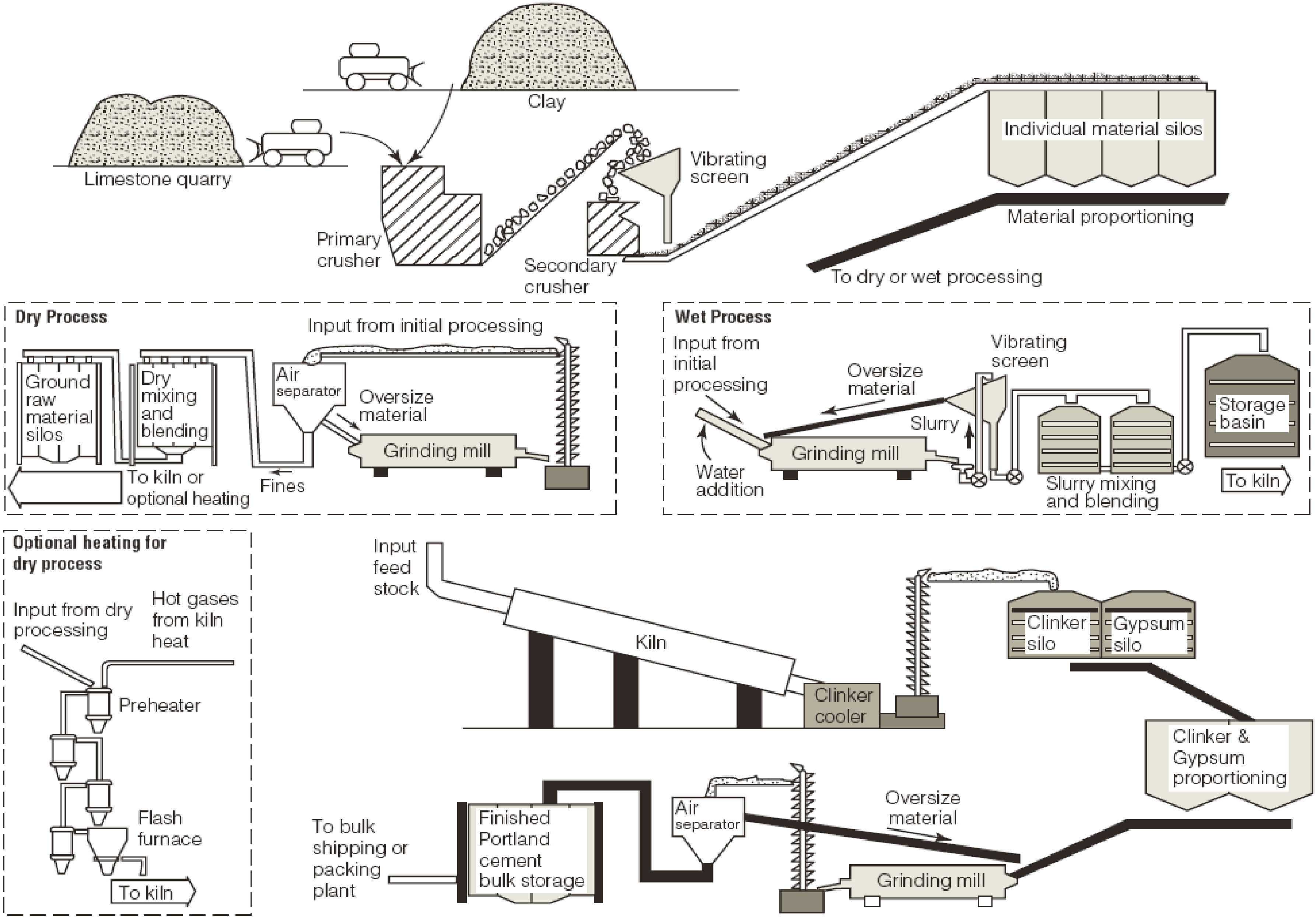
Raw Materials of Portland Cement

- Limestone, Chalk [$CaCO_3$ = CaO (**lime**) + CO_2]
  - Calcareous materials
- Clay, Shale – **silica** (SiO_2) & **alumina** (Al_2O_3)
  - Argillaceous materials
- Iron Ore – Iron Oxide (Fe_2O_3)
  - Flux to lower the clinkering temperature
- Gypsum – Calcium Sulphate ($CaSO_4 \cdot 2H_2O$)
  - Control the rate of setting of cement

Manufacture of Portland Cement

- Cement, how it is made http://youtu.be/n-Pr1KTVSXo
- Collect the raw materials such as; limestone, clay, sea sand, shale, and etc.
- Grind the raw material into a very fine powder
- Mix them in predetermined proportions
- Burn them in a large rotary klin at a temperature of about 1400^{o}C when the material sinters and partially fuses into clinker
- The clinker is cooled and ground to a fine powder, with some gypsum added, and resulting product is the commercial Portland cement

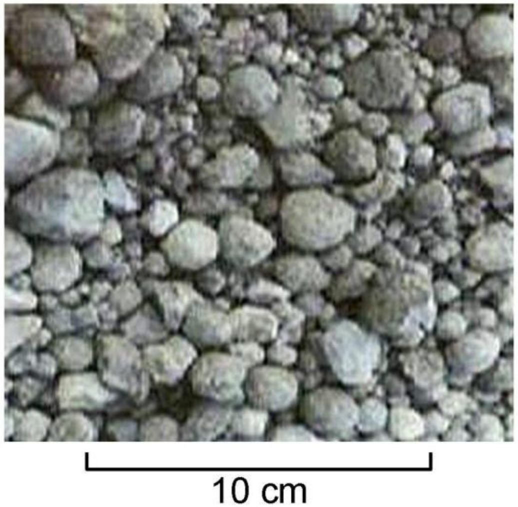
Scheme of Cement Production



http://www.cement.ca/images/stories/portland.swf

Clinker

Clinker (6 to 50 mm in diameter)



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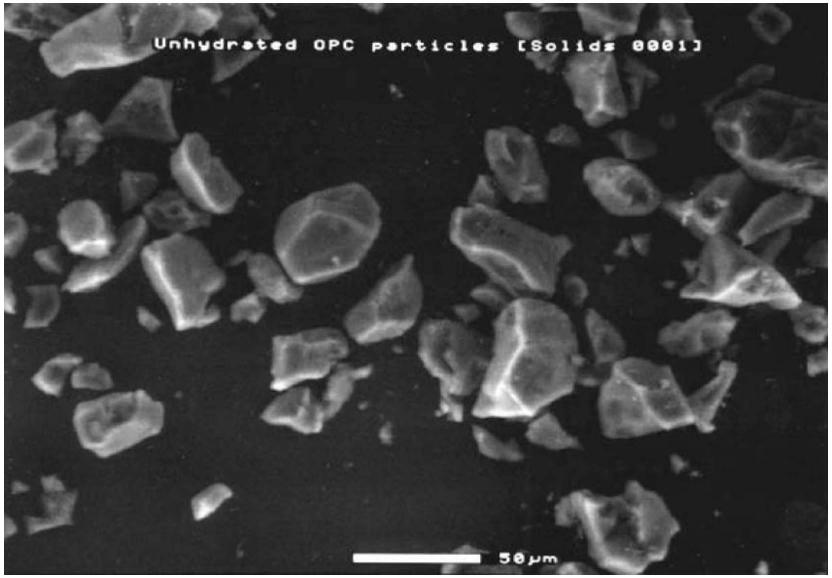
Unhydrated Ordinary Portland Cement Particles

Ordinary Portland cement



SEM of unhydrated OPC particles [courtesy David Lange, UIUC]

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Major Chemical Compounds of Ordinary Portland Cement

Major Compounds

- **Tri-calcium silicate [C_3S]**
  - $3CaO.SiO_2$
- **Di-calcium silicate [C_2S]**
  - $3CaO.SiO_2$
- **Tri-calcium Aluminate [C_3A]**
  - $3CaO.Al_2O_3$
- **Tetra-calcium Alumino-ferrite [C_4AF]**
  - $4CaO.Al_2O_3.Fe_2O_3$

C: Calcium Oxide (CaO)

S: Silicon Oxide (SiO_2)

A : Aluminum Oxide (Al_2O_3)

F: Iron Oxide (Fe_2O_3)

Minor Chemical Compounds of Ordinary Portland Cement

- Alkalis (Soda Na_2O and Potash K_2O)

  Alkali Content = $Na_2O + 0.658\ K_2O$

- Other Oxides: MgO; Mn_2O_3; Free Lime

Minor refers to quantity only;

Significant effect on concrete durability

- Alkali aggregate reaction → Alkalis react with silica causing disintegration & expansion of concrete
- Soundness of cement
- Setting of cement

Composition Limits of Ordinary Portland Cement

Oxide	Common Name	Content, %
CaO	Lime	60-67
SiO_2	Silica	17-25
Al_2O_3	Alumina	3-8
Fe_2O_3	Ferric/iron oxide	0.5-6.0
MgO	Magnesia	0.5-4.0
Na_2O/K_2O	Alkalis	0.2-1.3
SO_3	Sulfur trioxide (gypsum)	2.0-3.5

	Usual Range by Weight (%)
C_3S	45 – 60
C_2S	15 – 30
C_3A	6 - 12
C_4AF	6 - 8

Bogue's Equations to Correlate Oxides to Compounds

- A/F ≥ 0.64
  - $C_3S = 4.07(CaO) – 7.60(SiO_2) – 6.72(Al_2O_3) – 1.43(Fe_2O_3) – 2.85(SO_3)$
  - $C_2S = 2.87(SiO_2) – 0.75(C_3S)$
  - $C_3A = 2.65(Al_2O_3) – 1.69(Fe_2O_3)$
  - $C_4AF = 3.04(Fe_2O_3)$
- A/F < 0.64
  - $C_3S = 4.07(CaO) – 7.60(SiO_2) – 4.48(Al_2O_3) – 2.86(Fe_2O_3) – 2.85(SO_3)$
  - $C_2S = 2.87(SiO_2) – 0.75(C_3S)$
  - $C_3A = 0$
  - $C_4AF = 2.1(Al_2O_3) + 1.70(Fe_2O_3)$

The terms in brackets represent the percentage of the given oxide in the total mass of cement

Example – Calculate the Bogue Composition of the Cements

	Percentage in Cement No.		
	(1)	(2)	(3)
Oxide			
CaO	66.0	63.0	66.0
SiO_2	20.0	22.0	20.0
Al_2O_3	7.0	7.7	5.5
Fe_2O_3	3.0	3.3	4.5
Others	4.0	4.0	4.0
Compound			
C_3S			
C_2S			
C_3A			
C_4AF			

Influence of Change in Oxide Composition of Compound Composition

	Percentage in Cement No.		
	(1)	(2)	(3)
Oxide			
CaO	66.0	63.0	66.0
SiO_2	20.0	22.0	20.0
Al_2O_3	7.0	7.7	5.5
Fe_2O_3	3.0	3.3	4.5
Others	4.0	4.0	4.0
Compound			
C_3S	**65**	**33**	**73**
C_2S	**8**	**38**	**2**
C_3A	14	15	7
C_4AF	9	10	14

Minor changes in oxide composition changes C_3S:C_2S ratio significantly

Properties of Major Compounds

C_3S: Hardens quickly; Heat evolved (500 J/g);

Early age strength; Light colour

C_2S: Hardens slowly; Less heat evolved (250J/g) ;

Later age strength; Light colour

C_3A: Reacts quickly; Heat evolved (850J/g);

Very early setting and strength gain;

Poor resistance to Sulphate; Light colour

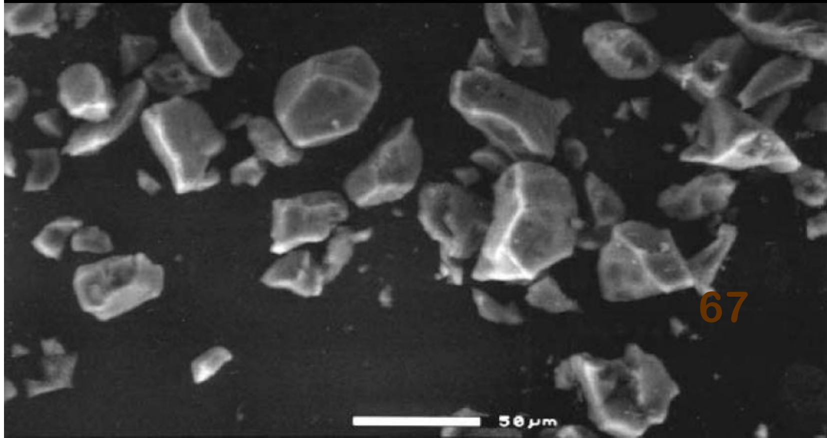
C_4AF: Reacts quickly; Heat evolved (400J/g);

Little strength; Dark colour

Physical Properties of Portland Cement

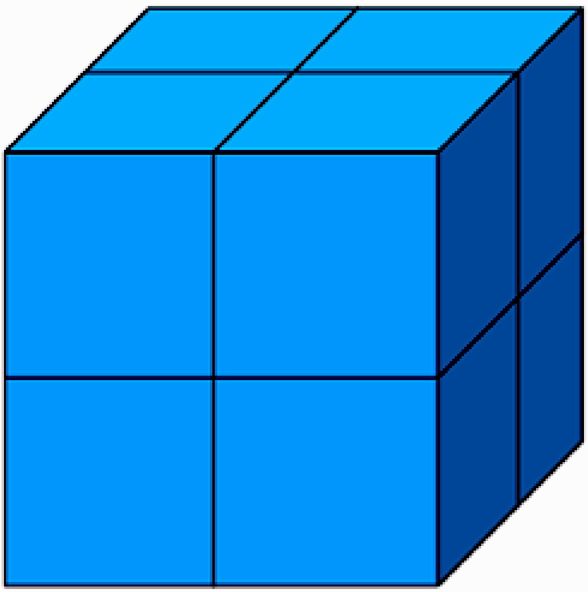
- Specific gravity $G_{cement} \approx 3.15$
  - Measured for cement particles without air voids
  - Bulk unit weight (weight required to fill a container) is highly variable.
  - Cement should not be measured by volume
- Particle shape: Angular
- Particle Sizes: 0.1 to 90 μm

SEM of unhydrated OPC particles [Photo courtesy David Lange, UIUC]



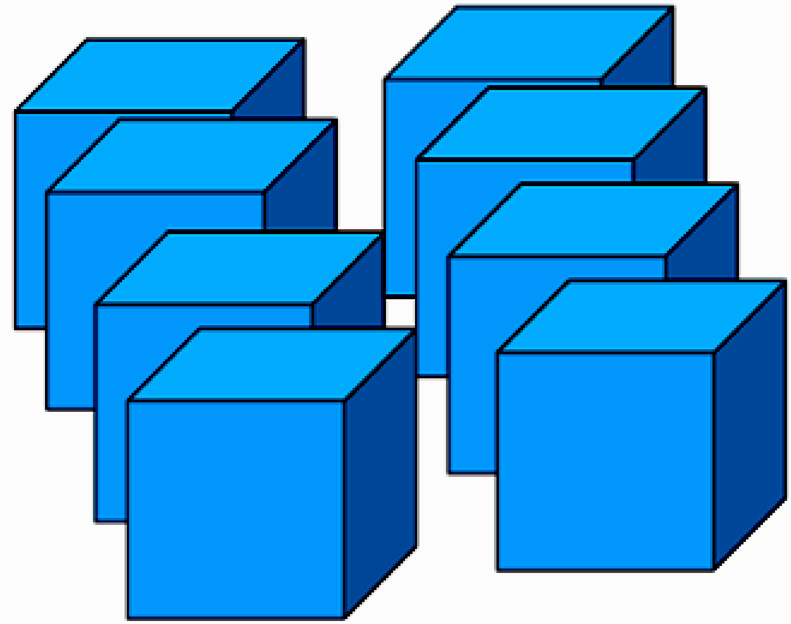
Fineness on Surface Area

block surface area = $1 \times 1 \times 6 = 6$



volume = 1 cubic mm
surface area = 6 square mm

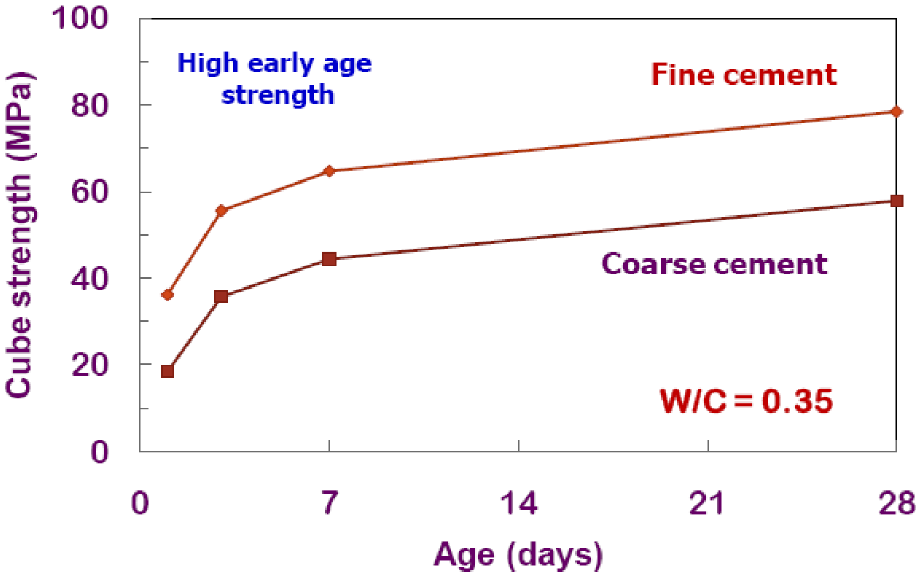
block surface area = $0.5 \times 0.5 \times 6 = 1.5$



volume = 1 cubic mm
surface area = $8 \times 1.5 = 12$ square mm

Fineness of Cement

- Smaller cement particles have **more surface area** to react with water
  - Fineness controls the rate of hydration (heat & strength gain)
  - Required more gypsum for proper set control (more C_3A for reaction)
  - Increased shrinkage & greater proneness to cracking



Effect of Fineness on strength development in mortar

ASCE Journal of Materials in Civil Engineering, ***20 (7), 502-508, 2008.***

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Measurement of Cement Fineness

- Specific surface or particle size distribution?
  - Specific surface is defined as the total **surface area** per unit **weight** of the material (m^2/kg or cm^2/g)
- No two methods measuring fineness will give the same results
  - Surface area measured indirectly
  - Different methods measure different properties
  - Assumptions in developing mathematical relationships, e.g. sphere shape of particle
  - Irregularly shaped cement

Wagner Turbidimeter (ASTM C 115)

- Principle: rate of sedimentation dependents on particle size
- Stokes' law: terminal velocity of a free fall **sphere** particle in a **viscous** medium

$$V = \frac{2ga^2(d_1 - d_2)}{9\eta}$$

V: terminal velocity
a: radius of sphere
d_1: density of sphere
d_2: density of viscous medium
η: viscosity
g: gravity

- Additional assumption: **uniform** size of 3.75 μm for particles in the range of 0 to 7.5 μm
- Measurement: intensity of light through suspension of cement particles in Kerosene
- Allows calculation of specific surface and particle size distribution

Blaine test (ASTM C 204)

- Measures time to pass air through cement sample
  - $$S = K\sqrt{t}$$
    S: specific surface (cm^2/g)
    K: constant
    t: time
  - K is determined by comparing against known standard material
- Blaine value is generally about 1.8 times the Wagner value
- Blaine method is more commonly used

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Hydration of Cement

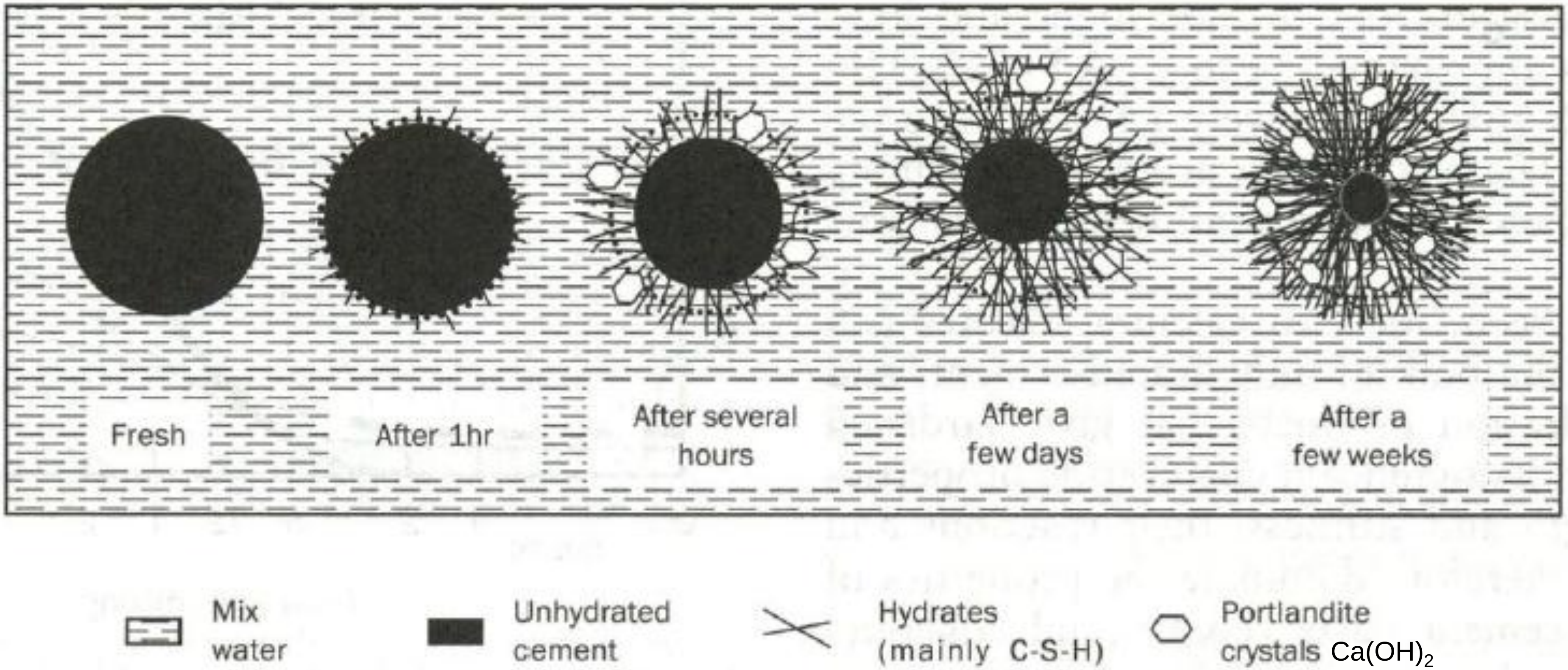
Reaction between cement particles and water

- Change in matter
  - Cement Hydration Products formed
  - Decrease in porosity
- Change in energy level
  - Heat is generated; Temperature rise
- Rate of reaction
  - Composition and Fineness of cement
  - Increased with the increase in temperature
  - Decrease with the increase in time
  - Decrease with the decrease in moisture content

When Water Is Added to Cement, What Happens?

- Dissolution of cement grains
- Growing ionic concentration in “water” (now a solution)
- Formation of compounds in solution
- After reaching a saturation concentration, compounds precipitate out as solids (“hydration products”)
- In later stages, products form on or very near the surface of the anhydrous cement

Hydration of A Cement Grain With Time



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Hydration of Calcium Silicates (75% of Cement)

- $2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \quad \Delta H = 500$ J/g

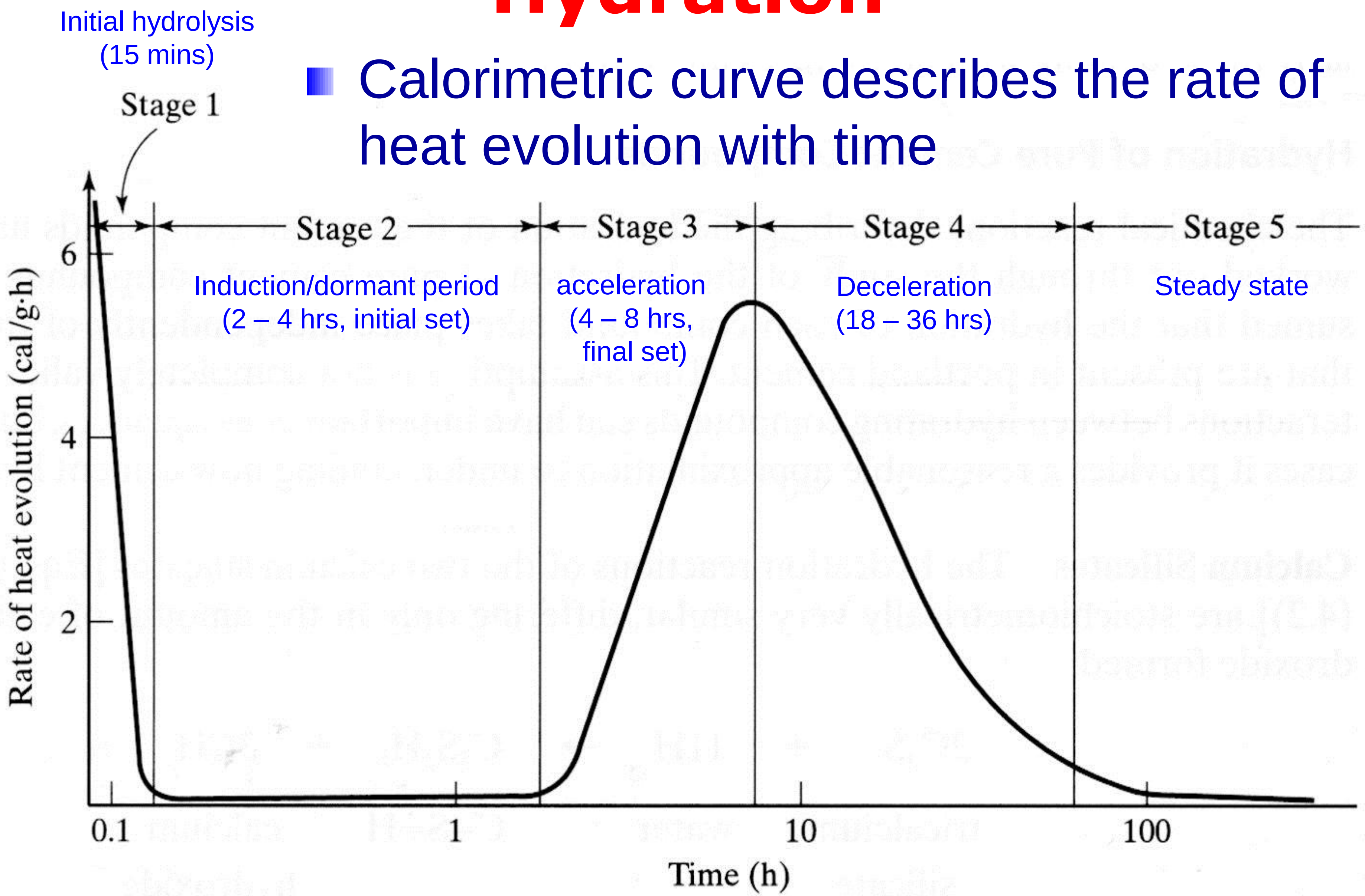
  $2C_2S + 4H \rightarrow C_3S_2H_3 + CH \quad \Delta H = 250$ J/g

  C-S-H

  - C_3S hydration is more rapid and evolving more heat
  - C_3S is responsible for the setting of cement (or concrete) and contributes to early age strength (2-3 hrs to 14 days)
  - C_2S hydration occurs more slowly and contributes to later age strength after ~7-14 days
  - C_3S produces more CH (source for sulfate attack, a durability concern)

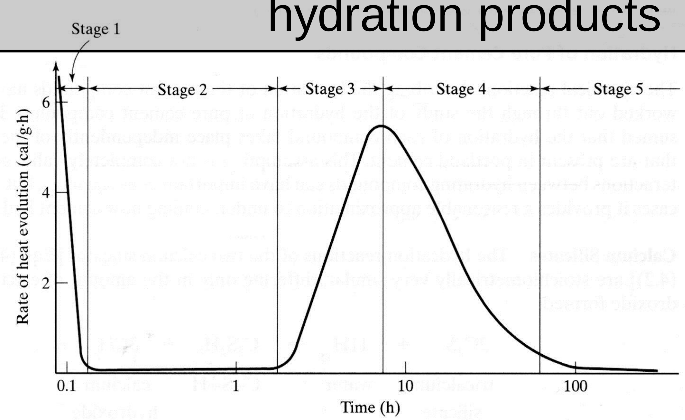
Calorimetric Curve of C_3S Hydration

- Calorimetric curve describes the rate of heat evolution with time



Sequence of Hydration of the C_3S

Reaction stage	Kinetics of reaction	Chemical process	Relevance to concrete properties
1 Initial hydrolysis	Chemical control; rapid	Initial hydrolysis; dissolution of ions	
2 Induction period	Nucleation control; slow	Continued dissolution of ions	Determines initial set
3 Acceleration	Chemical control; rapid	Initial formation of hydration products	Determines final set and rate of initial hardening
4 Deceleration	Chemical and diffusion control; slow	Continued formation of hydration products	Determines rate of early strength gain
5 Steady state	Diffusion control; slow	Slow formation of hydration products	Determines rate of later strength gain



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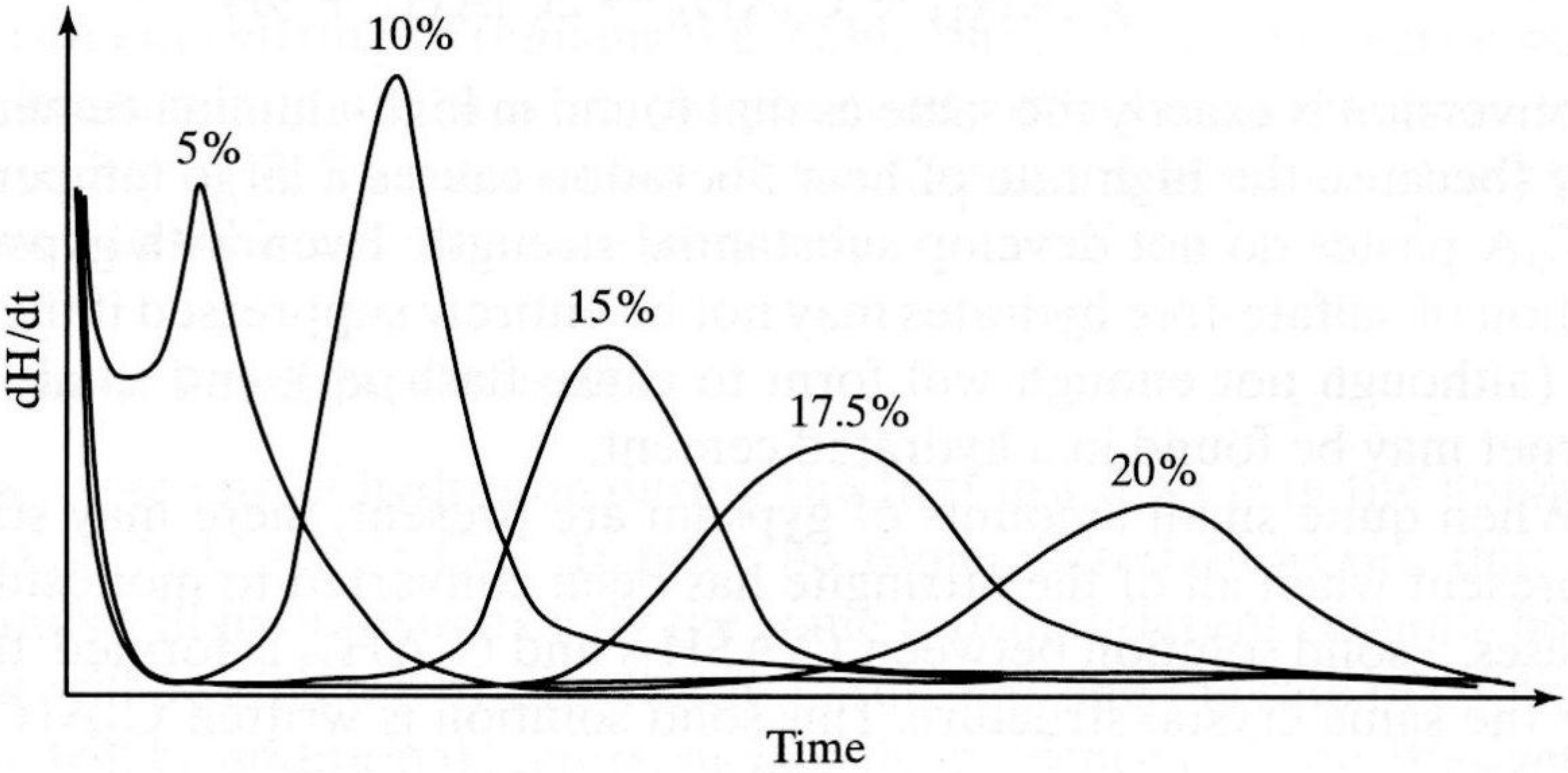
Hydration of Tricalcium Aluminate

- Pure C_3A hydrates rapidly and causes **flash set**, i.e. immediate stiffening of the paste
  - $2C_3A + 21H \rightarrow C_4AH_{13} + C_2AH_8 \rightarrow 2C_3AH_6 + 9H$

- In the presence of gypsum, C_3A hydration is controlled and flash setting is avoided
  - $C_3A + 3C\underline{S}H_2 + 26H \rightarrow C_6A\underline{S}_3H_{32}$ $\quad \Delta H = 850$ J/g
    Gypsum (for $3C\underline{S}H_2$); Calcium sulfoaluminate (Ettringite, AFt) (for $C_6A\underline{S}_3H_{32}$)
  - $2C_3A + C_6A\underline{S}_3H_{32} + 4H \rightarrow 3C_4A\underline{S}H_{12}$
    Monosulfoaluminate (AFm) (for $3C_4A\underline{S}H_{12}$)
- Additional C_3A is a source for sulfate attack
- The aluminates hydrates faster than silicates with increased heat of hydration

Calorimetric Curve of C_3A Hydration w/ Different Gypsum Dosage



Hydration of Ferrite Phase

- Reaction of C_4AF (ferrite) phase are slower and evolve less heat than C_3A
- C_4AF forms similar hydration products to C_3A
  - $C_4AF + 3C\underline{S}H_2 + 21H \rightarrow C_6(A,F)\underline{S}_3H_{32} + (A,F)H_3$
  - $C_6(A,F)\underline{S}_3H_{32} + C_4AF + 7H \rightarrow 3C_4(A,F)\underline{S}H_{12} + (A,F)H_3$
- Products of C_4AF are more resistant to sulfate attack than those of C_3A hydration

Characteristics of Hydration of the Cement Compounds

Compound	Reaction Rate	Contribution to Cement	
		Strength	Heat Liberation
C_3S	Moderate	High	High
C_2S	Slow	Low initially, high later	Low
$C_3A+C\underline{S}H_2$	Fast	Low	Very high
$C_4AF+C\underline{S}H_2$	Moderate	Low	Moderate

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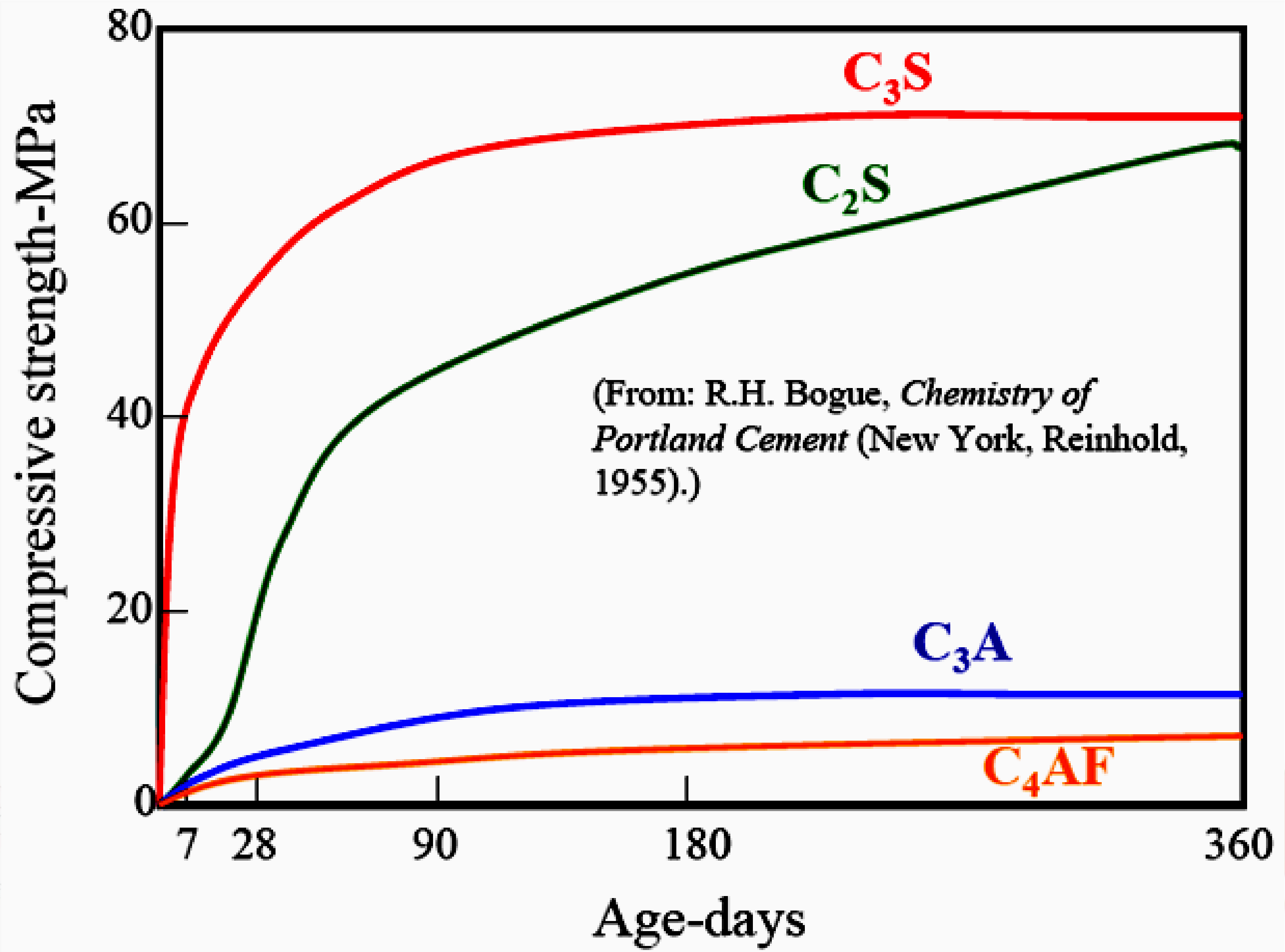
Strength Development of Major Chemical Compounds



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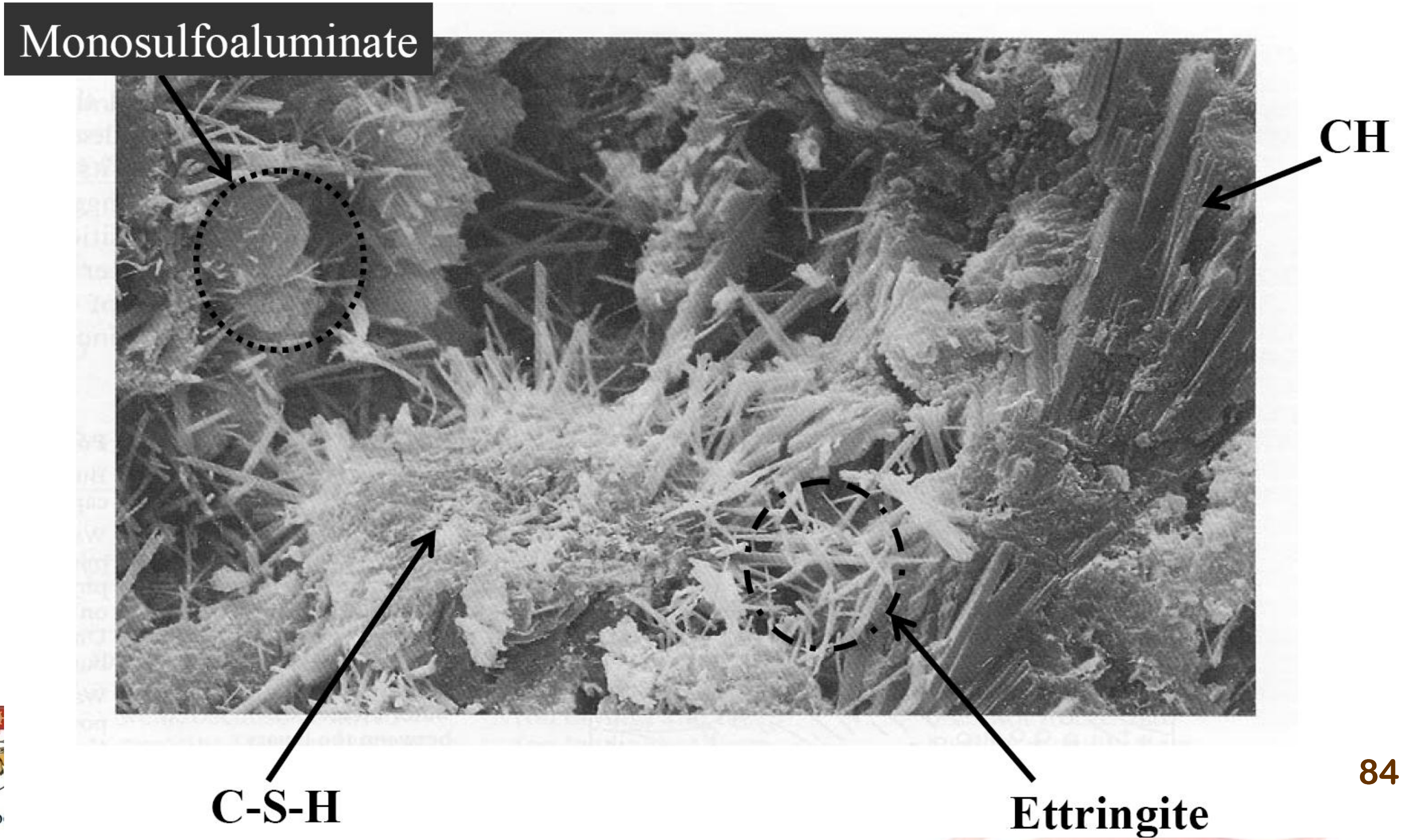
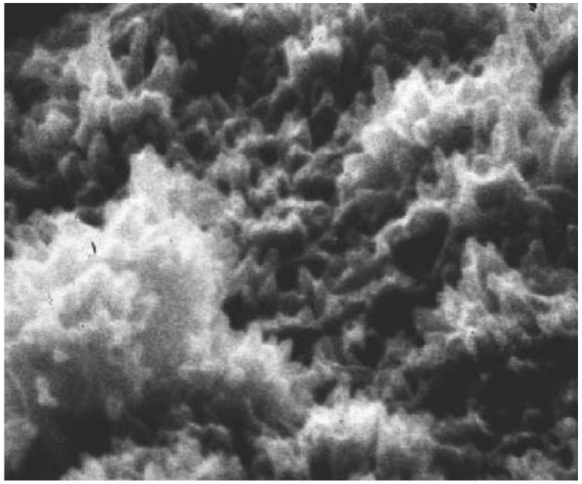
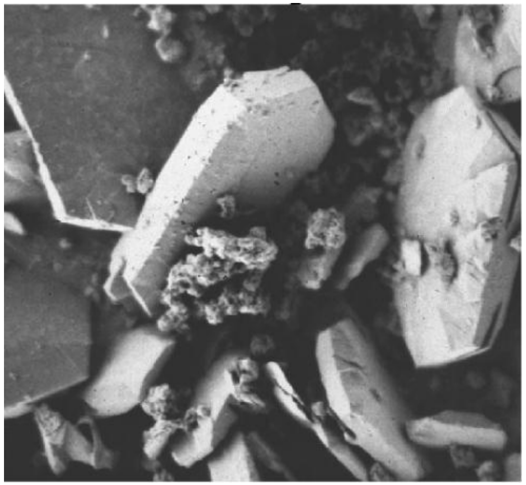
Microstructure of Hydrated Cement Paste



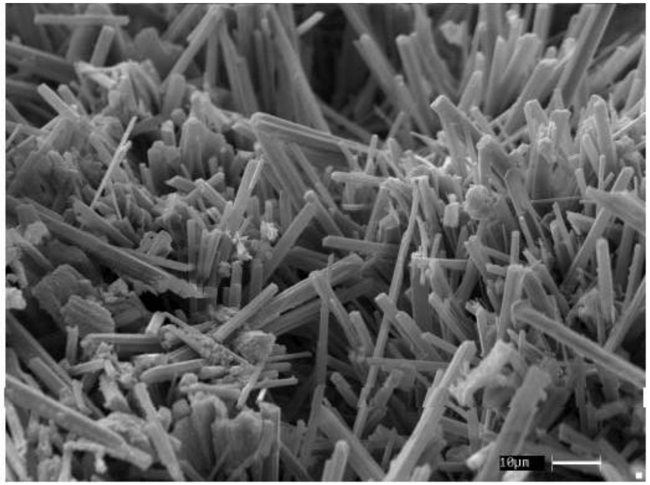
Microstructure of Hydration Products



C-S-H



Calcium Hydroxide



Ettringite

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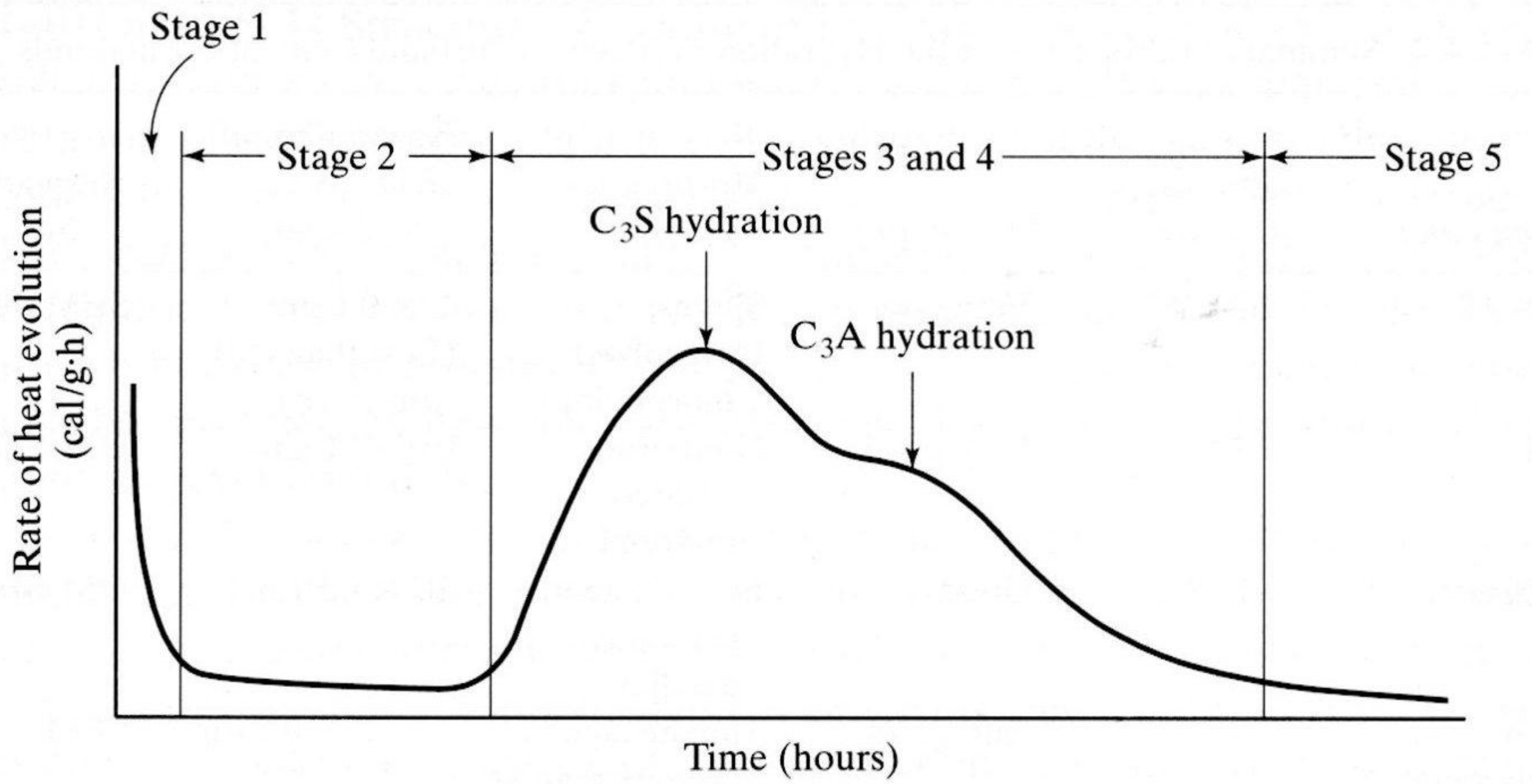
Photo courtesy of Paulo Monteiro, UC-Berkely

Characteristics of Hydration Products

Phase	% by Vol.	Characteristics
Calcium Silicate Hydrate (C-S-H)	50 – 60	Poorly crystalline C/S: 1.5-2.0 High surface area High Van der Walls force
Calcium Hydroxide (CH)	20 – 25	Well crystalline Low Van der Walls force
Calcium Sulfoaluminates (AFt $C_6A\underline{S}_3H_{32}$, AFm $C_4A\underline{S}H_{12}$)	15 – 20	Ettringite: crystalline Monosulfoaluminate: Fairly crystalline
Unhydrated cement	~ 5	Remnants of original cement grains

Calorimetric Curve of Portland Cement Hydration



Heat of Hydration of Cement

- The hydration reaction of Portland cement are all exothermic, meaning liberates heat
- Quantity of heat evolved depends on
  - Chemical composition
  - Temperature
  - Time
  - Fineness of cement
- Heat evolved (J/g)

$$H = a \,.\, C_3S + b.\, C_2S + c.\, C_3A + d.\, C_4AF$$

a (= 502J/g), b (= 260J/g), c (= 867J/g), d (= 419J/g) are heat of hydration for the respective compounds

Example

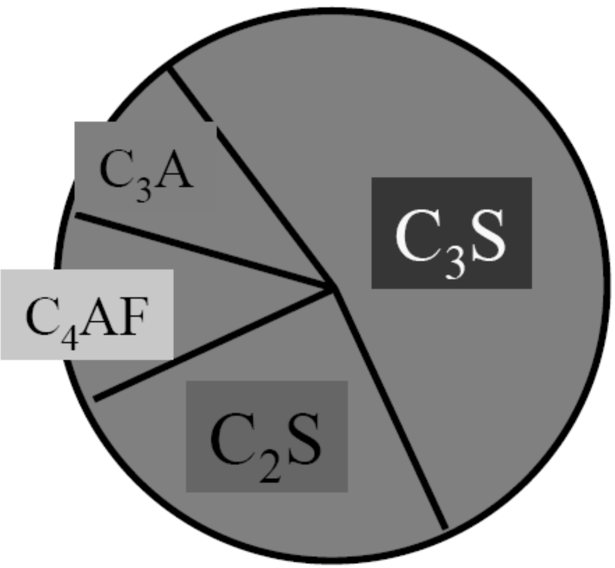
(a) Determine the temperature rise in a mass concrete member after 7 days. The mix proportion of concrete is: 1:1.60:2.40:0.50 (Cement: Fine aggregate: Coarse aggregate: Water). Assume that the Heat of hydration of cement after 7 days = 500 kJ/kg; Specific heat of water = 4.18 kJ/kg/^{o}C; Specific heats of solids = 0.22 times that of water.

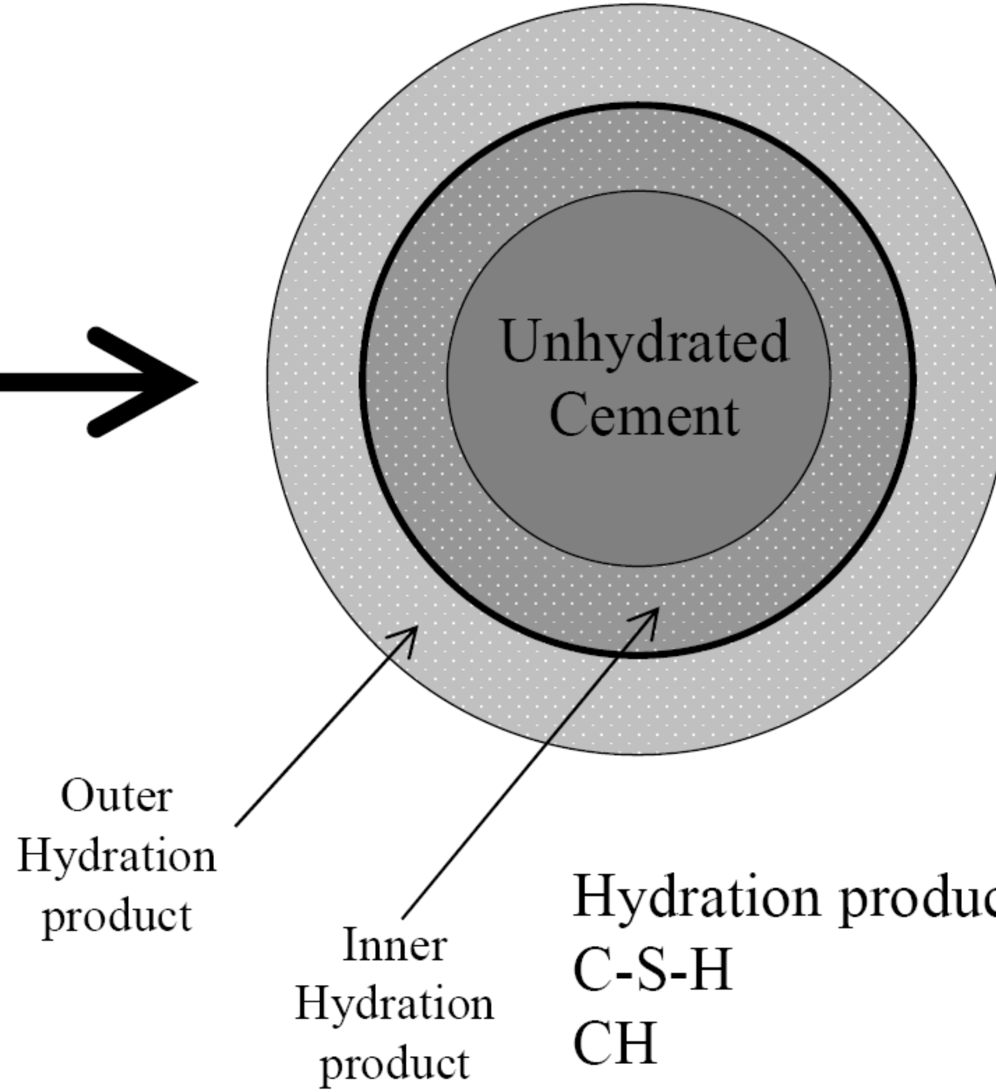
(b) If the 30% heat loss is expected near the surface due to lower ambient temperature, what will be the concrete temperature near the surface?

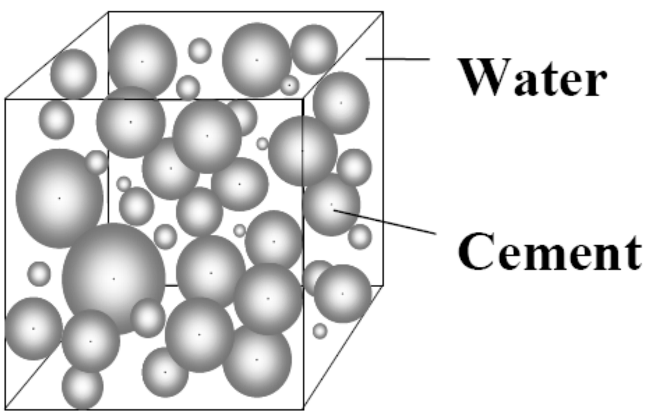
(c) If you have decided to replace 20% of cement with fly ash, what will be the rise in temperature after 7 days at the core and near the surface? Assume negligible heat evolved by the pozzolanic reaction of fly ash.

Volume Changes During Hydration

Original cement particle







Hydration products:

C-S-H

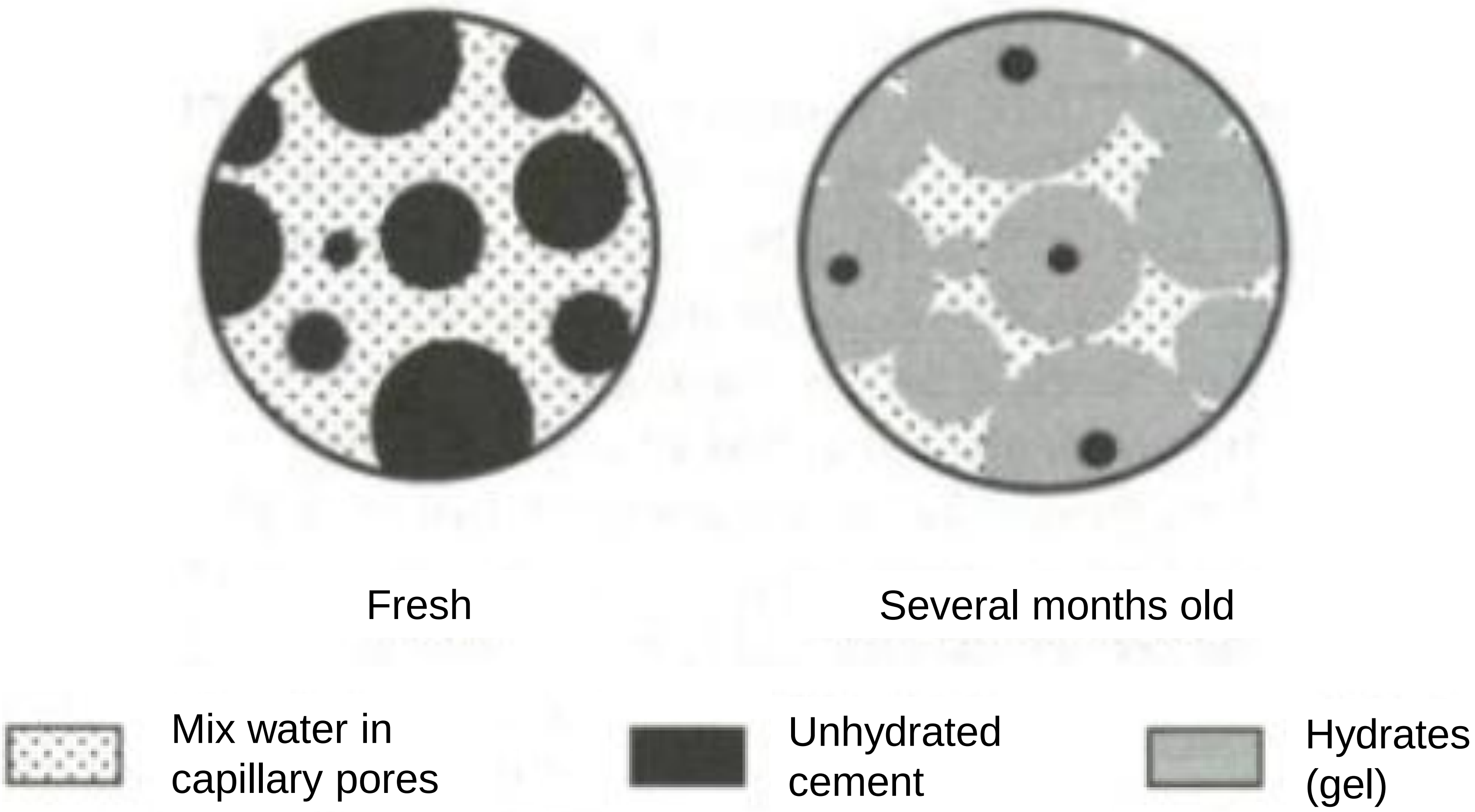
CH

$C_6A\underline{S}_3H_{32}$

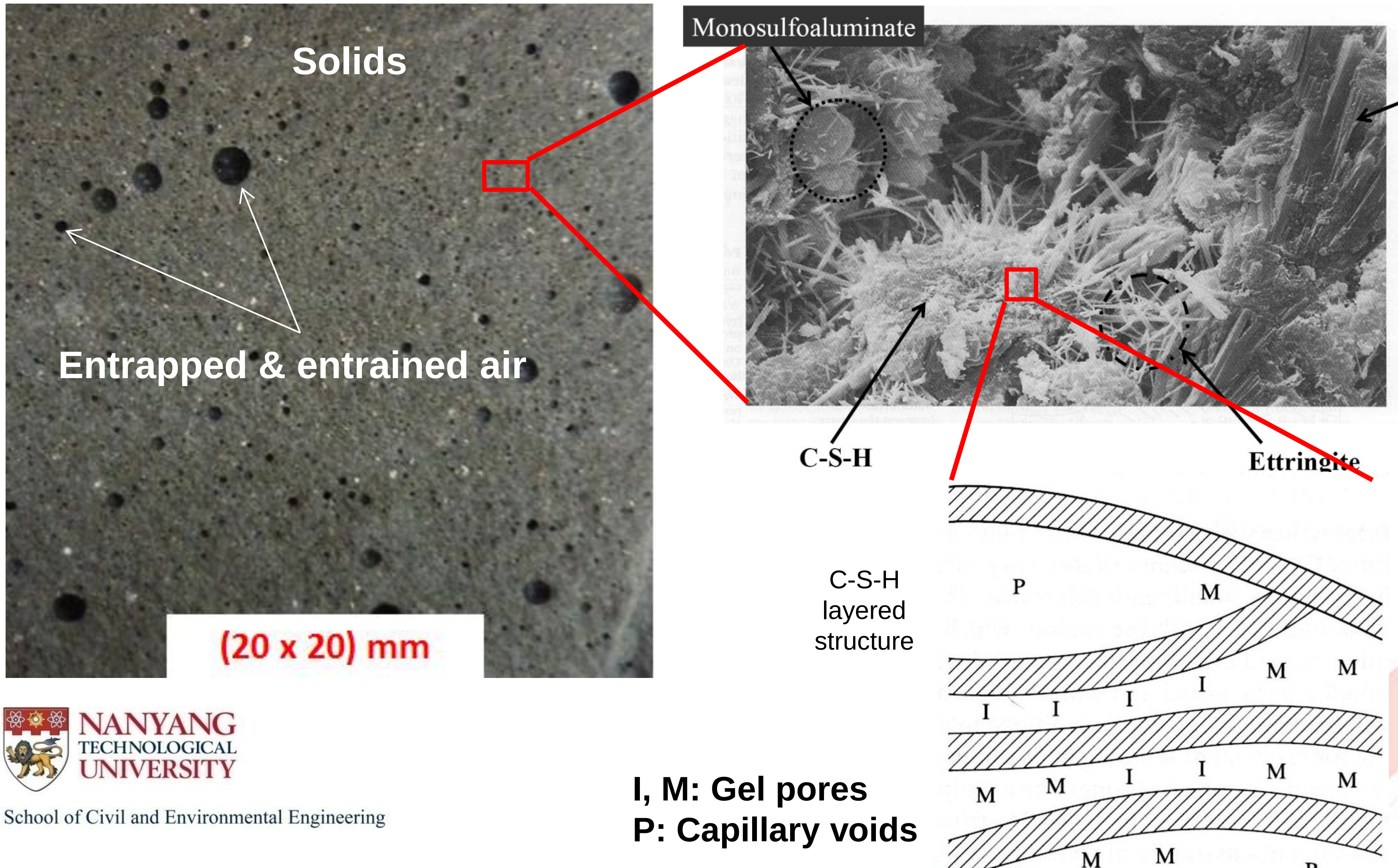
$C_4A\underline{S}H_{12}$

Volume of hydration product = 2.14x volume of cement

Structure of Cement Paste



Structure of Hydrated Cement Paste



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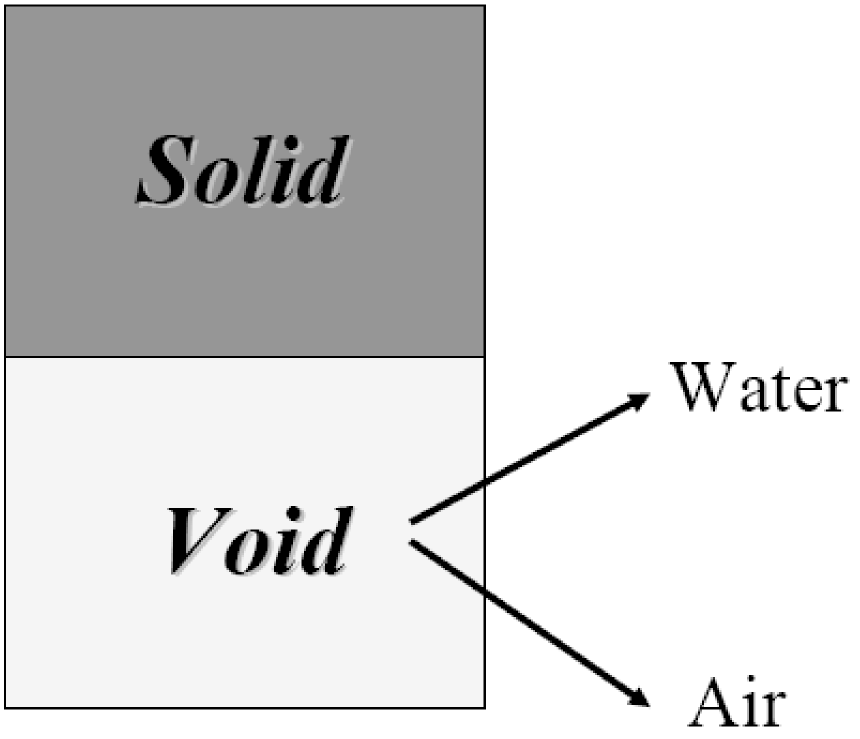
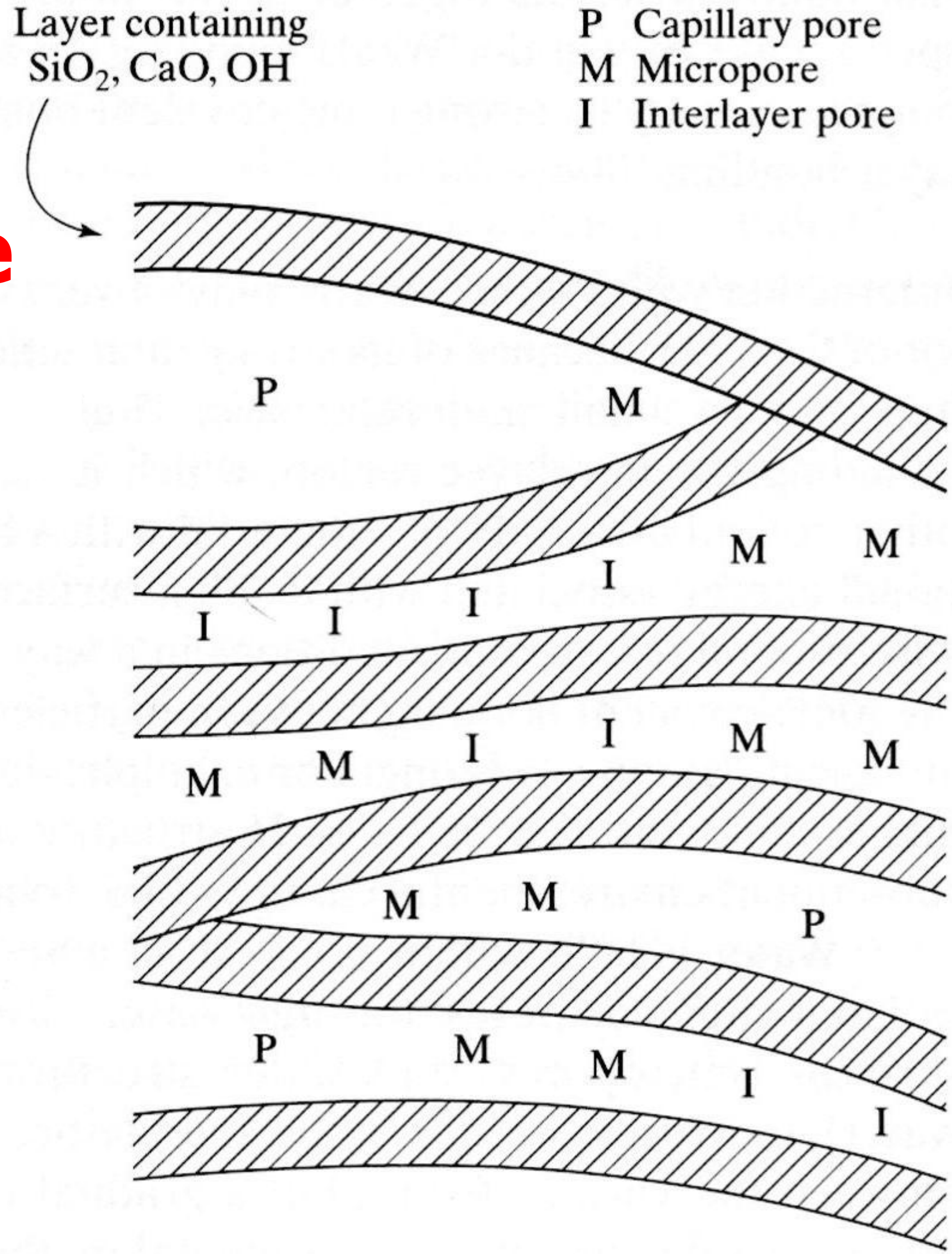
Structure of Hydrated Cement Paste

- Solids in HCP
- Voids in HCP
- Water in HCP



Voids in Hydrated Cement Paste

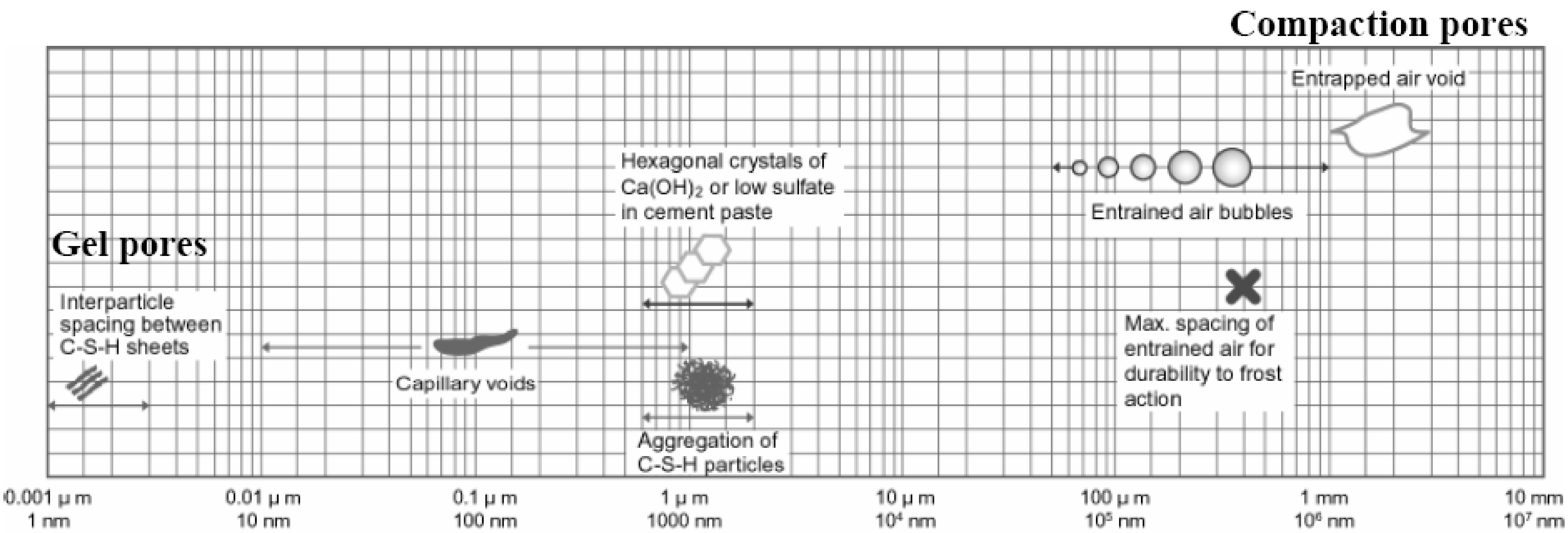


Schematic model of C-S-H in hydrated cement past, poorly crystallized C-S-H

Voids in Hydrated Cement Paste

- Gel pores (0.5 – 10 nm): Interlayer hydration space
  - Space between C-S-H gel atomic layers
  - Gel porosity = 26% (independent of w/c ratio and age)
  - Water held by strong hydrogen bonds
  - Loss of water leads to high shrinkage
  - High temperature & low humidity (<11%RH) removes gel water
- Capillary voids (10 nm to 10 μm)
  - Reduces strength/stiffness and increases permeability
  - Depends on initial porosity (w/c ratio) and degree of hydration
- Entrained air (10 μm – 1 mm)
  - Microscopic bubbles caused by admixtures
  - No effect on permeability; improved durability
- Entrapped air (> 1 mm)
  - Large pockets caused by handling
  - Decrease strength and increase permeability

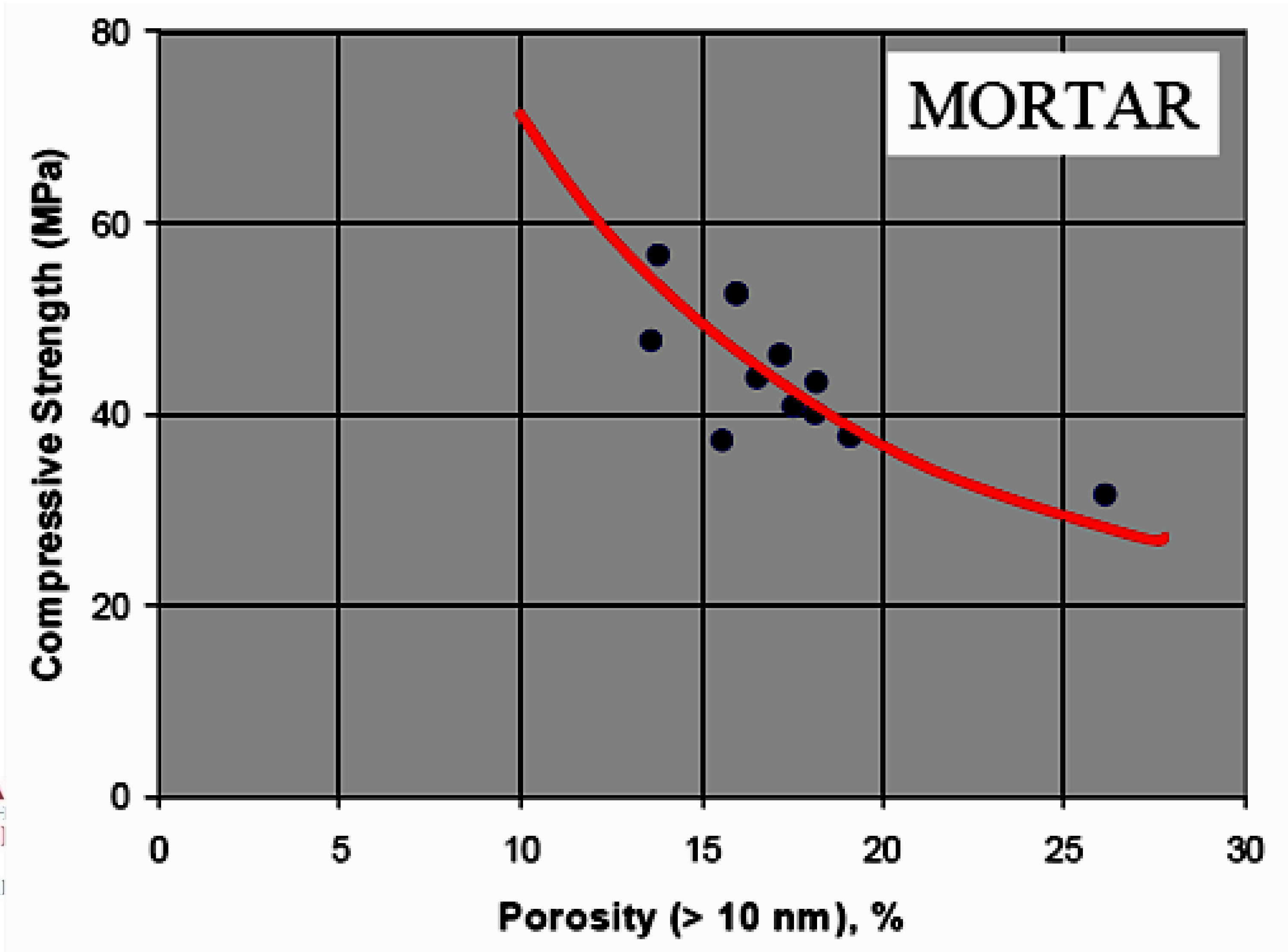
Dimensional Range of Solids and Pores in Hydrated Cement Paste



Measuring Method of Pore Structure in Hardened Cement Paste, Mortar, and Concrete

Types	Method
Gel pore space	Nitrogen gas adsorption-desorption method
Capillary pore space	Mercury porosimetry
Entrained air	Optical microscopy
Entrapped air	X-ray computerized tomography

Compressive Strength as A Function of Capillary Porosity



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Water to Cement Ratio

- The most important property of hydrating cement
- Water is essential for hydration; however, **extra water** beyond hydration needs causes capillary voids
  - Increases porosity and permeability
  - Decreases strength
  - Decreases durability
- Water to cement ratio (W/C) is expended to water to cementitious material ratio (W/CM) or water to binder ratio (W/B) when supplementary cementitious materials are used as the binder system

Initial Porosity of Cement Paste

Initial Porosity of cement paste (p_i)

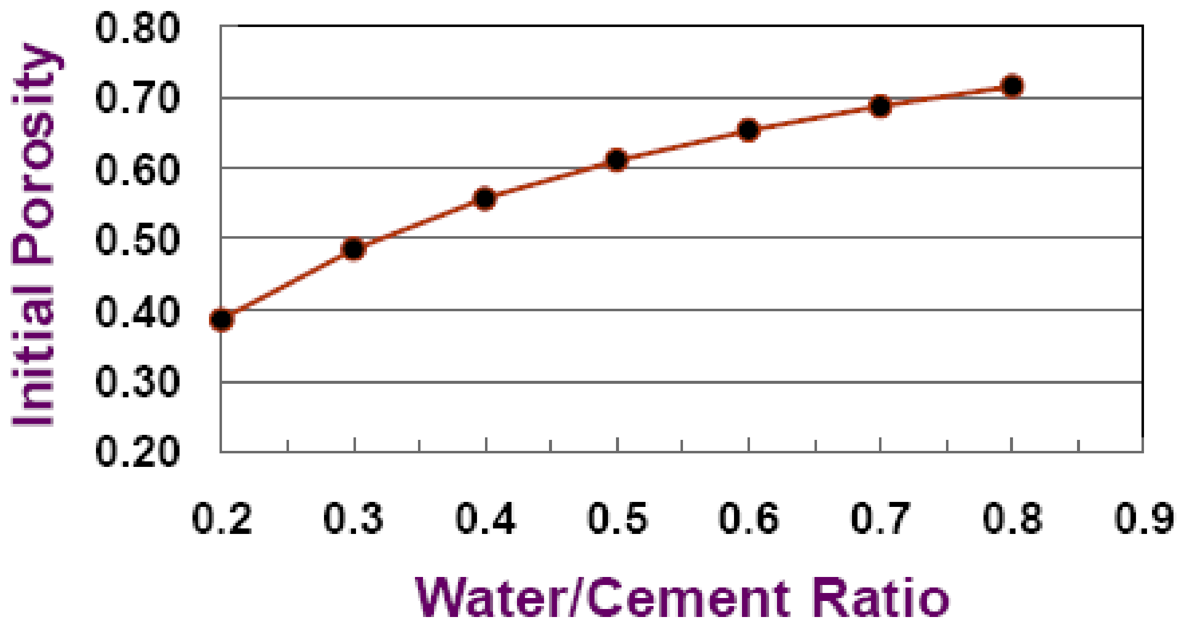
$= \text{Volume of water} / \text{Volume of cement paste}$

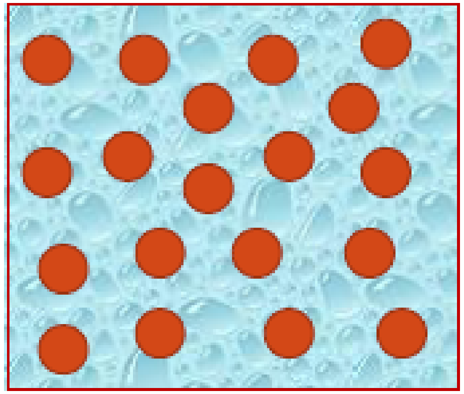
$= (w \times C/1) / [(C / 3.15) + (w \cdot C / 1)]$

$p_i = w / (w + 0.317)$ i.e. P_c @ $\alpha = 0$

where w = W/C ratio; C = weight of cement;

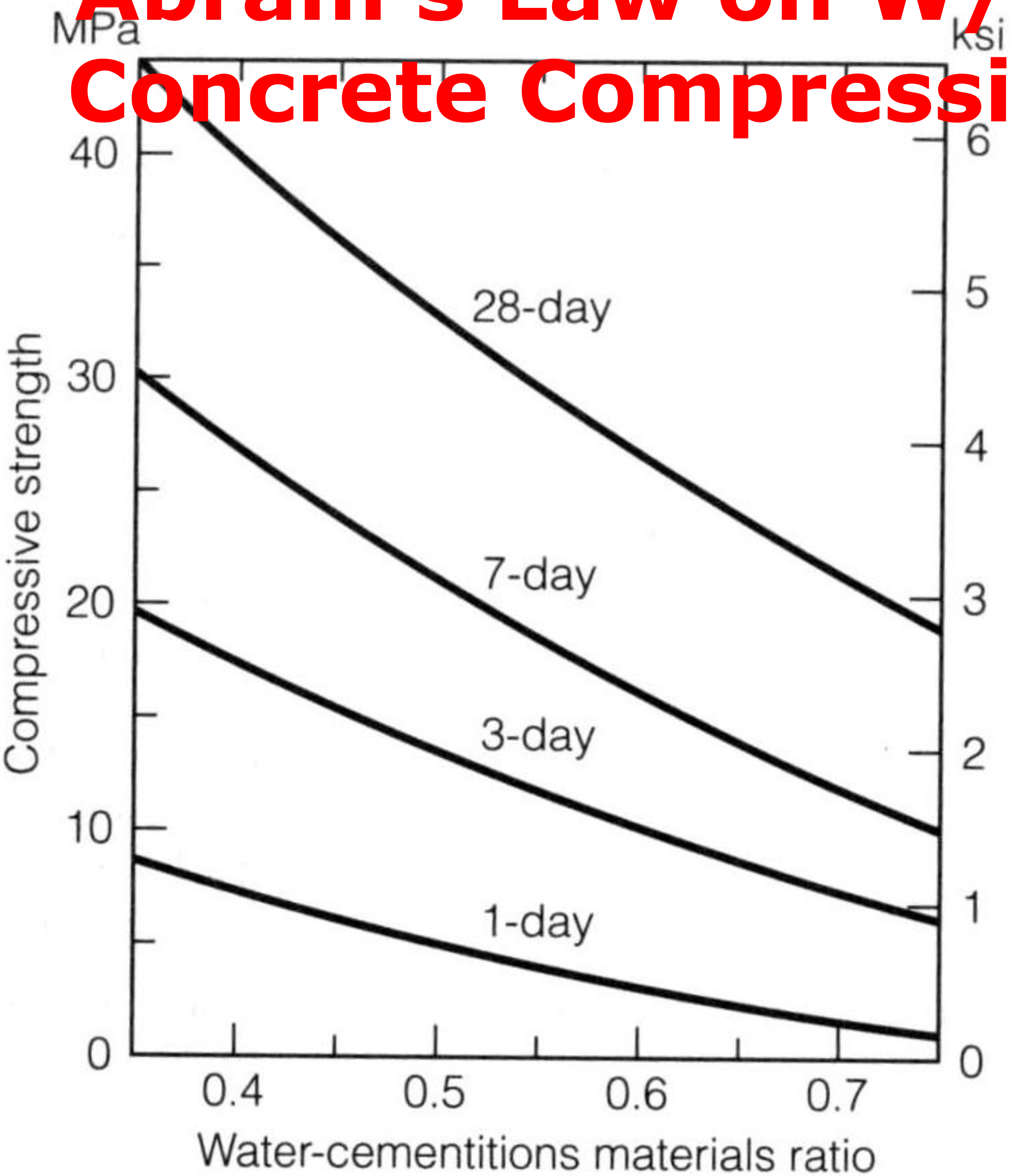
Sp. gr. of cement = 3.15





Cement particles in water

Abram's Law on W/C Ratio and Concrete Compressive Strength



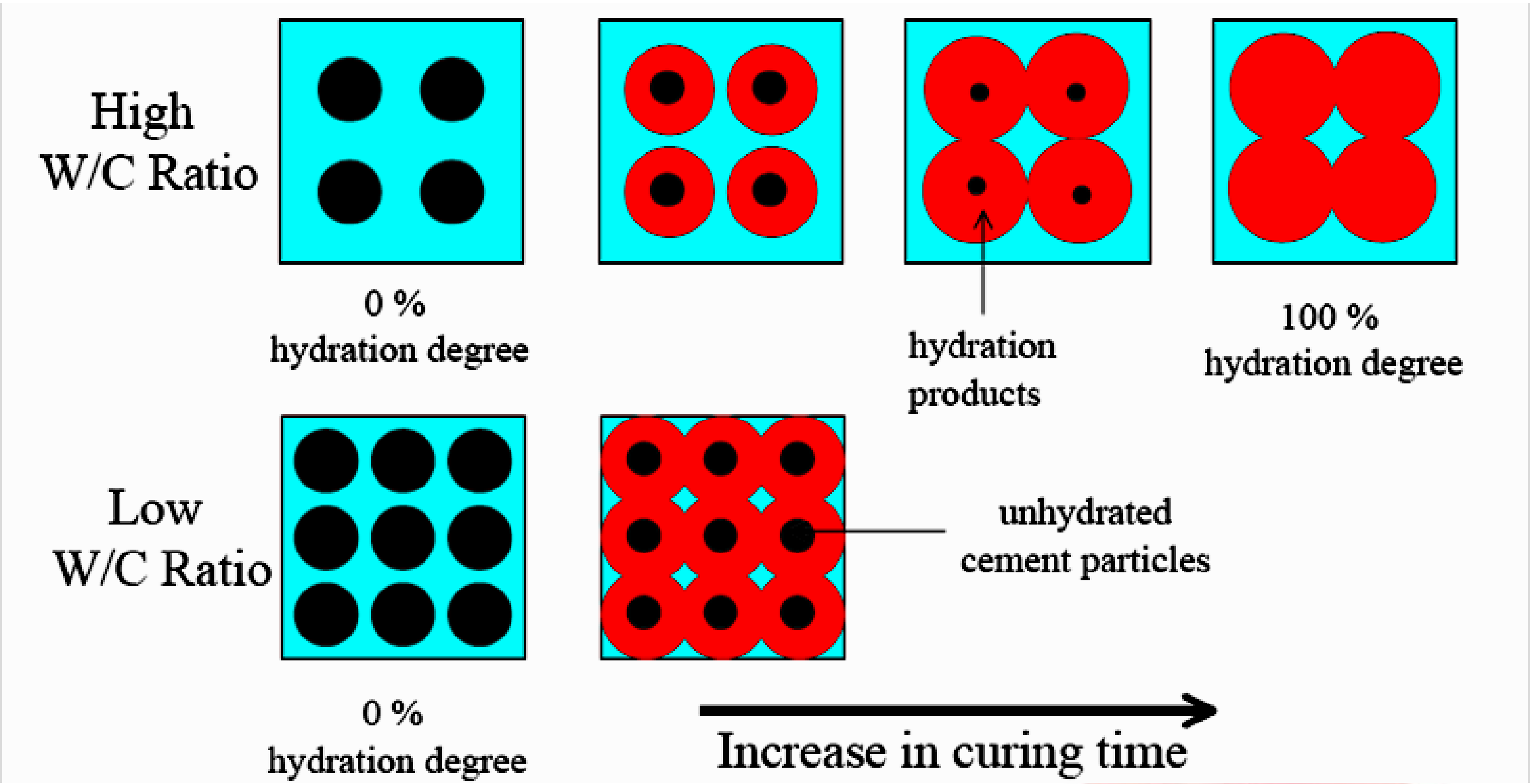
- Abram's law

$$\sigma = \frac{A}{B^{w/c}}$$

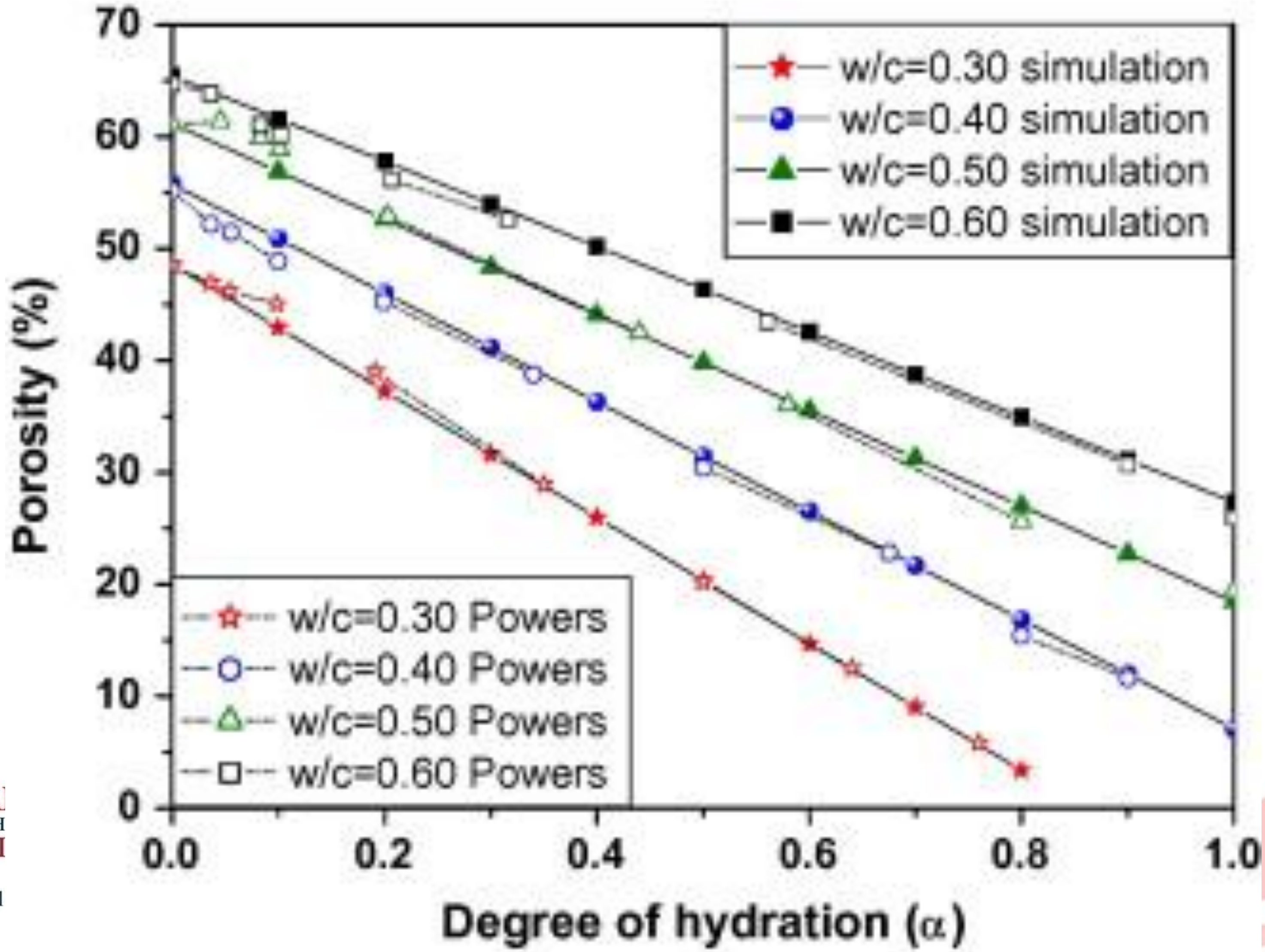
Degree of Hydration (Maturity)

- The fraction of cement that has hydrated
- Degree of hydration, α, ranging from 0 to 1
- Can be determined by different means, such as the measurement of
  - Amount of $Ca(OH)_2$ in paste;
  - Heat evolved by hydration;
  - Specific gravity of paste;
  - Amount of chemically combined water;
  - Amount of unhydrated cement (using X-ray quantitative analysis); and
  - Strength of hydrated paste

Schematic Description of Hydration Process



Capillary Porosity as A Function of Degree of Hydration



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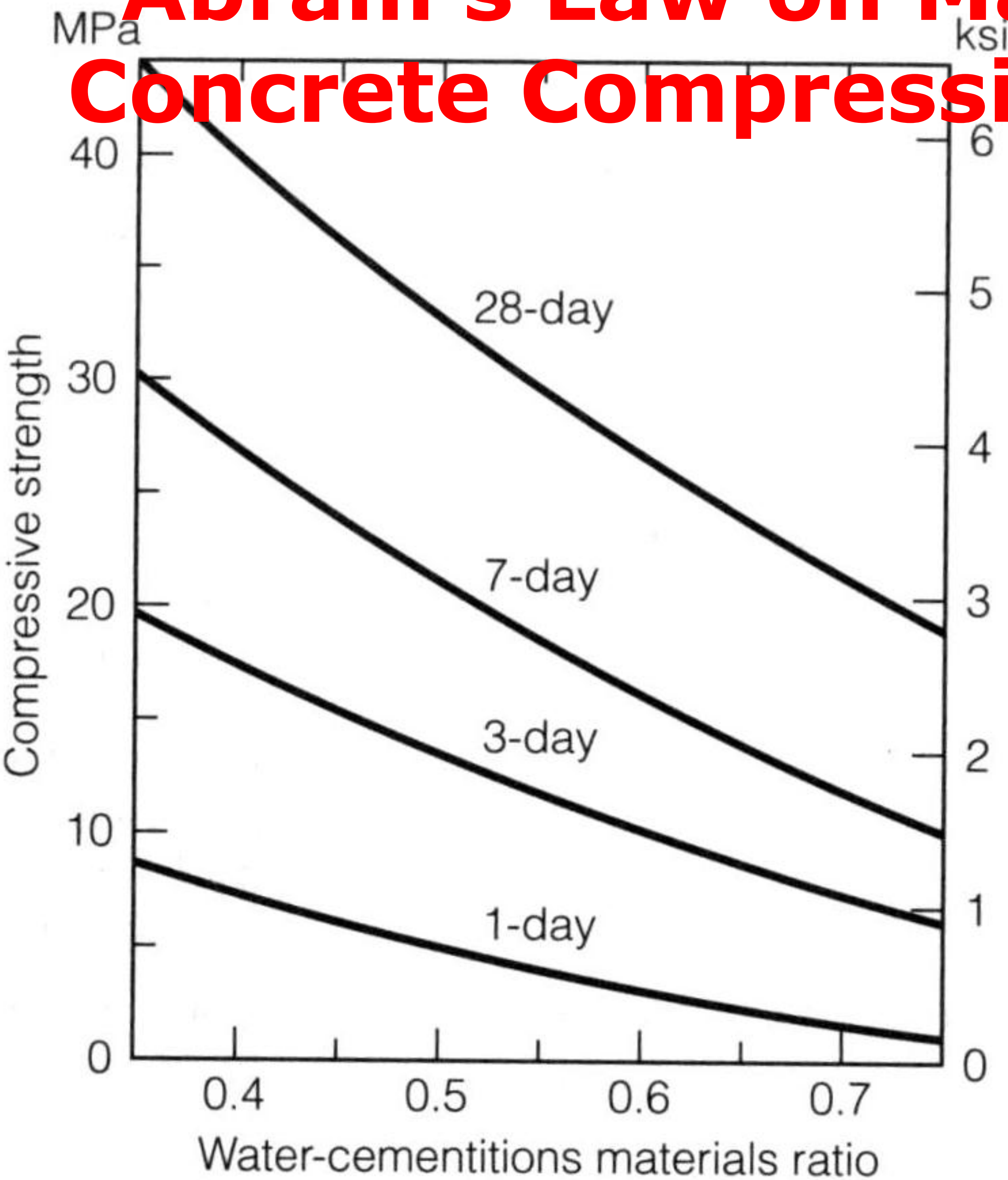
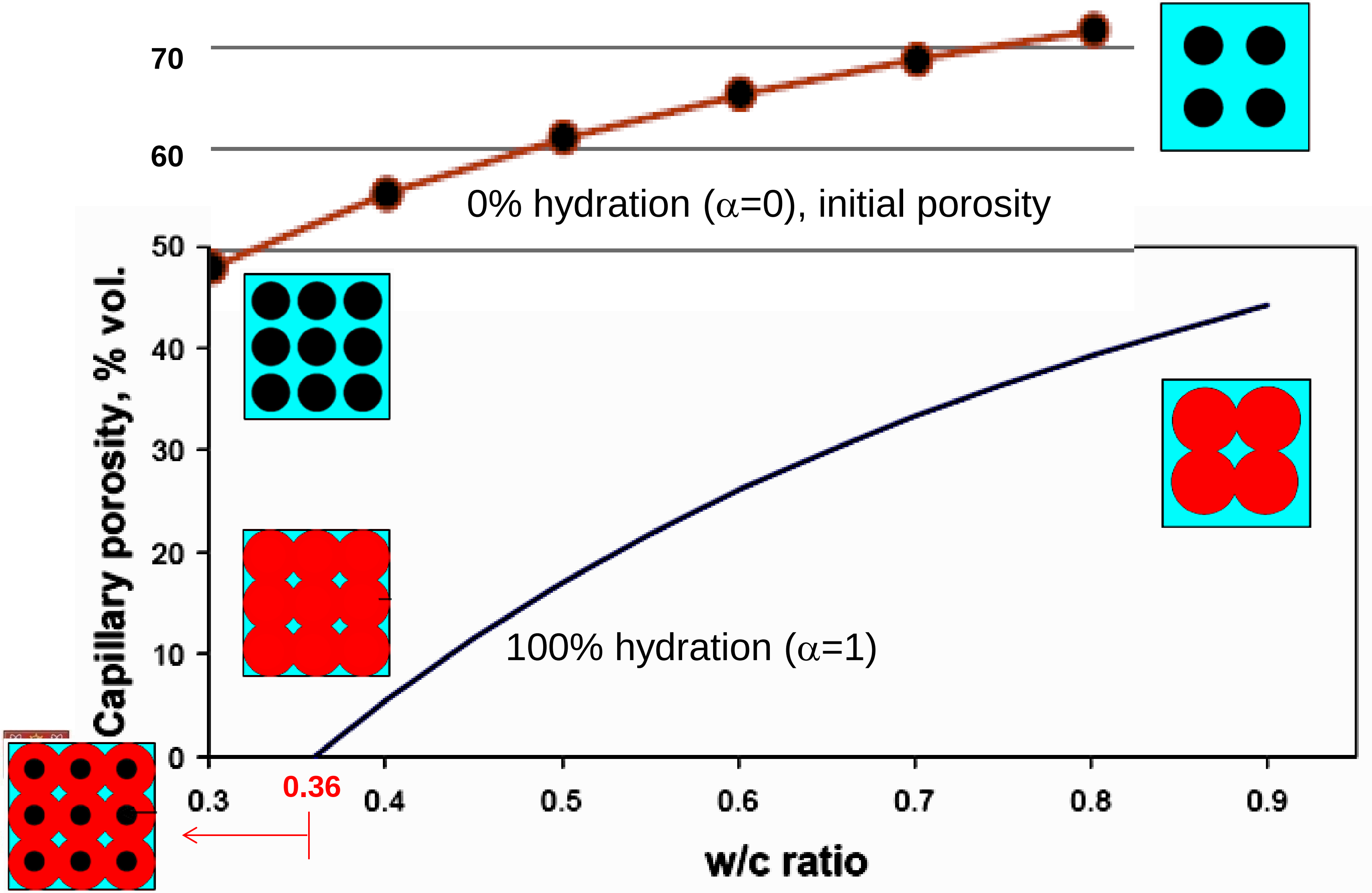
Abram's Law on Maturity and Concrete Compressive Strength



- Abram's law

$$\sigma = \frac{A}{B^{w/c}}$$

Capillary Porosity as A Function of W/C Ratio and Maturity

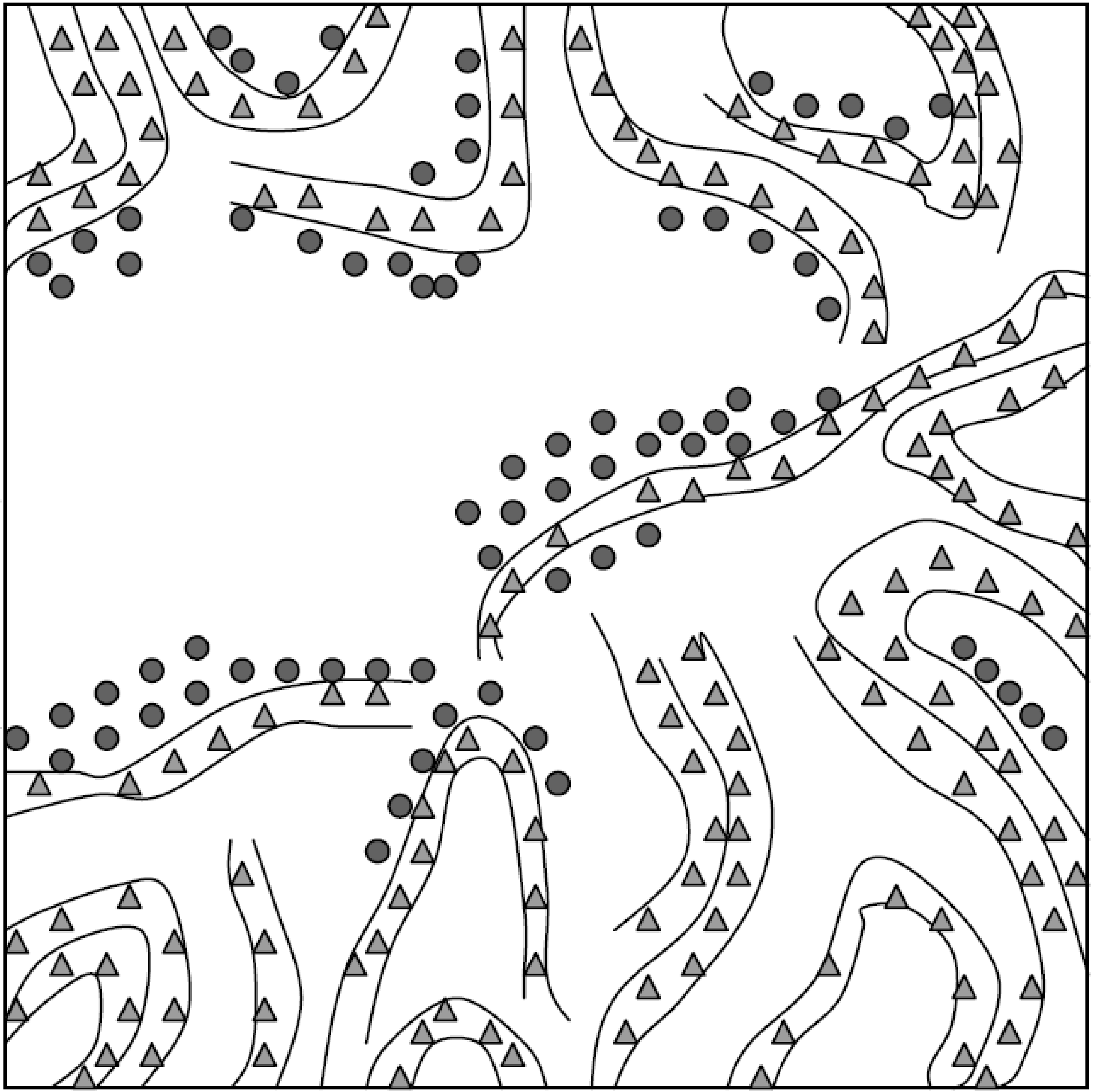


Water in Hydrated Cement Paste

Interlayer water

Capillary water

Physically adsorbed water

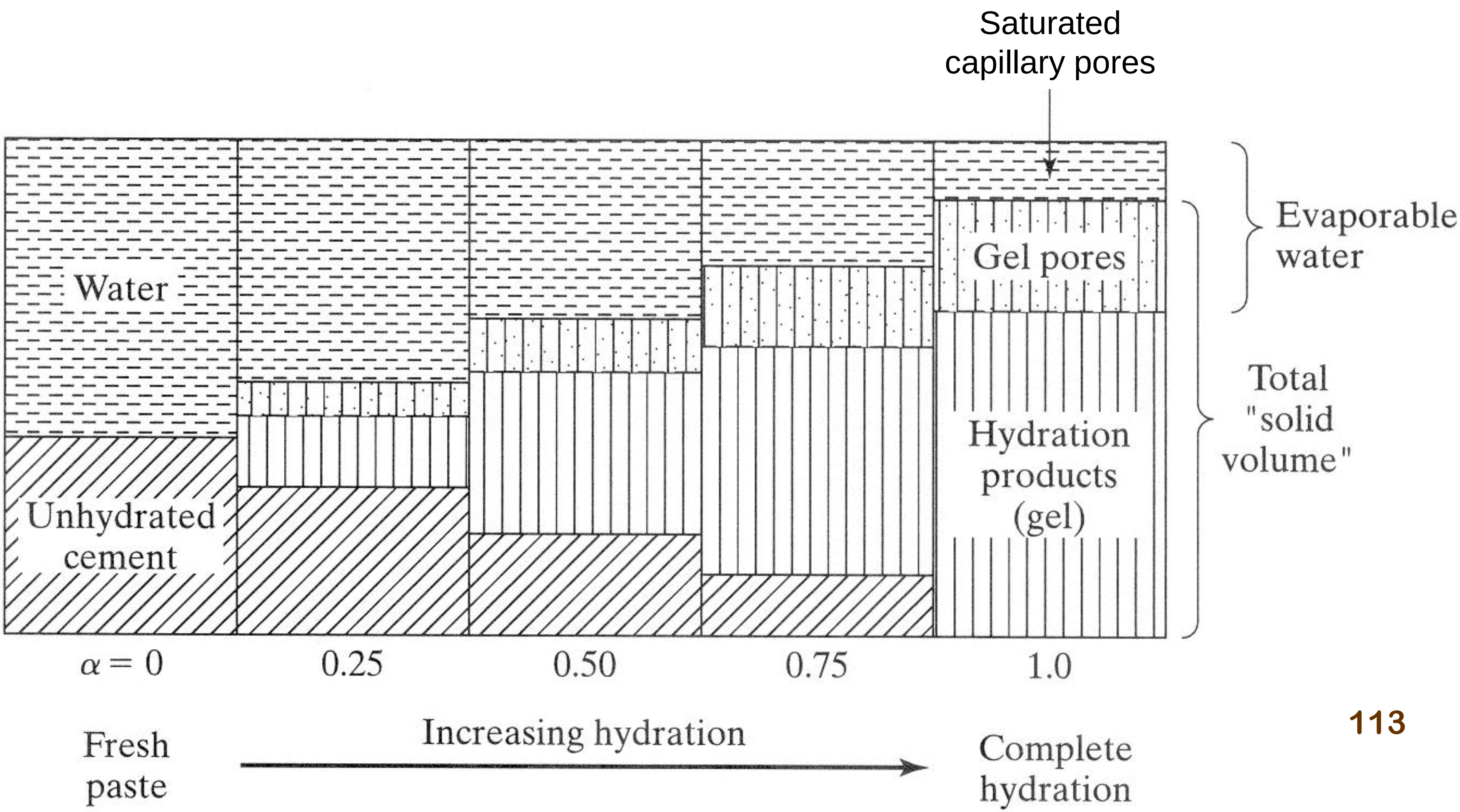


Another C-S-H model

Water in Hydrated Cement Paste

- Concrete is essentially a **wet** material
- **Evaporable Water** is lost when a saturated paste is oven-dried at 105^{o}C for 24 hrs
  - Capillary water
  - Physically adsorbed water
  - Interlayer water
- **Nonevaporable Water** is lost when paste is heated to 1000^{o}C
  - Chemically combined water

Volume Relationships of Hydrated Cement Pastes (constant w/c ratio of 0.5)



Calculation of Volume Changes

Description	Formula
Nonevaporable water, w_n	$w_n = 0.24\alpha$ g/g of original cement
Gel water, w_g	$w_g = 0.18\alpha$ g/g of original cement
Volume of gel pores, V_g	$V_g = w_g / \rho_w = w_g / 1.0 = 0.18\alpha$ cm^3/g of original cement
Total volume of hydration products (cement gel), V_{hp}	$V_{hp} = 0.68\alpha$ cm^3/g of original cement
Capillary pore volume, V_c	$V_c = w/c - 0.36\alpha$ cm^3/g of original cement
Volume of undydrated cement, V_u	$V_u = (1 - \alpha)\upsilon_c = 0.32\ (1 - \alpha)$ cm^3/g of original cement
Original volume of paste, V_p	$V_p = w/c + \upsilon_c = w/c + 0.32$ cm^3/g of original cement

The above equations are based on Powers' Model

Calculation of Porosity

- Porosity has a strong influence on paste properties, particularly strength and durability

Description	Formula
Gel porosity, P_g	$P_g = V_g/V_{hp} = w_g/V_{hp} = 0.26$ (independent of α)
Capillary porosity, P_c	$P_c = \frac{V_c}{V_p} = \frac{w/c - 0.36\alpha}{w/c + 0.32}$
Gel/space ratio, X	$X = \frac{V_{hp}}{V_{hp} + V_c} = \frac{0.68\alpha}{w/c + 0.32\alpha}$

The above equations are based on Powers' Model

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Compressive Strength vs. Gel/Space Ratio

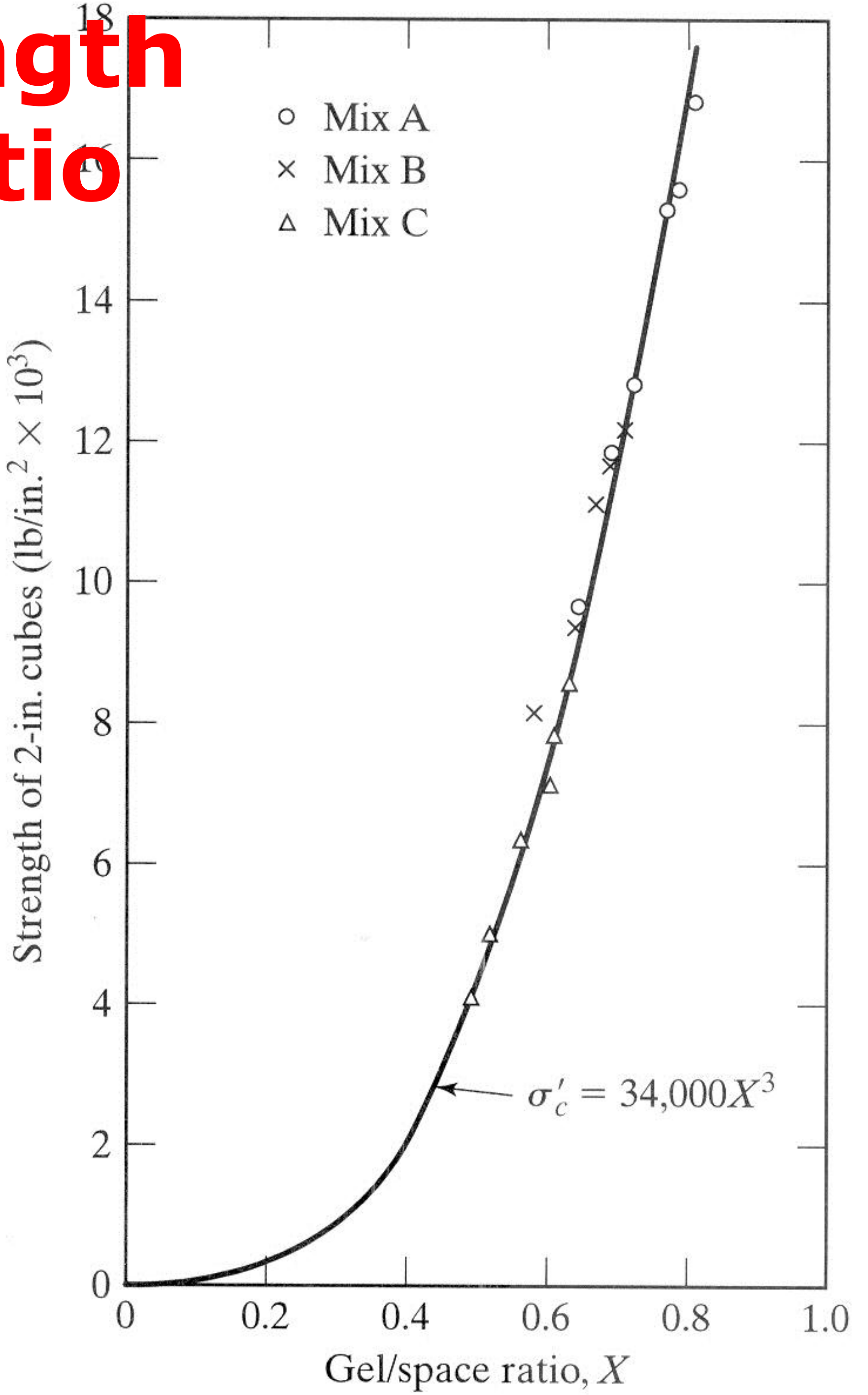
- Increase in compressive strength of Portland cement mortars is directly proportional to the increase in gel/space ratio regardless of age, original w/c ratio, or identity of cement (Powers and Brownyard, 1946-47)
- Relationship between compressive strength, f'_c, and the gel/space ratio, X

$$f_c^{'} = AX^n$$

Compressive Strength vs. Gel/Space Ratio for Mortar

$$f_c' = \begin{cases} 235X^3 & MPa \\ 34{,}000X^3 & lb/in^2 \end{cases}$$

- Based on strengths obtained from 50 mm mortar cubes
- Coefficient, *A*, *n*, could be different for paste or specimens of different geometries



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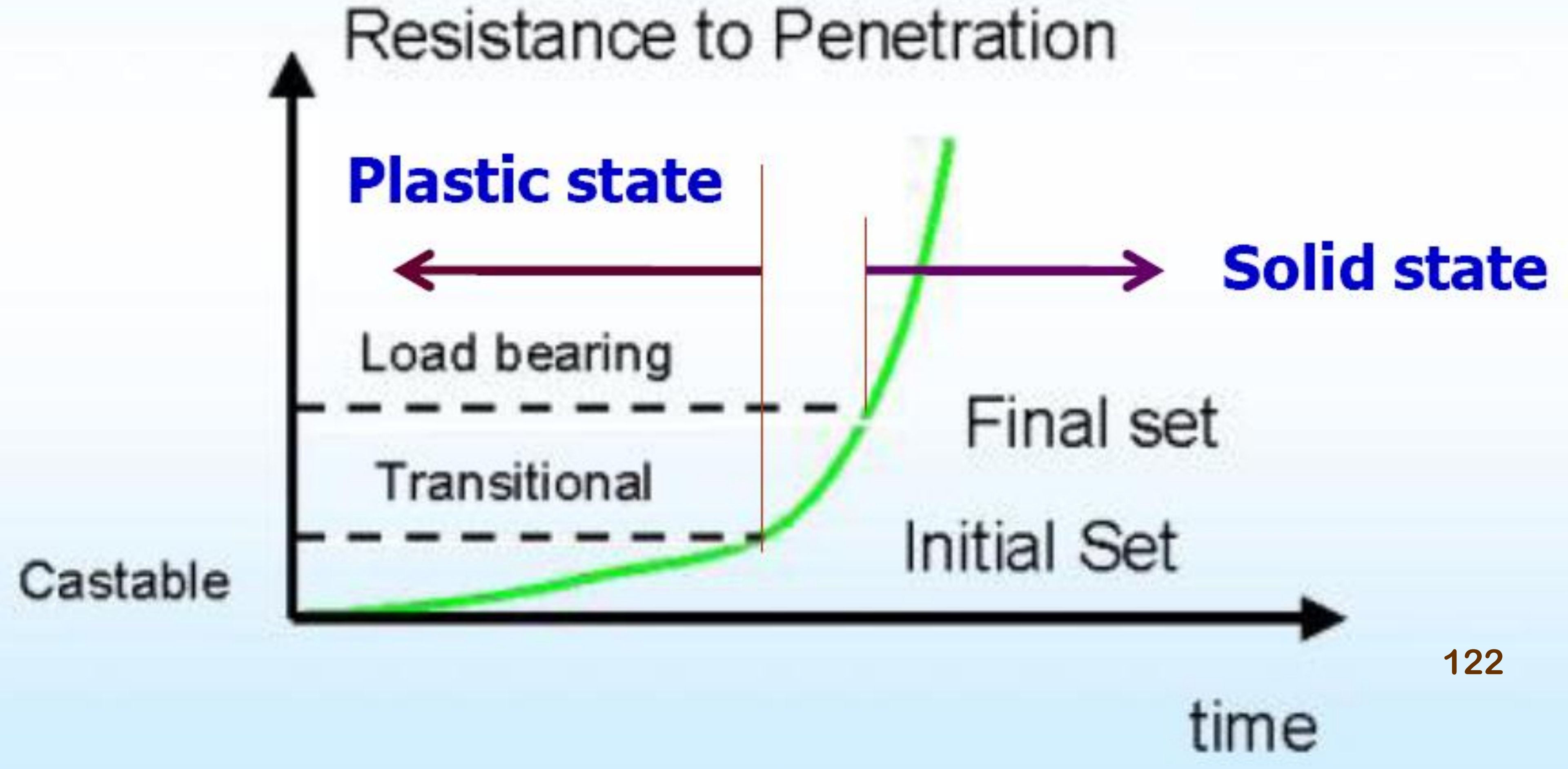
Example

- Calculate (a) the volume of hydration products; (b) the capillary porosity; (c) the gel/space ratio, and (d) mortar strength given $w_n = 0.14$ and $w/c = 0.42$

Setting of Portland Cement

Setting: stiffening of the cement paste from a fluid to a rigid stage

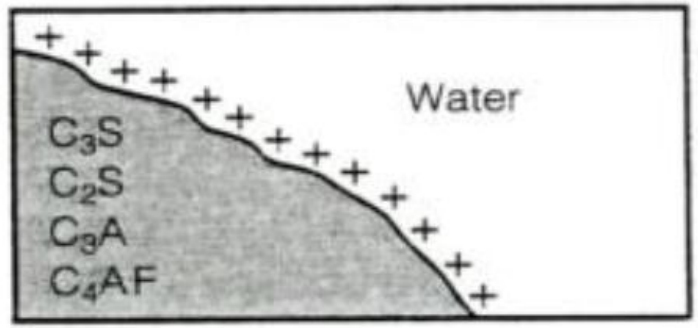
- Initial set: paste is beginning to stiffen considerably and can no longer be molded. Generally occurs in 2 to 4 hrs.
- Final set: paste has hardened to the point at which it can sustain some load. Generally occurs in 5 to 8 hrs.



Development of Structures in Hydrating Cement Paste

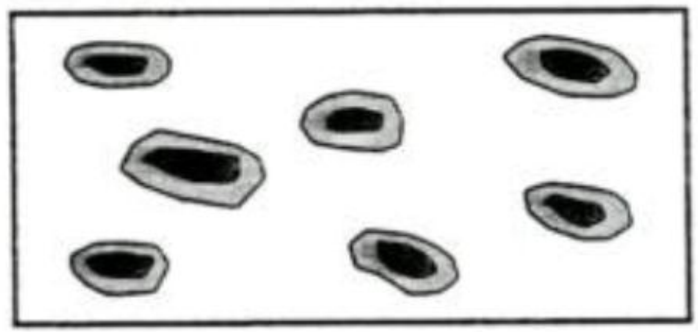
The C-S-H phase is initially formed. C_3A forms a gel fastest.

Cement grains are separated by water



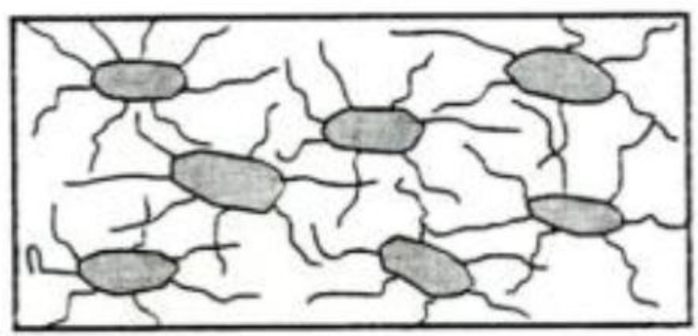
(a)

The volume of cement grain decreases as a gel forms at the surface. Cement grains are still able to move independently, but as hydration grows, weak interlocking begins. Part of the cement is in a thixotropic state; vibration can break the weak bonds.



(b)

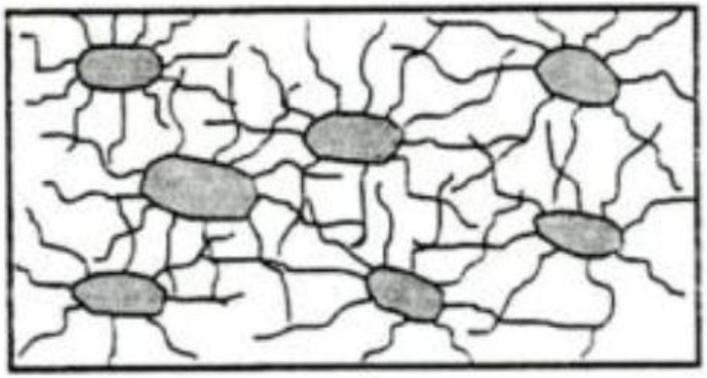
The initial set occurs with the development of a weak skeleton in which cement grains are held in place.



(c)

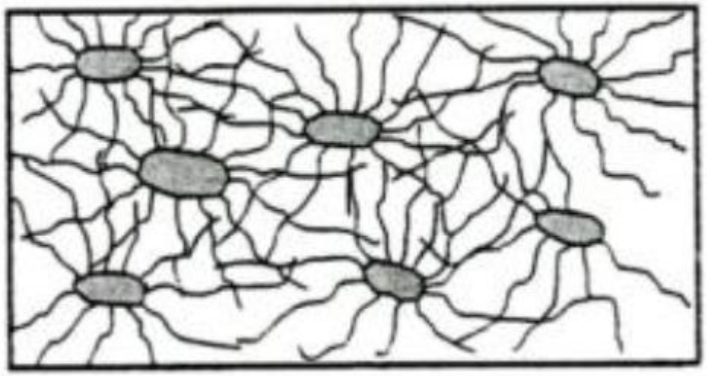
Development of Structures in Hydrating Cement Paste

Final set occurs as the skeleton becomes rigid, cement particles are locked in place, and spacing between cement grains increases due to the volume reduction of the grains.



(d)

Spaces between the cement grains are filled with hydration products as cement paste develops strength and durability.



(e)

FIGURE 6.4 Development of structure in the cement paste: (a) initial C-S-H phase, (b) forming of gels, (c) initial set—development of weak skeleton, (d) final set—development of rigid skeleton, (e) hardening. (Hover and Phillco, 1990)

Tests on Time of Setting - Penetration of Weighted Needle

- The time from the addition of the water to the initial and final set are known as the setting times.
- Vicat Needle (ASTM C 191)
  - Initial set occurs when needle penetrates 25 mm into paste
  - Final set when there is no visible penetration
- http://youtu.be/6Hh8i0lpuCs

Remarks on Setting

- Handling, placing, & vibrating must be completed before initial set
- Finishing between initial and final
- Curing after final set
- **False/Plaster Set**: premature stiffening within a few minutes $C\underline{S}H_2 \leftrightarrow C\underline{S}H_{1/2}$

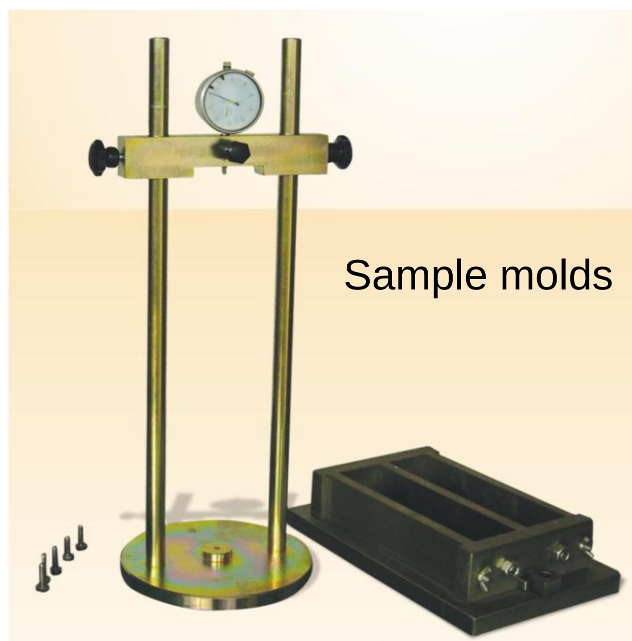
  gypsum β-hemihydrate/plaster

  - Due to crystallization of gypsum and/or formation of ettringite
  - Remix vigorously without adding water to resolve this problem
  - False set is different than a flash set – cannot be fixed

Soundness

- **Soundness**: Ability to retain is volume against expansion after setting
- Expansion after setting due to delayed or slow hydration or other reactions
- Autoclave expansion test (ASTM C151) is used to check the soundness of the cement paste
  - Cement paste bars are subjected to heat and high pressure

Frame for measuring length of sample before and after autoclave conditioning



Compressive Strength of Cement (ASTM C 109)

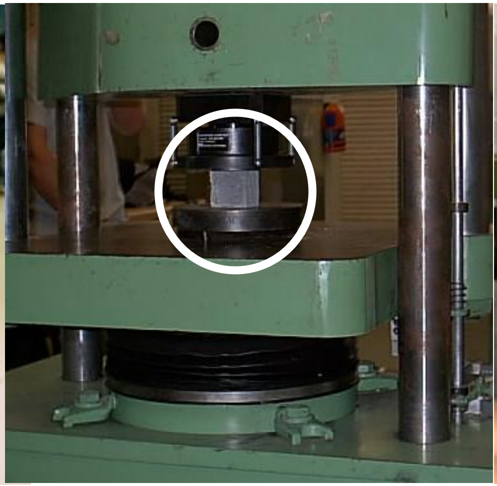
- Average of three 50 mm **mortar** cubes
- Mix proportions and sample preparation
  - Sand/cement ratio = 2.75 : 1
  - w/c ratio = 0.485 (0.460 for air-entraining cement)
  - Curing: stored in a moist storage room and demolded after 24 h and cured in saturated lime water at 23^{o}C until tested at predetermined age
  - Tested wet
  - Loading rate: specimen shall fail in 20 to 80 s

Compressive Strength of Cement

- Proportional to compressive strength of cylinders
- Compressive strength of concrete cannot be accurately predicted from cement strength

Mold

Prepare sample



Compression test

Typical failure

http://youtu.be/gX4dD0li38I

Standard Portland Cement Types (ASTM C 150)

- I Normal
- II Moderate Sulfate Resistance/Heat of Hydration
  - Lower C_3A content
- III High Early Strength
  - Finer; greater surface area
  - Becoming cheaper & more common
  - We can strip forms earlier and speed up production
- IV Low Heat of Hydration
  - Lower C_3S and C_3A content
  - For large, massive pours to control heat of hydration
- V High Sulfate Resistance
  - Lower C_3A content

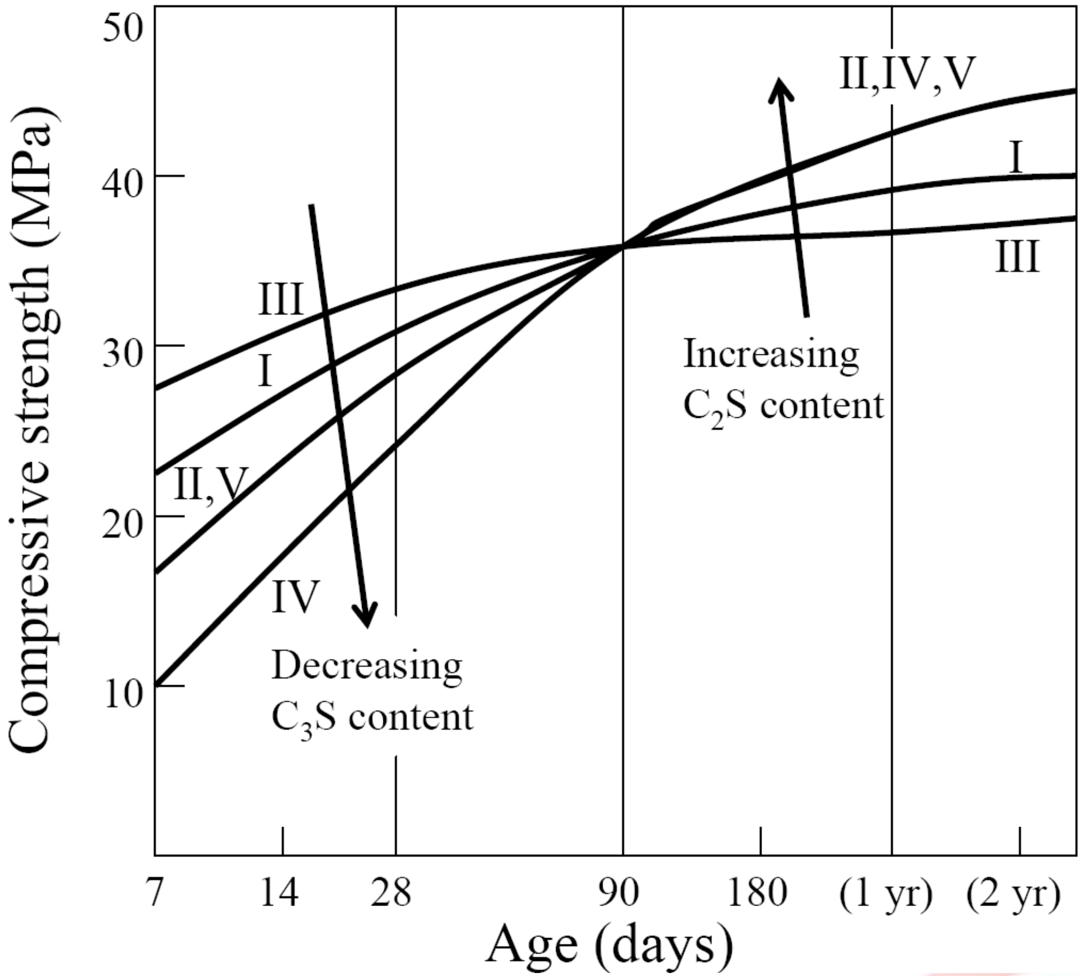
Typical Chemical Composition and Physical Properties of Portland Cements, ASTM Types I to V

ASTM Type[a]	I	II	III	IV	V
C_3S	55	55	55	**42**	55
C_2S	18	19	17	32	22
C_3A	10	**6**	10	**4**	**4**
C_4AF	8	11	8	15	12
$C\underline{S}H_2$	6	5	6	4	4
Fineness (Blaine, m^2/kg)	365	375	**550**	340	380
Compressive strength[b] (1 day, MPa)	15	14	**24**	**4**	12
Heat of Hydration (7 days, J/g)	350	265	370	**235**	310

[a] Canadian Standards Association designations are 10, 20, 30, 40, and 50, respectively
[b] Test on 50 mm mortar cubes (ASTM C 109)

Strength Development of Concrete w/ Different Cements

Strength gain of Type III over the first **24 h** is about double that of Type I



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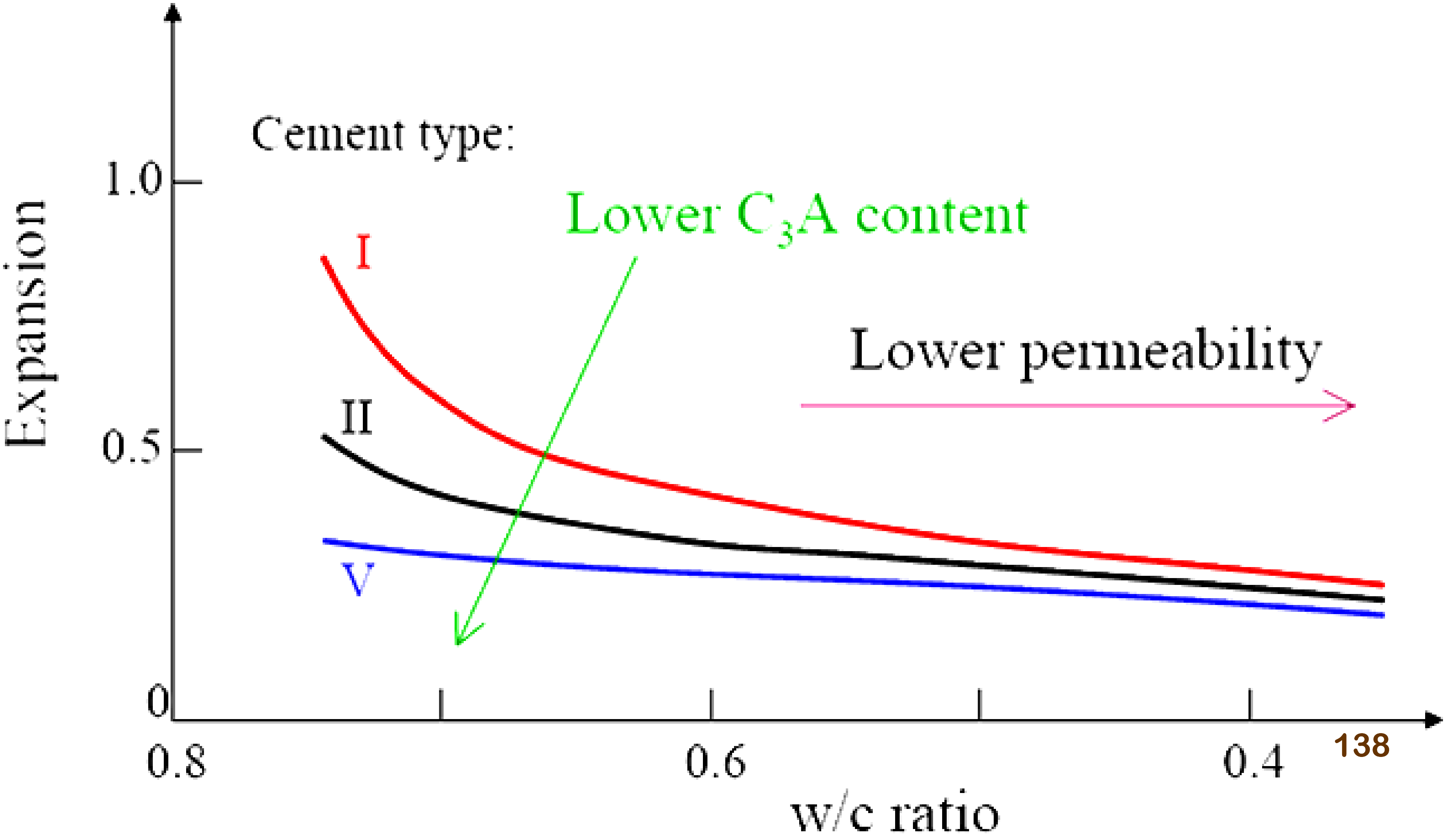
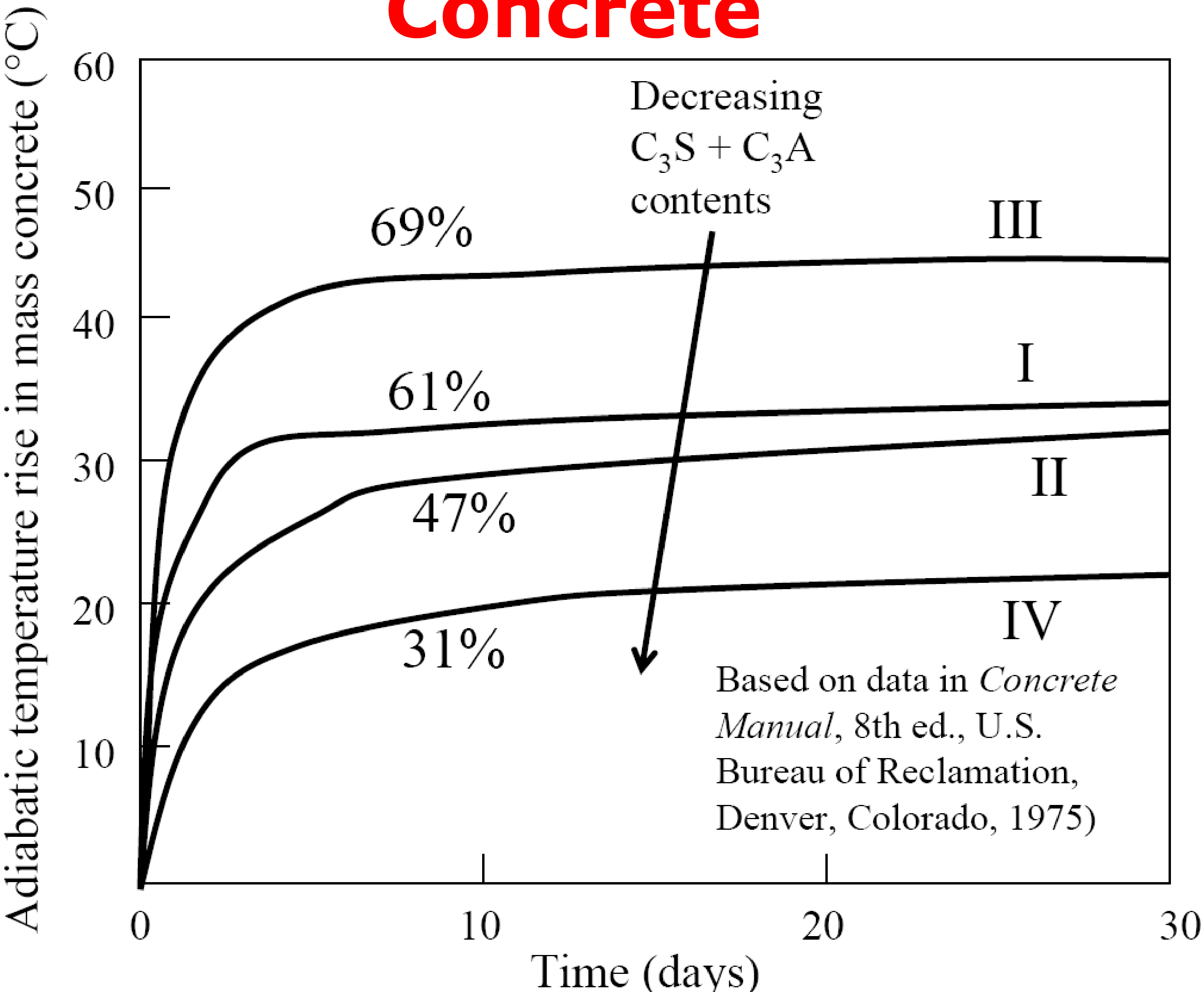
Effects of Cement Type and W/C Ratio on Sulfate Attack



Adiabatic Temp. Rise in Mass Concrete



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Chemical Requirements for Portland Cements – ASTM C 150

TABLE 1 Standard Chemical Requirements

Cement Type[A]	I and IA	II and IIA	III and IIIA	IV	V
Silicon dioxide (SiO_2), min, %	...	20.0[B,C]	...	...	...
Aluminum oxide (Al_2O_3), max, %	...	6.0	...	...	...
Ferric oxide (Fe_2O_3), max, %	...	6.0[B,C]	...	6.5	...
Magnesium oxide (MgO), max, %	6.0	6.0	6.0	6.0	6.0
Sulfur trioxide (SO_3),[D] max, %					
When (C_3A)[E] is 8 % or less	3.0	3.0	3.5	2.3	2.3
When (C_3A)[E] is more than 8 %	3.5	[F]	4.5	[F]	[F]
Loss on ignition, max, %	3.0	3.0	3.0	2.5	3.0
Insoluble residue, max, %	0.75	0.75	0.75	0.75	0.75
Tricalcium silicate (C_3S),[E] max, %	...	...	...	35[B]	...
Dicalcium silicate (C_2S),[E] min, %	...	...	...	40[B]	...
Tricalcium aluminate (C_3A)[E] max, %	...	8	15	7[B]	5[C]
Tetracalcium aluminoferrite plus twice the tricalcium aluminate[E] ($C_4AF + 2(C_3A)$), or solid solution ($C_4AF + C_2F$), as applicable, max, %	...	...	...	...	25[C]

TABLE 2 Optional Chemical Requirements[A]

Cement Type	I and IA	II and IIA	III and IIIA	IV	V	Remarks
Tricalcium aluminate (C_3A),[B] max, %	...	...	8	...	...	for moderate sulfate resistance
Tricalcium aluminate (C_3A),[B] max, %	...	...	5	...	...	for high sulfate resistance
Sum of tricalcium silicate and tricalcium aluminate,[B] max, %	...	58[C]	...	...	...	for moderate heat of hydration
Equivalent Alkalies ($Na_2O + 0.658K_2O$), max, %	0.60[D]	0.60[D]	0.60[D]	0.60[D]	0.60[D]	low-alkali cement

Physical Requirements for Portland Cements – ASTM C 150

TABLE 3 Standard Physical Requirements

Cement Type[A]	I	IA	II	IIA	III	IIIA	IV	V
Air content of mortar,[B] volume %:								
max	12	22	12	22	12	22	12	12
min	...	16	...	16	...	16	...	...
Fineness,[C] specific surface, m^2/kg (alternative methods):								
Turbidimeter test, min	160	160	160	160	...	...	160	160
Air permeability test, min	280	280	280	280	...	...	280	280
Autoclave expansion, max, %	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Strength, not less than the values shown for the ages indicated as follows:[D]								
Compressive strength, MPa (psi):								
1 day	...	...	...	...	12.0 (1740)	10.0 (1450)	...	...
3 days	12.0 (1740)	10.0 (1450)	10.0 (1450) 7.0[E] (1020)[E]	8.0 (1160) 6.0[E] (870)[E]	24.0 (3480)	19.0 (2760)	...	8.0 (1160)
7 days	19.0 (2760)	16.0 (2320)	17.0 (2470) 12.0[E] (1740)[E]	14.0 (2030) 9.0[E] (1310)[E]	...	...	7.0 (1020)	15.0 (2180)
28 days	...	...	...	...	...	...	17.0 (2470)	21.0 (3050)
Time of setting (alternative methods):[F]								
Gillmore test:								
Initial set, min, not less than	60	60	60	60	60	60	60	60
Final set, min, not more than	600	600	600	600	600	600	600	600
Vicat test:[G]								
Time of setting, min, not less than	45	45	45	45	45	45	45	45
Time of setting, min, not more than	375	375	375	375	375	375	375	375

Physical Requirements for Portland Cements – ASTM C 150

TABLE 4 Optional Physical Requirements[A]

Cement Type[A]	I	IA	II	IIA	III	IIIA	IV	V
False set, final penetration, min, %	50	50	50	50	50	50	50	50
Heat of hydration:								
7 days, max, kJ/kg (cal/g)	...	...	290 (70)[B]	290 (70)[B]	...	...	250 (60)[C]	...
28 days, max, kJ/kg (cal/g)	...	...	...	...	...	...	290 (70)[C]	...
Strength, not less than the values shown:								
Compressive strength, MPa (psi)								
28 days	28.0 (4060)	22.0 (3190)	28.0 (4060) 22.0[B] (3190)[B]	22.0 (3190) 18.0[B] (2610)[B]	...	...	...	...
Sulfate resistance,[D] 14 days, max, % expansion	...	...	...[E]	...[E]	...	...	...	0.040

Supplementary Cementitious Materials in Cement

- Inorganic material
- Particle size similar or smaller than that of cement
- Used as either partial cement replacement (or addition)
  - Property modification of concrete
  - Reduce energy cost and economic benefit
  - Environmental benefit
- Added separately as concrete ingredient
- Incorporated in cement (Blended cement)

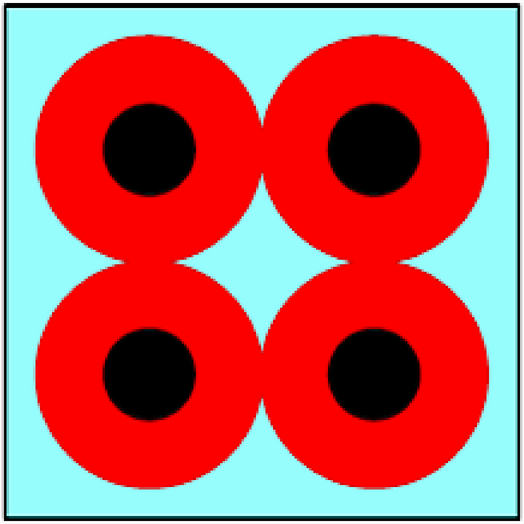
Common SCM

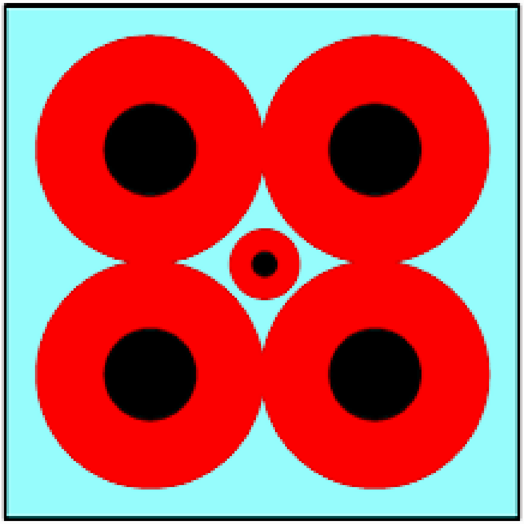
- **Fly ash**
  - Low-lime fly ash (Class F: lime < 10%)
    - pozzolanic
  - High-lime fly ash (Class C: lime 15 to 30%)
    - Pozzolanic and cementitious
- **Ground granulated blast-furnace slag**
  - Pozzolanic and cementitious
- **Silica fume** (super pozzolanic)
- Rice-husk ash (pozzolanic)
- Volcanic ash (pozzolanic)
- Natural pozzolans (pozzolanic)

Pozzolanic Reaction

- Portland cement
  - $C_3S + H \xrightarrow[\text{fast}]{} \text{C-S-H} + CH$
- Pozzolanic reaction
  - $CH + \text{pozzolan (S)} + H \xrightarrow[\text{slow}]{} \text{C-S-H}$
- Addition of pozzolan has similar effect to raising C_2S content of cement (i.e. lower heat evolution and lower early strength)
- Slow reaction requires prolonged moist curing; otherwise pozzolan act mainly as a filler

SCM Filler Effect





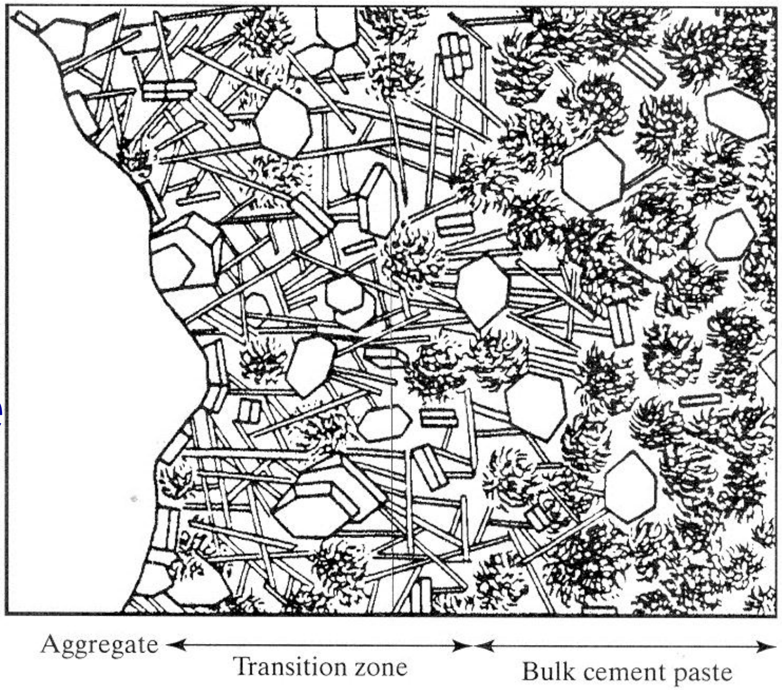
Without Mineral Admixture

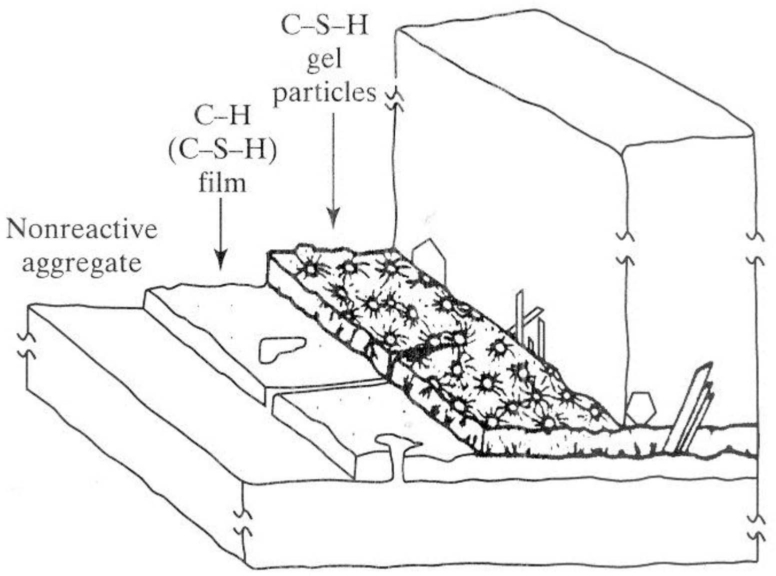
With Mineral Admixture

Mineral admixtures reduce porosity and pore size of bulk cement paste and ITZ.

Interfacial Transition Zone

- A thin zone surrounding the aggregate particles in which the structure of the cement paste is quite different from that of the bulk paste further away from the physical interface, in terms of morphology, composition, and density
- Due to the inability of the cement particles to pack efficiently around the aggregate (wall effect). This raises the local w/c ratio, which can be further increased by localized bleeding





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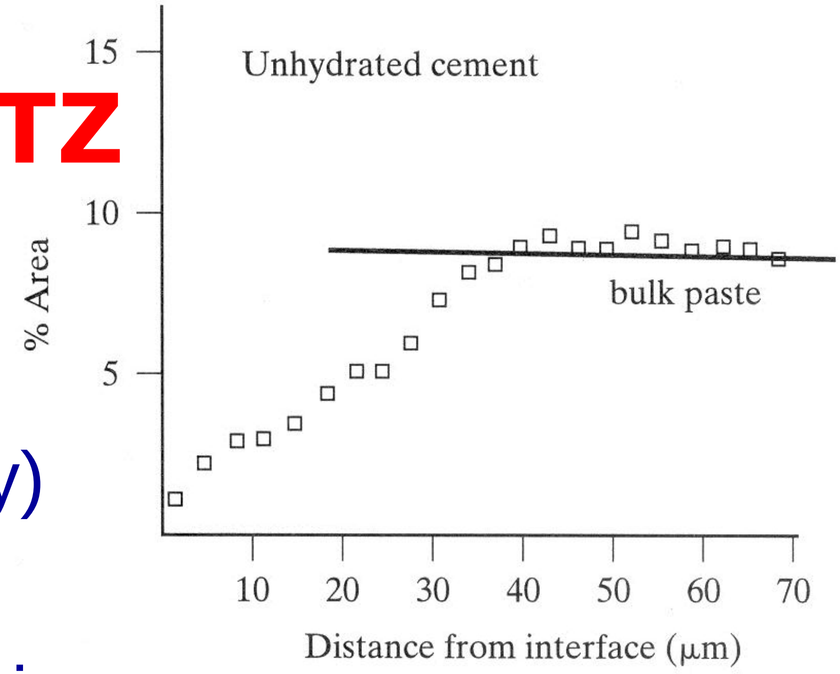
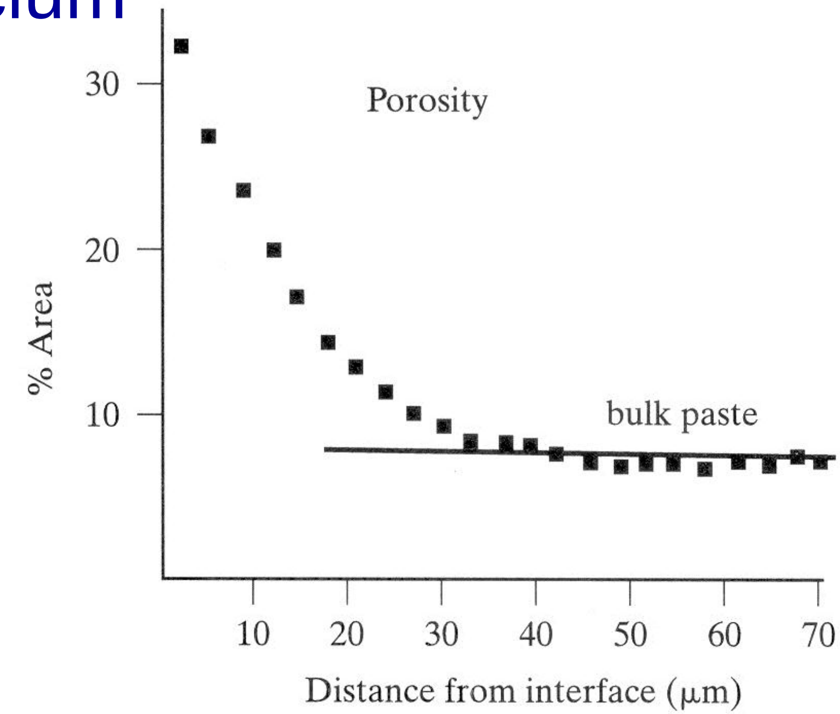
Characteristics of ITZ

- Thickness: 20 – 40 μm
- Less unhydrated cement
- Higher porosity (lower density)
- Less C-S-H
- Large, oriented crystal of calcium hydroxide
- Greater concentration of ettringite
- ITZ makes up 20-40% of the matrix





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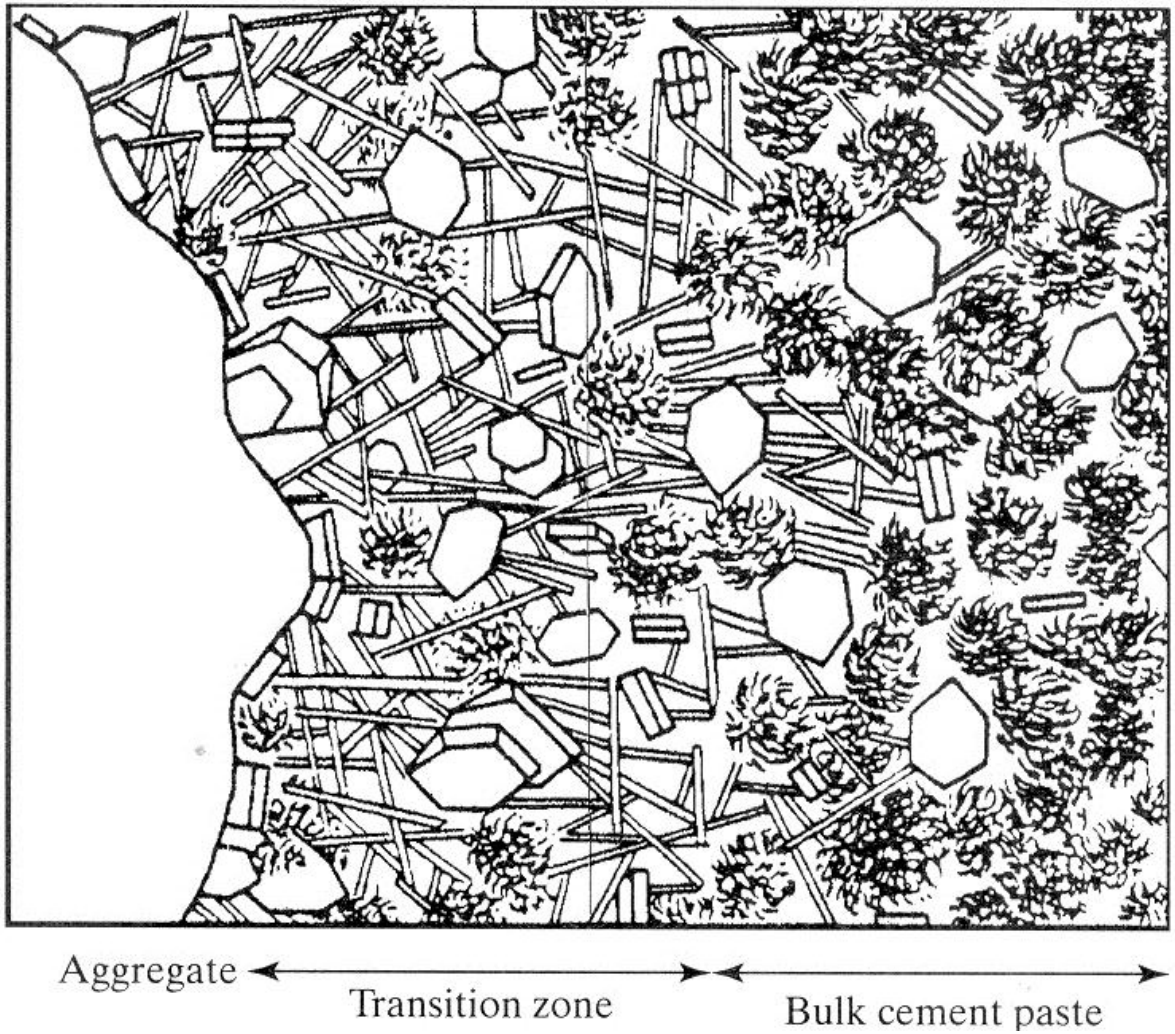
Effect of ITZ on Mechanical and Transport Properties

- Interfacial porosity in ITZ provides interconnected macroporosity and therefore has a strong influence in concrete permeability
- In ordinary concrete, ITZ has less crack resistance than other phases, and therefore fracture occurs preferentially in the ITZ (weak link in the concrete)
- Generally speaking, weak ITZ results in low strength and high transport properties (i.e. poor durability)



Pozzolanic reaction increases:

(1) C-S-H content and binder paste strength **(reduced bleeding)**

(2) improve aggregate-cement paste bond strength

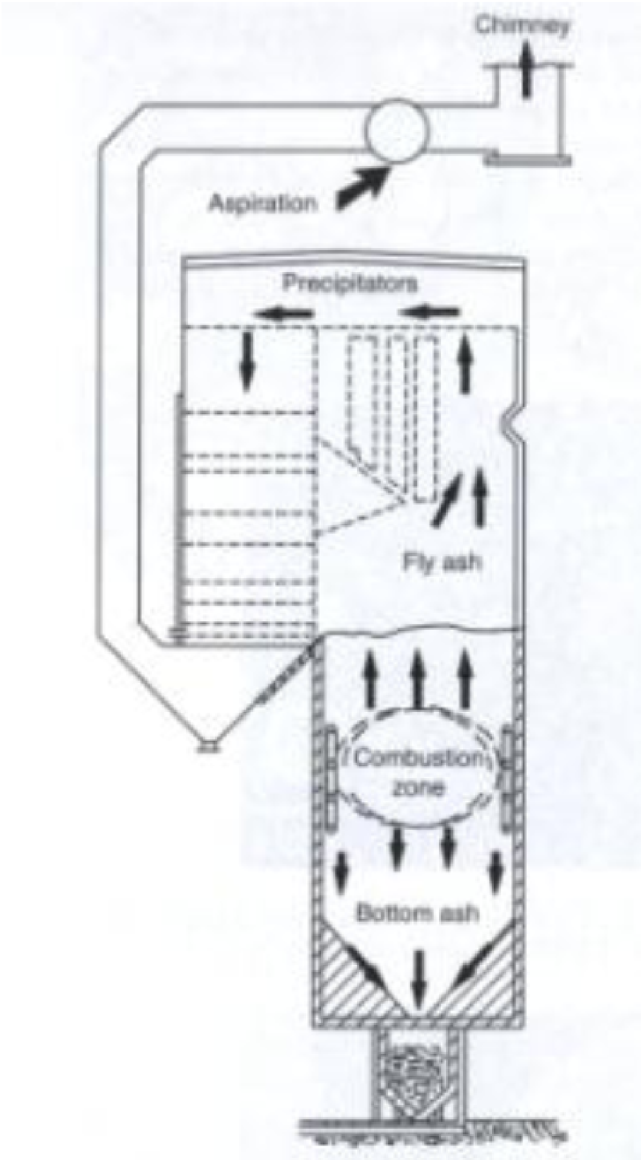
(3) reduces the porosity and modifies pore-size distribution

Typical Composition and Properties of SCM

Addition	Fly Ash (F)	Fly Ash (C)	Slag	Silica fume	Cement
SiO_2	44 - 58	27 - 52	30 - 37	94 - 98	17 - 25
CaO	1.5 – 6.0	8 - 40	34 – 45	< 1	60 - 67
Al_2O_3	20 - 38	9 - 25	9 - 17	< 1	3 - 8
Fe_2O_3	4 - 18	4 - 9	0.2 – 2.0	< 1	0.5 – 6.0
MgO	0.5 – 2.0	2 - 8	4 - 13	< 1	0.1 – 4.0
Size (μm)	1 - 80		3 - 100	0.3 – 3.0	0.5 - 100
Fineness m^2/kg	350		400	20,000	350
Sp. Gr.	2.30		2.90	2.50	3.15
Shape	Spherical		Irregular	Irregular	Angular
Max. Cement replacement (%)	40	90	90	25	-

Fly Ash

- By-product of coal combustion in power stations
- at 1500 °C coal burn; residue melt; on rapid cooling form spherical particles
- Very fine particles carried by flue gas and collected by electrostatic precipitators [FLY ASH]
- Larger ash particles remains at the bottom of the furnace [BOTTOM ASH]



http://youtu.be/wwM880Savhg

Fly Ash

ACI Standard 116: Definition of Fly Ash

Finely divided residue resulting from the combination of ground or powdered coal and which is transported from the firebox through the boiler by flue gases.

Fly Ash properties

- Spherical shaped particles
- Size: 1 to 100 μm diameter
- Fineness: 250 to 600 m^2/kg
- Sp. gr. = 2.35 (typical value)
- Darker than cement
- Variable material

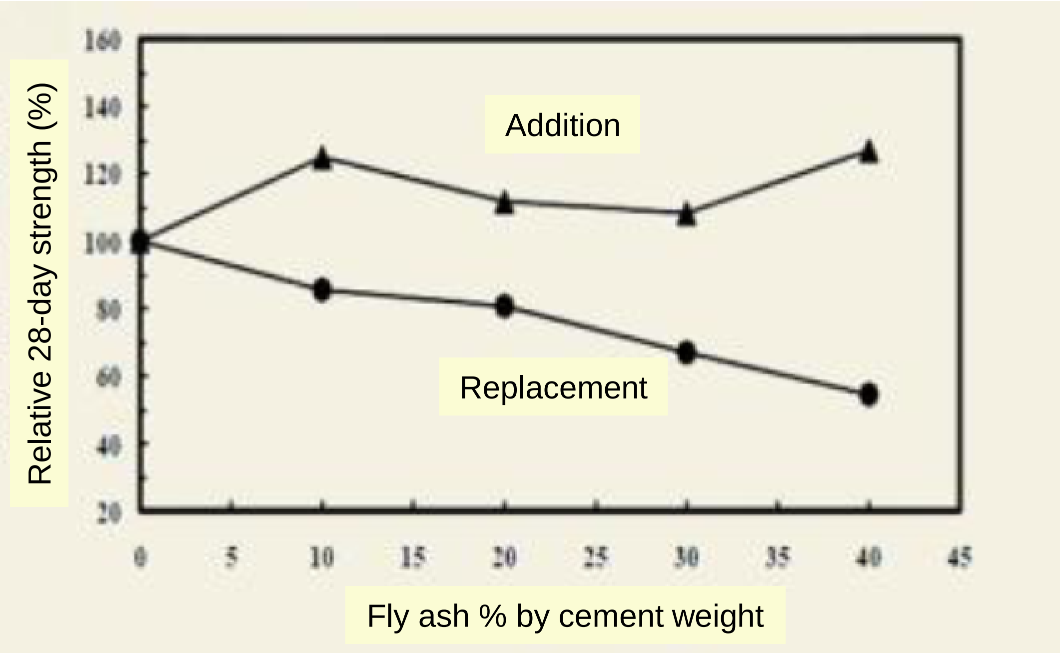
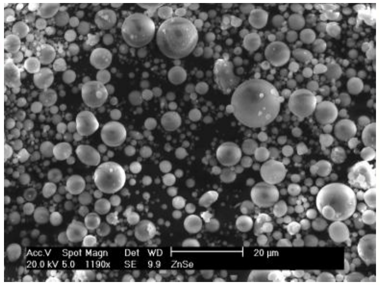


Figure 2: Effect of Fly Ash as Cement Replacement and Addition on 28-day Compressive Strength

Fly Ash Types (ASTM C 618)

ASTM Fly Ash Types



Class F – Bituminous coal
(low lime: Pozzolanic)

Class C – Sub-bituminous coal and lignite
(high lime content:
Pozzolanic and Cementitious)

Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (ASTM C618 - 08a)

- Silica + Alumina + Ferric Oxide:
  70% (min.) for Class F; 50% (min.) for Class C
- Sulphur Trioxide: 5% (maximum) [BS3892 2.5% maximum]
- Loss of ignition: 6% (maximum)
- Alkali: 1.5% (Na_2O equivalent)

Cement particles: angular

Fly Ash Particles: spherical

(Improves workability of concrete)

Use of Fly Ash in Concrete

- To reduce cement content (Economical)
- To control temperature rise in mass concrete (minimise thermal cracking)
- To improve durability of concrete

Effects of cement replacement with fly ash on concrete properties

- Increased workability (spherical fly ash)
- Reduction in bleeding of concrete
- Increased stability against segregation
- Delay in setting time and early age strength development
- Improved later age strength when fly ash content is below 20%

Cement Efficiency Factor

Reactive Silica + Lime liberated from cement hydration

= Cementitious Compounds

Pozzolanic reaction occurs in moist environment at the room temperature

$$SiO_2 + Ca(OH)_2 + H_2O = C\text{-}S\text{-}H$$

Cement Efficiency Factor (CEF) for Fly Ash (k)

= 0.30 (approximately)

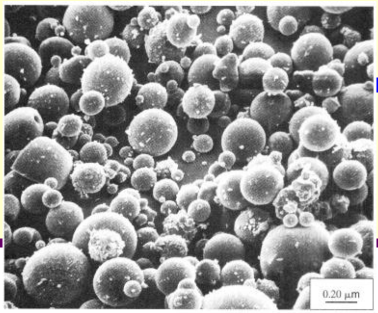
i.e. 1 kg of Fly Ash Equivalent to k kg of cement

This value is used in the design of concrete mixes with fly ash

CEF (k): function of (age, composition, fineness)

Silica Fume (Micro Silica)

Quartz + Coal + Iron + Wood Chips + Electricity



→ Silicon (or Ferrosilicon)

+ Condensed Silica Fume + Heat

- By-product of the production of silicon and ferrosilicon or of zirconium
- Fumes are collected in the dedusting system of arc furnace
- Silicon Oxide (SiO) vapour oxidised and solidifies into spherical particles

Silica Fume

ACI Standard 116: Silica Fume

Very fine non-crystalline silica produced in an electric arch furnace as a by-product of the production of elemental silicon or alloys containing silicon (ferrosilicon)

Silica fume properties

- Spherical shaped particles
- Average diameter 0.10 µm
- Fineness: 15,000 -20,000 m^2/kg
- Sp. gr.: 2.35 (typical value)
- Bulk Density: 200 to 250 kg/m^3
- Colour: White or Grey
- Silica: 93.7% (silicon);
  87.3% (ferrosilicon)

Available forms (Bulk density kg/m^3)

- Undensified: 200 -350
- Densified: 500 to 600 easy to handle with less dust; loosely agglomerated
- Micropelletized (0.5 to 1.0mm): 700 -1000 – used for intergrinding with cement clinker
- Slurry: 1400 (undensified silica fume in water)

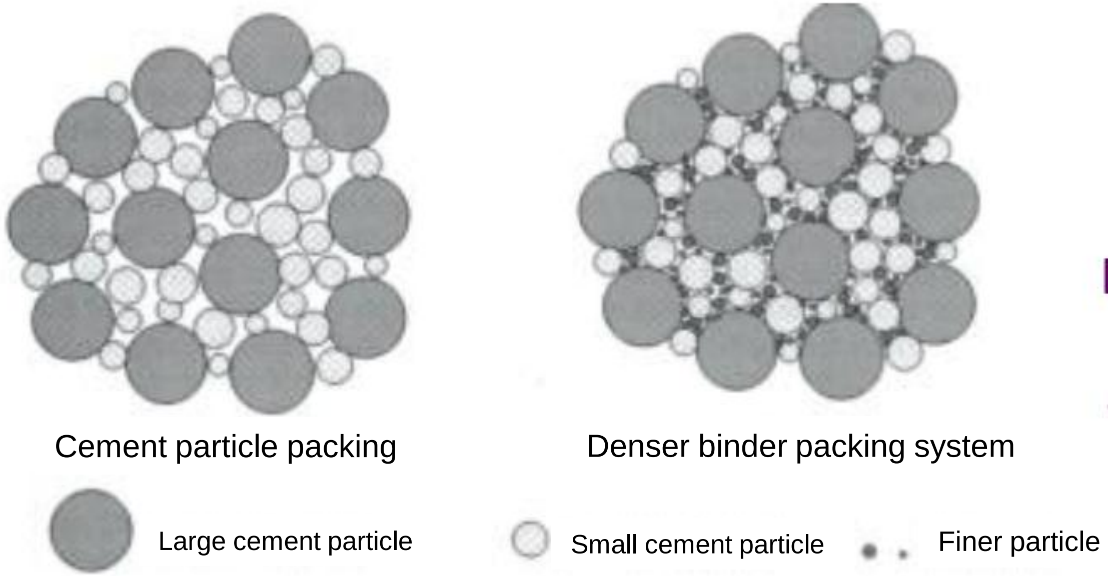
Use of Silica Fume in Concrete

Usage of Silica Fume

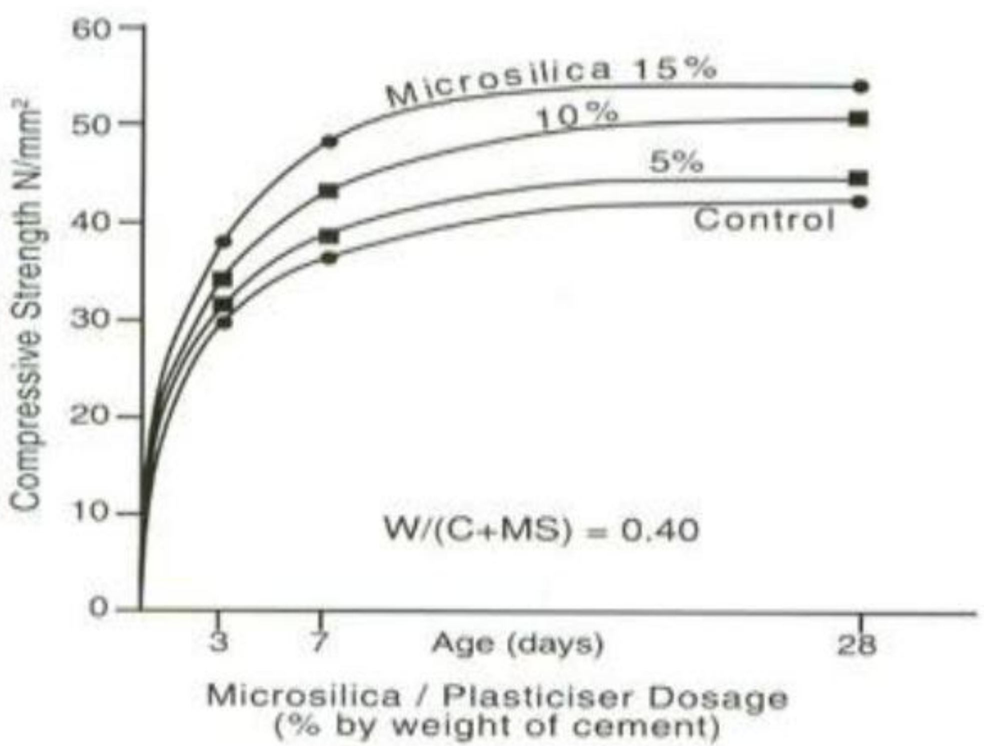
- Cement Replacement
- Reduce bleeding
- Increase water demand
- Plastic shrinkage cracking
- Addition to concrete
  - Reduce permeability
  - Increase early age strength
  - Increase electrical resistivity (corrosion resistance of steel)

Silica Fume content in Concrete of Total cementitious materials contents by wt.

- Normal 4 – 7%
- High Performance 8 – 10%
- High Chemical Resistance 10 - 12%
- Underwater 10 – 15%
- Pumped 2 – 5%



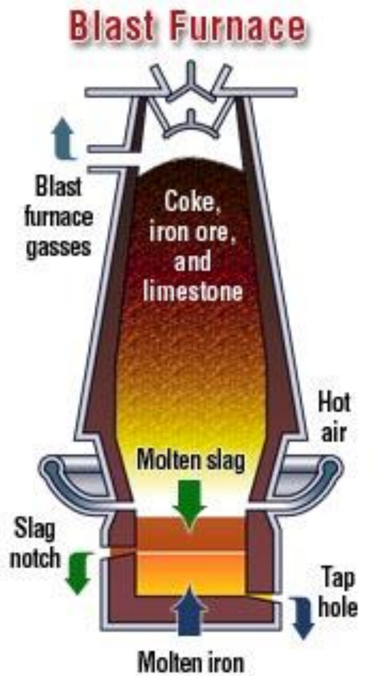
Densification of binder system with silica fume

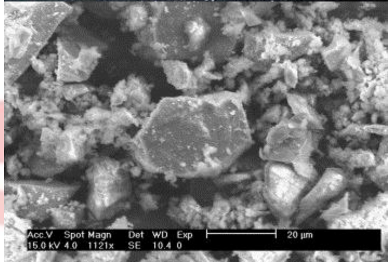


Silica fume content in concrete is limited to 15% by cement weight

Blast-furnace Slag

- Residues from metallurgical processes, i.e. the blast furnace production of ***iron*** from ore (rich in lime, silica, and alumina)
- Slag must be rapidly cooled (quenched) to form a hydraulically active calcium aluminosilicate glass
- The smaller granules (< 4 mm) are ground for use as a mineral admixture, i.e. ground granulated blast-furnace slag (GGBS)
- The larger pellets, which are porous and partially crystalline, can be used as a lightweight aggregate





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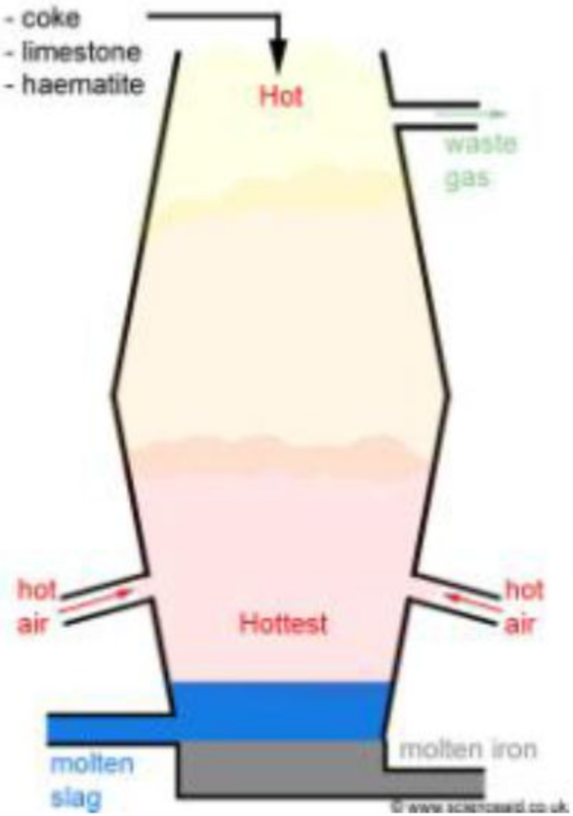
Blast-furnace Slag



Composition ranges

Lime	40 to 50 %
Silica	30 to 40%
Alumina	8 to 18%
Magnesia	0 to 8%

GRANULATED BLAST FURNACE SLAG

- Rapid water cooling of blast-furnace slag from 1500°C to 100 °C
- Sand size particles; Sp. gr. = 2.90
- Slag is harder to grind compared to clinker
- ground to required fineness (250 to 1500 m^2/kg)
- possesses hydraulic properties when suitably activated

ACI Standard 116: Definition of Blast-Furnace Slag

A non metallic product, consisting essentially of silicates and alumino-silicates of calcium and other bases developed in a molten condition simultaneously with iron in a blast furnace.

BS 146:1991 and BS 4246:1991: Requirements for Slag for Concrete

- Granulated blast-furnace slag shall consist of at least two-thirds by mass consist of glass
- At least two third of total mass of slag consists of the sum of CaO, MgO and SiO_2
- Ratio by mass $(CaO + MgO)/(SiO_2)$ must exceed 1.0 to assure high alkalinity

Slag Hydration

- Slag reacts slowly with water due to the presence of impervious coatings of amorphous silica and alumina that form around slag particles early in the hydration process
- Slag needs to be activated by alkaline compounds
- Slags are most commonly activated by Portland cement, where $Ca(OH)_2$ formed during hydration is the principal activator. Only 10-20% of cement is needed for activation
- The rate of hydration of activated slag is slow, similar to that of C_2S, as is the heat of hydration

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ASTM C989 - 10: Standard Specification for Slag Cement for Use in Concrete and Mortars

Grades 80, 100, 120, according to slag activity index

Slag activity index – SAI (%) = (SP/P) x 100

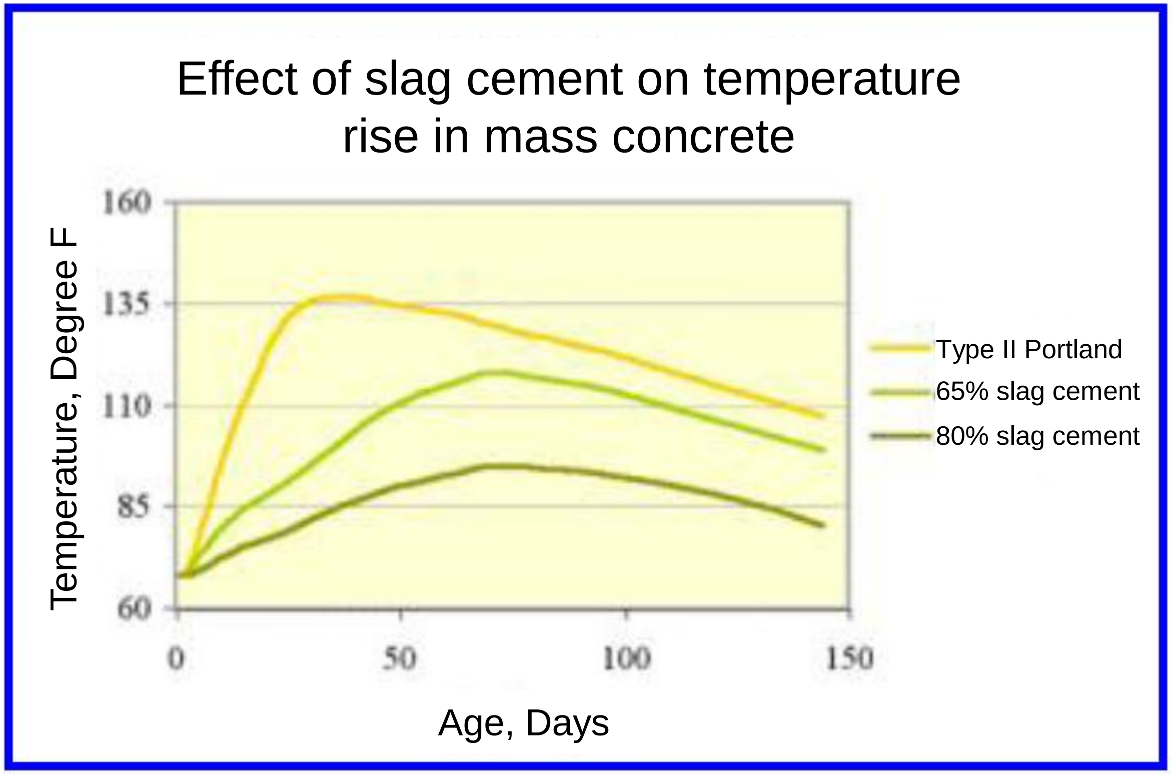
SP = Mean comp. strength of slag-reference cement mortar cubes

P = Mean comp. strength of cement mortar cubes

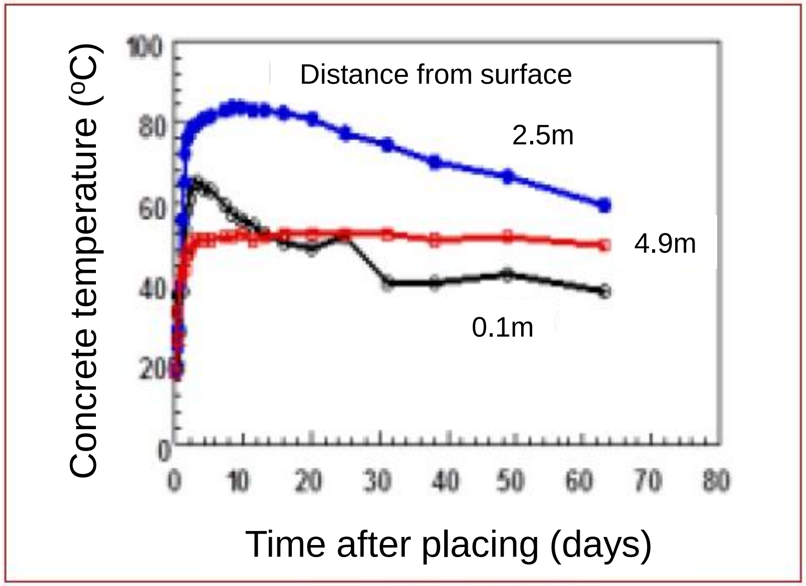
Minimum Mean SAI (%) of 5 Tests		
Grade	7-day	28-day
80	-	75
100	75	95
120	95	115

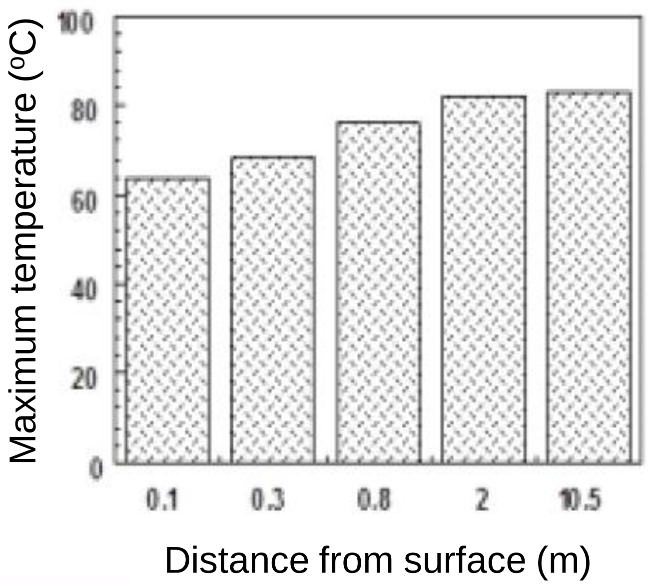
Use of GGBS in Concrete

- REPLACE CEMENT UP TO 70%
- REDUCE HEAT IN MASS CONCRETE
- REDUCE PERMEABILITY
- IMPROVE CHEMICAL RESISTANCE



Blended Cement (65% slag) for Pile Cap (5m x 21m x 26m) Concrete (ANZAC Bridge, Sydney)



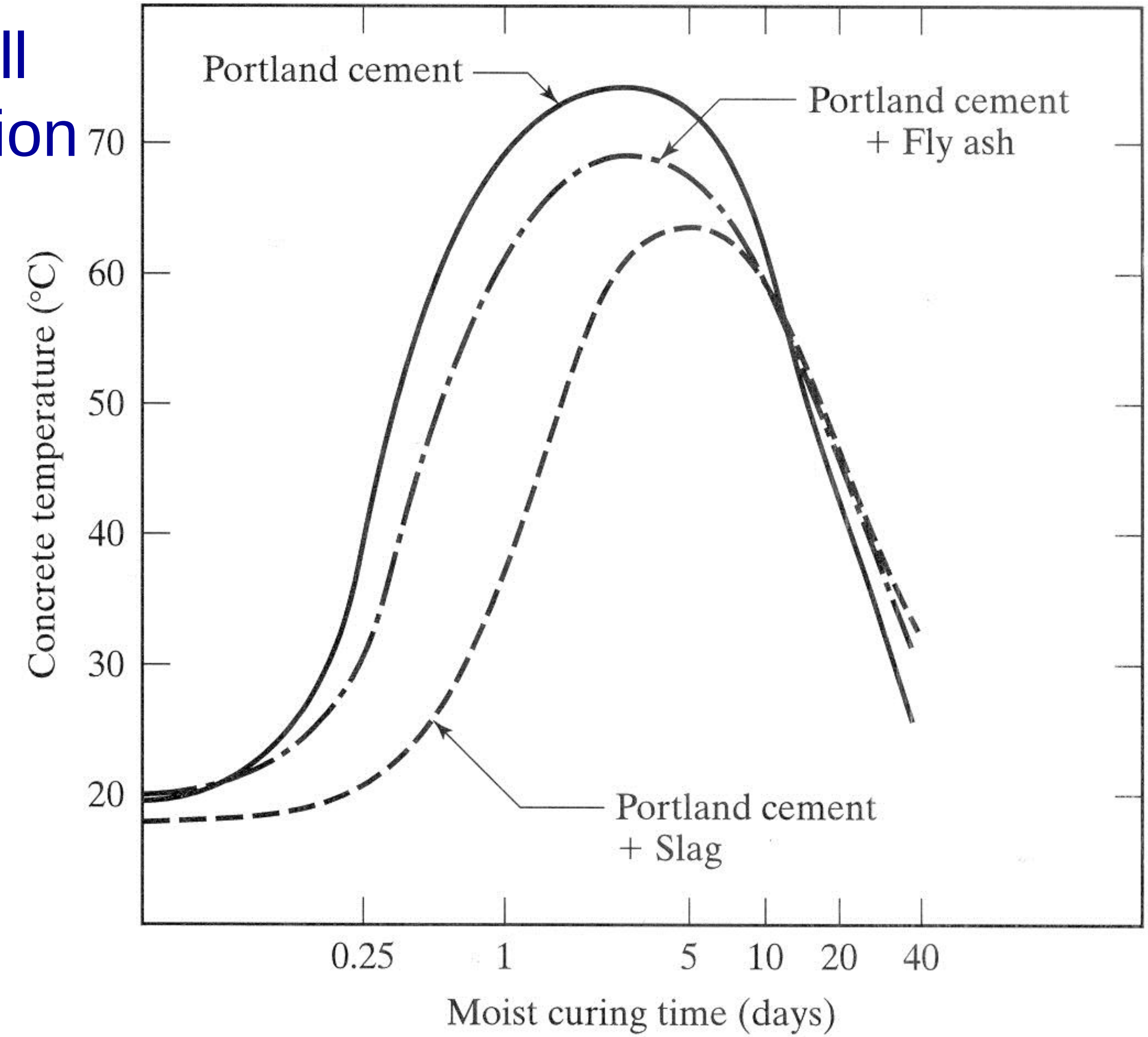


Maximum Temperature = 84 °C after 10 days

SCM …

- Reduce overall heat of hydration

Temperature rise in mass concrete made with fly ash or slag. Type I cement, w/c = 0.5



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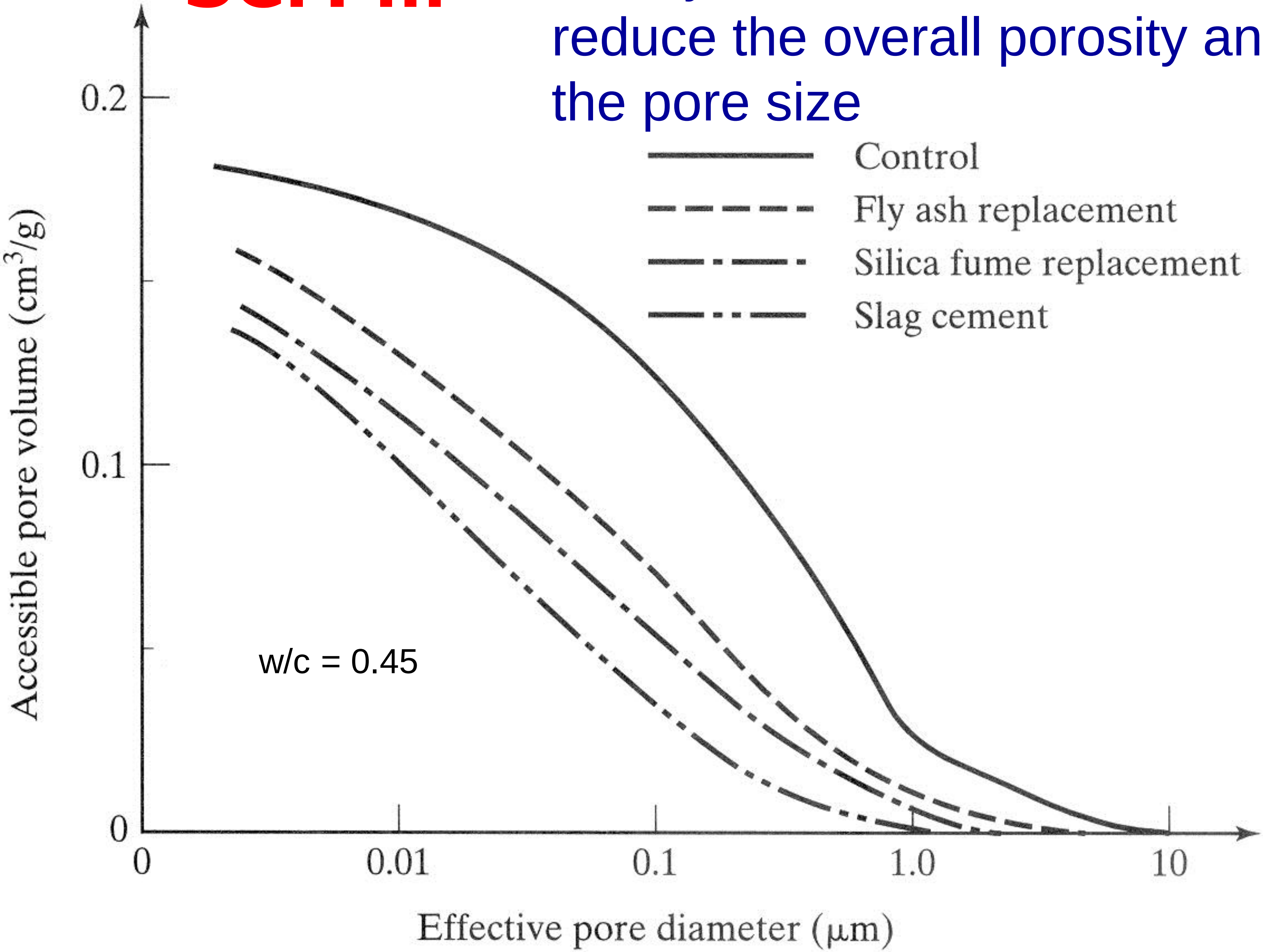
SCM …

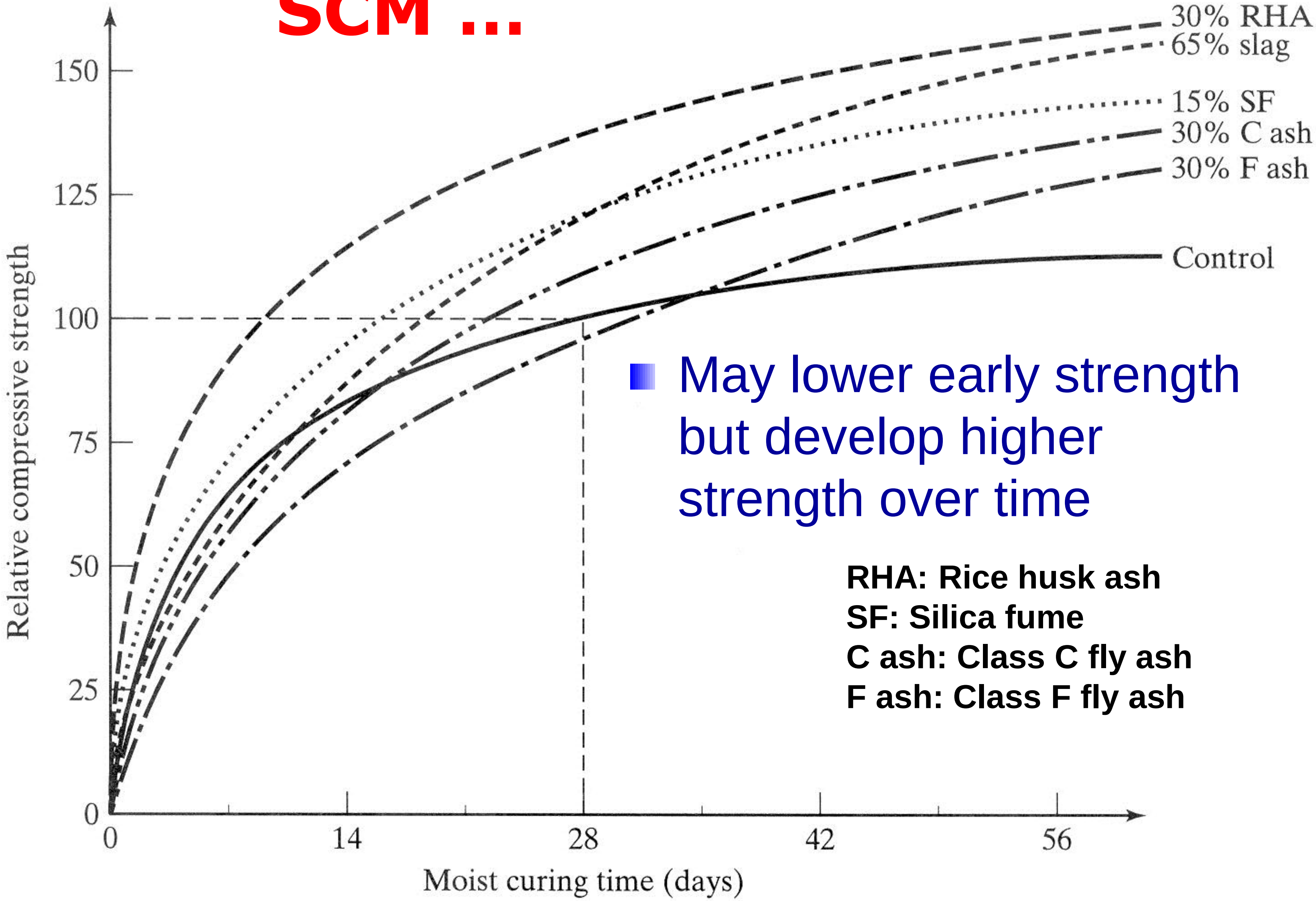
- Improve workability and reduce w/cm ratio
  - Fly ash and silica fume are particularly beneficial to workability because of their spherical morphology which acts small ball bearings to reduce interparticle friction
- Does not significantly affect the drying shrinkage or creep of concrete

SCM …

- Modify the microstructure; reduce the overall porosity and the pore size

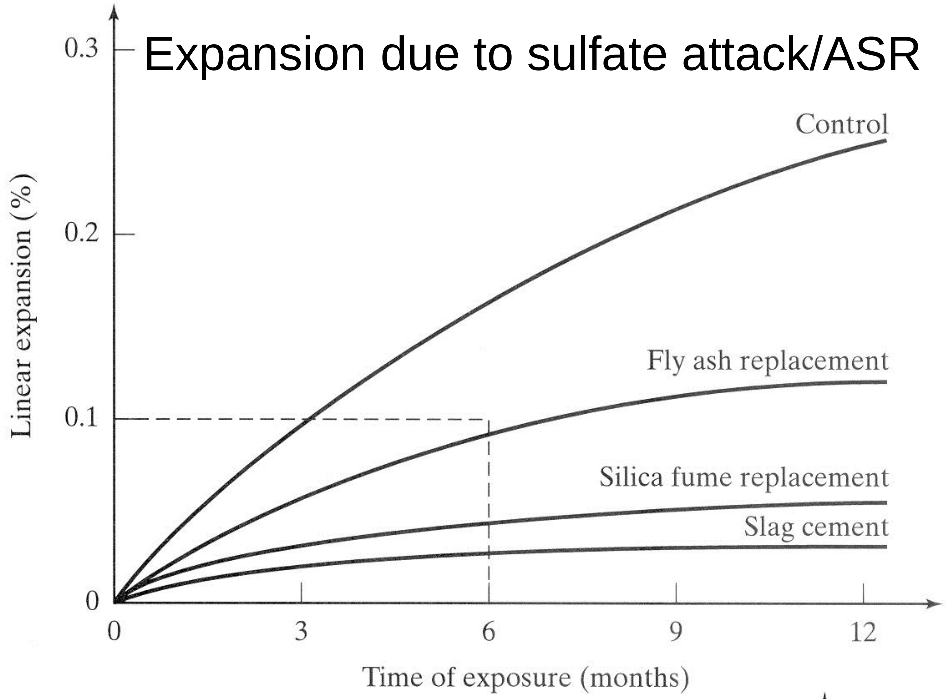


SCM ...



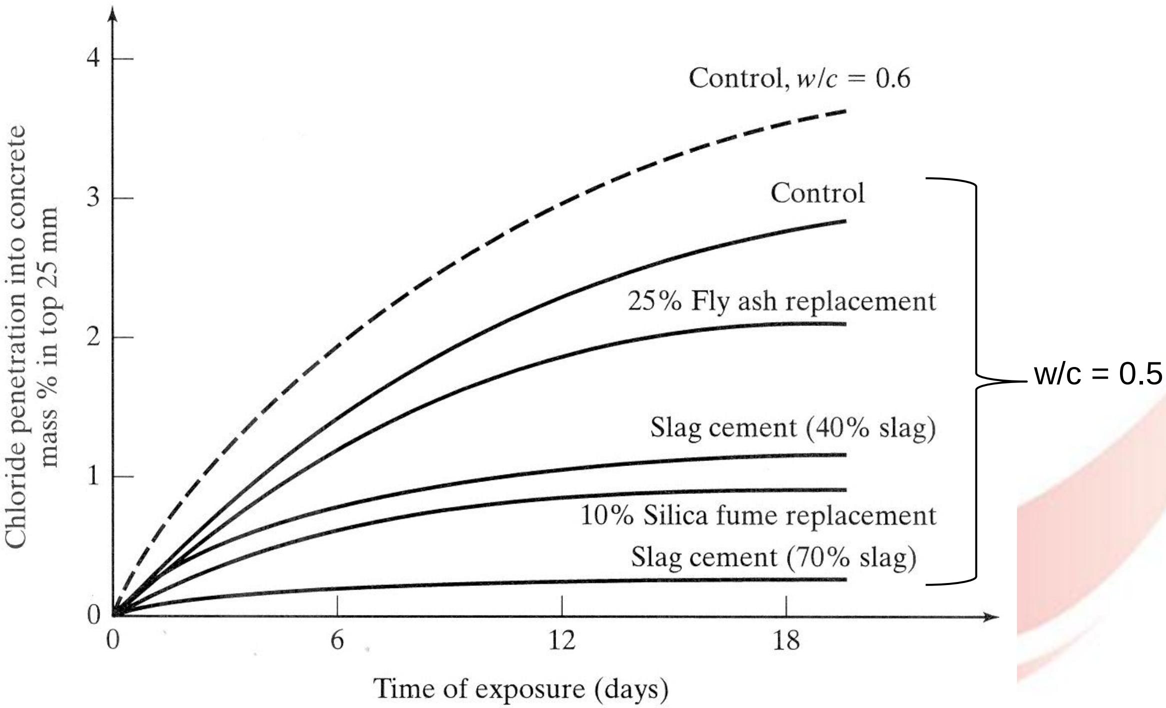
- May lower early strength but develop higher strength over time

RHA: Rice husk ash
SF: Silica fume
C ash: Class C fly ash
F ash: Class F fly ash



- Improve the durability of concrete because of the reduction in calcium hydroxide, changes in pore structure, and reduction in the w/cm ratio

SCM …



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SCM on Fresh Concrete

Quality Measure	Effect
Water Requirement	Increases (Silica fume); Reduces (Fly ash)
Air Content	Reduces (Silica fume and Fly Ash)
Workability	Increases (Fly ash & ggbfs); Reduces (Silica fume)
Heat of Hydration	Reduces (Fly ash & ggbfs); No effect (Silica fume)
Setting Time	Increases (Fly ash, ggbfs and natural pozzolans)

SCM on Hardened Concrete

Quality Measure	Effect
Strength	Reduces early age strength & increases ultimate strength (FA & GGBS); both early & ultimate strength increase (SF)
Shrinkage & Creep	Increases (large amount of ggbfs & Fly Ash); Reduces (SF)
Permeability	Reduces (Fly ash, ggbfs and SF)
Alkali-aggregate	Reduces reactivity (Fly ash and ggbfs)
Sulphate Resistance	Improves (Fly ash, ggbfs and natural pozzolans)

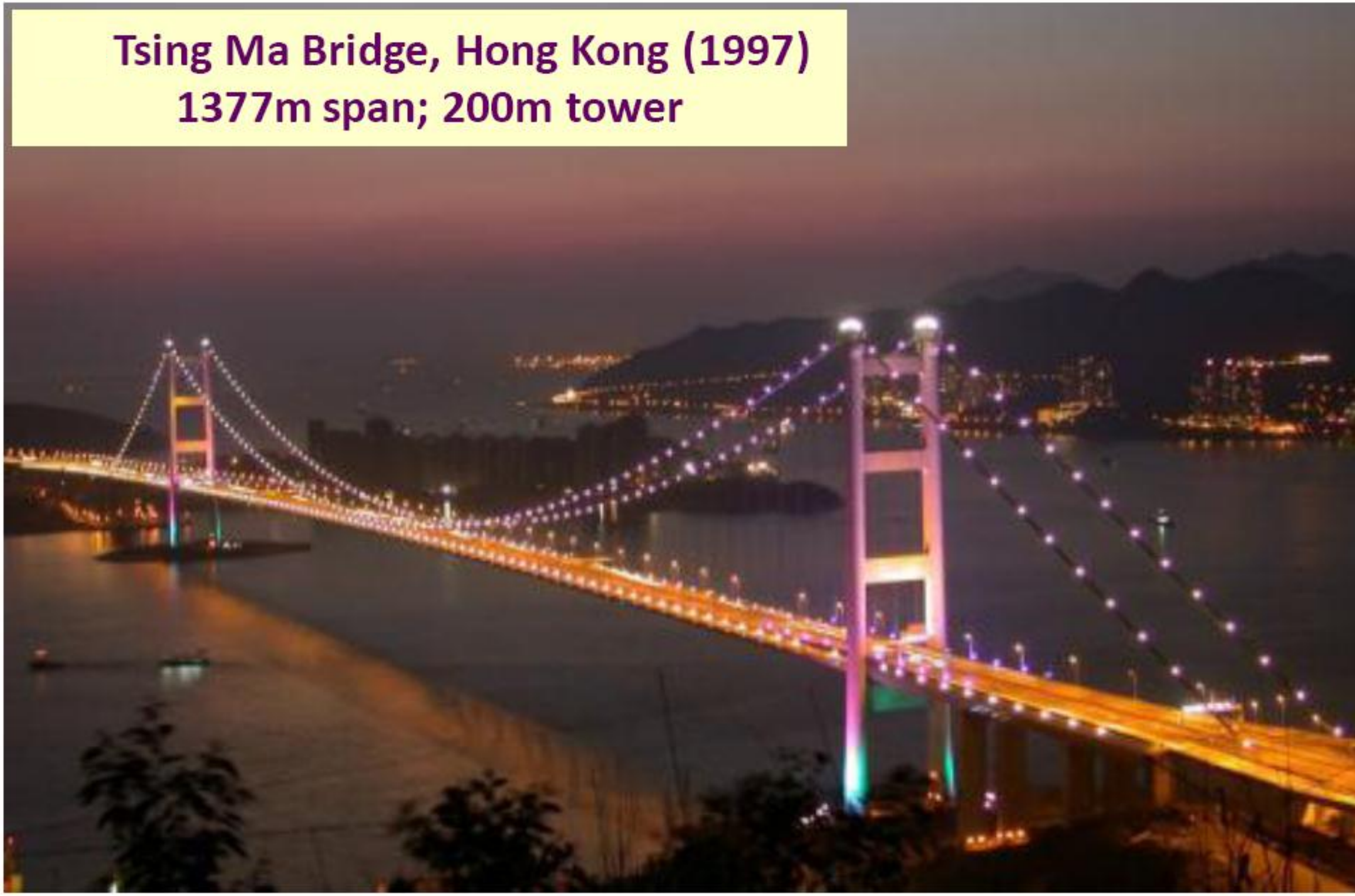
SCM Is A Key Material To …

- Produce "High Performance Concrete"
  - Low heat
  - High durability
  - Self compacting
  - High strength
  - Workability-retention

Petronas Twin Towers , 452m, Malaysia (1996)

80 MPa concrete	
OPC	184
Masscrete (20% Fly ash)	345
Silica Fume	35
Water	152
Coarse aggregate (20/25 mm)	1006
Fine aggregate	728
Retarder	0.8
Superplasticiser	8.48
Slump	220
W/Cm	0.27

Tsing Ma Bridge, Hong Kong (1997)
1377m span; 200m tower



Concrete for Towers: 30% OPC, Slag (65%) & 5% Silica fume
Compressive Strength = 80MPa

Other concrete: 70% OPC, 25% Fly Ash and 5% Silica Fume

SCM and Sustainability

One Tonne of Portland Cement

- *1.7 Tonne of Raw Materials required*
- *4000 to 7500 MJ Energy consumed*
- *1 tonne of Carbon Dioxide liberated*

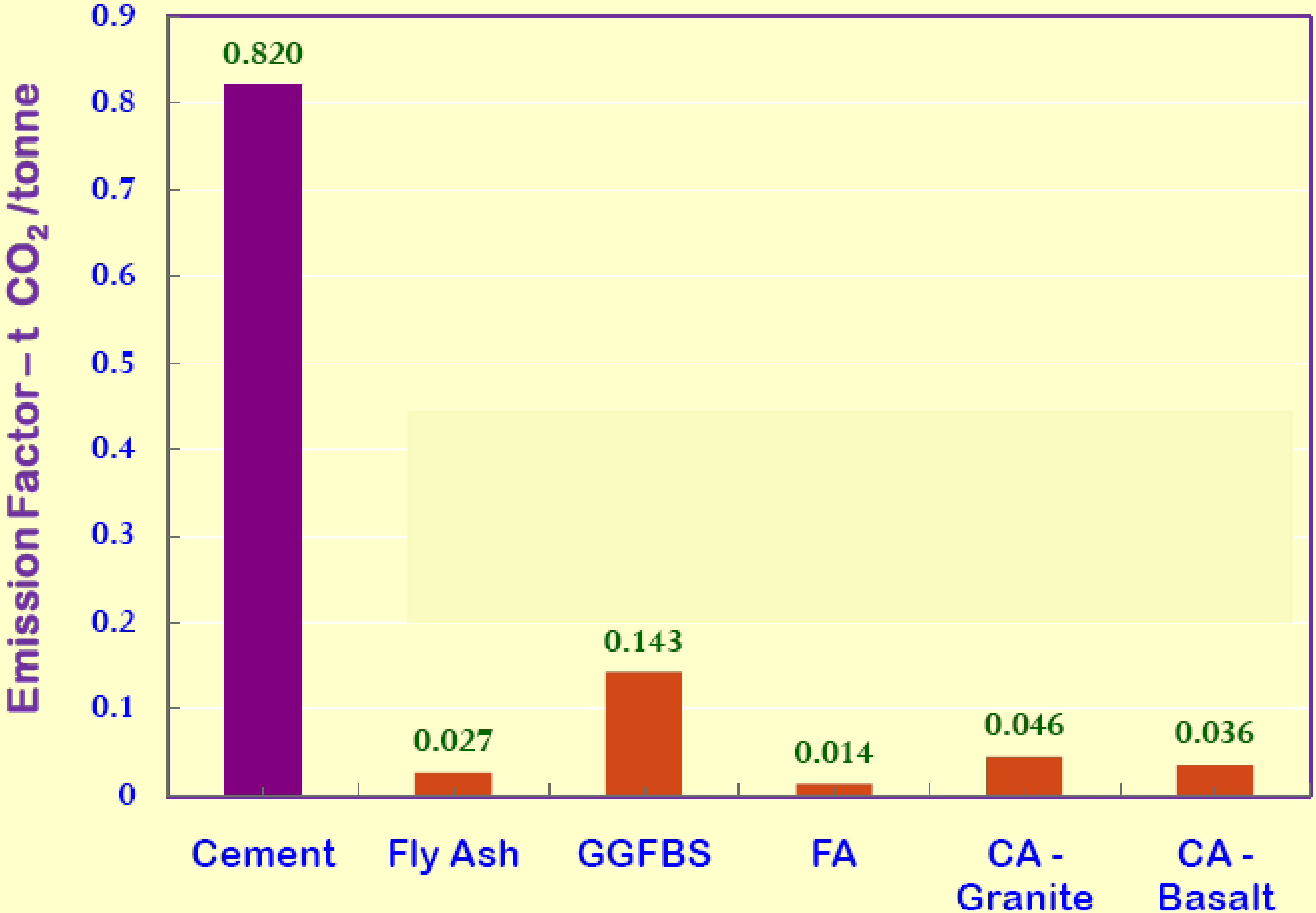
One Tonne of Supplementary Cementitious Materials (SCM) production requires:

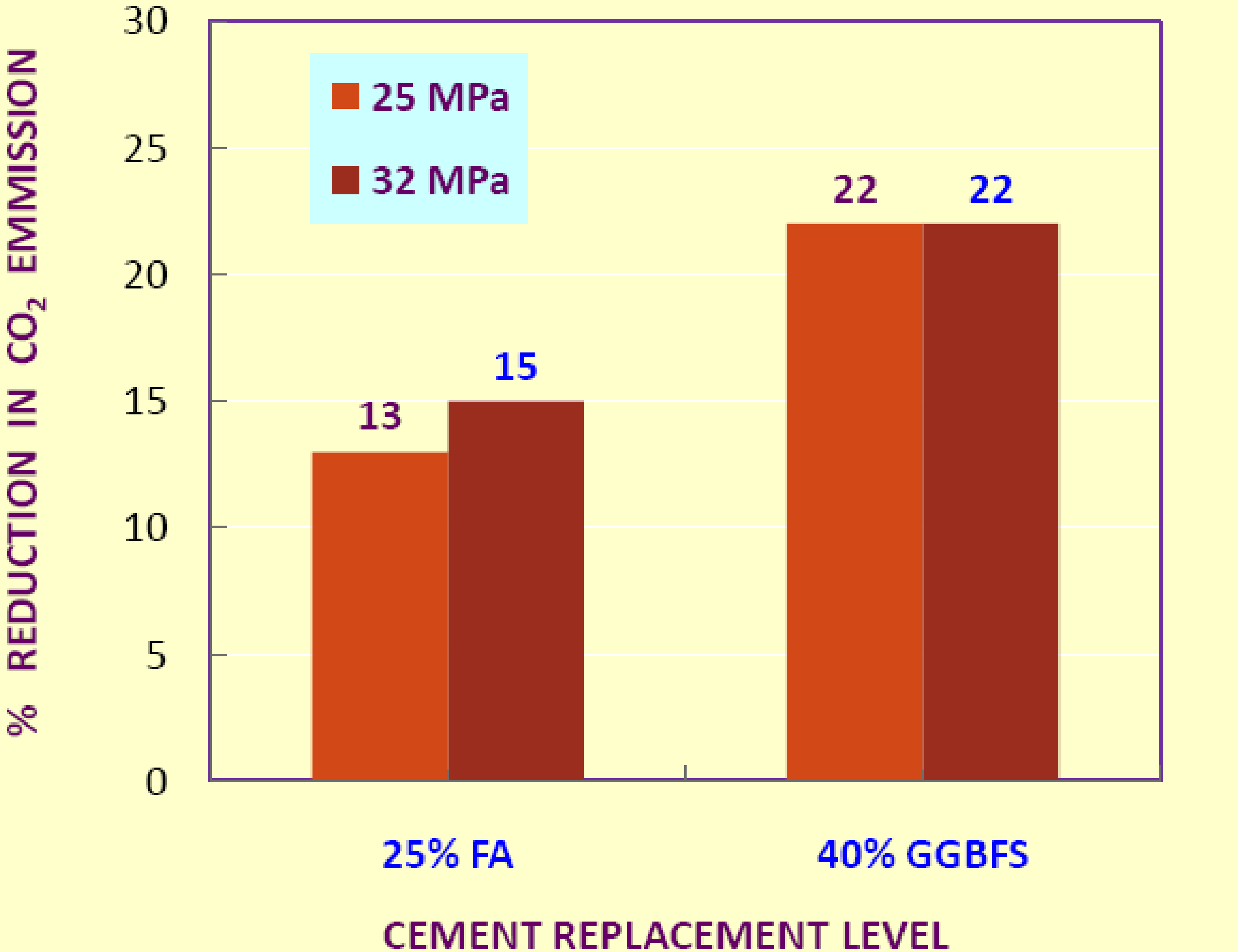
- *700 to 1000 MJ for Slag*
- *150 to 400 MJ for Fly Ash*

One Tonne of Blended Cement with 65% Slag content requires

* *50% reduction in raw materials*
* *1500 MJ (Saving of 2500 TO 6000 MJ)*

Emission Factor of SCM





25 MPa
32 MPa
13
15
22
22
30
25
20
15
10
5
0
% REDUCTION IN CO_2 EMMISSION
25% FA
40% GGBFS
CEMENT REPLACEMENT LEVEL

AGGREGATES

Stone As A Building Material

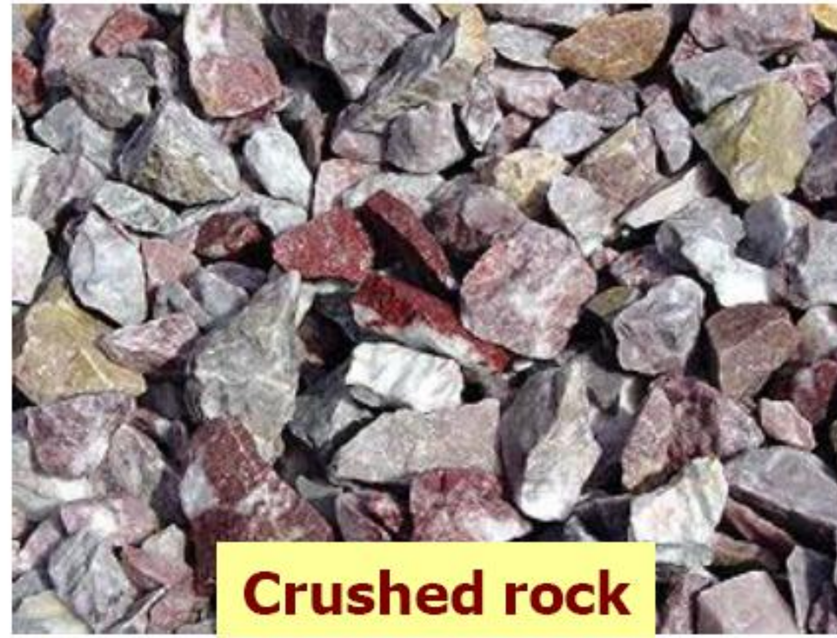
stone pylons for an old bridge

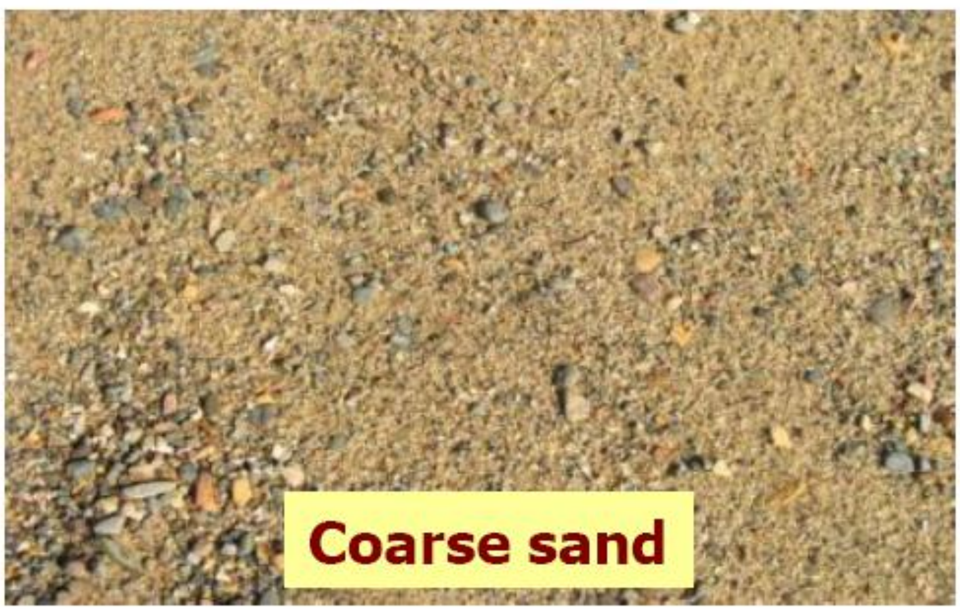
Church building

Machu Picchu – Incas structure

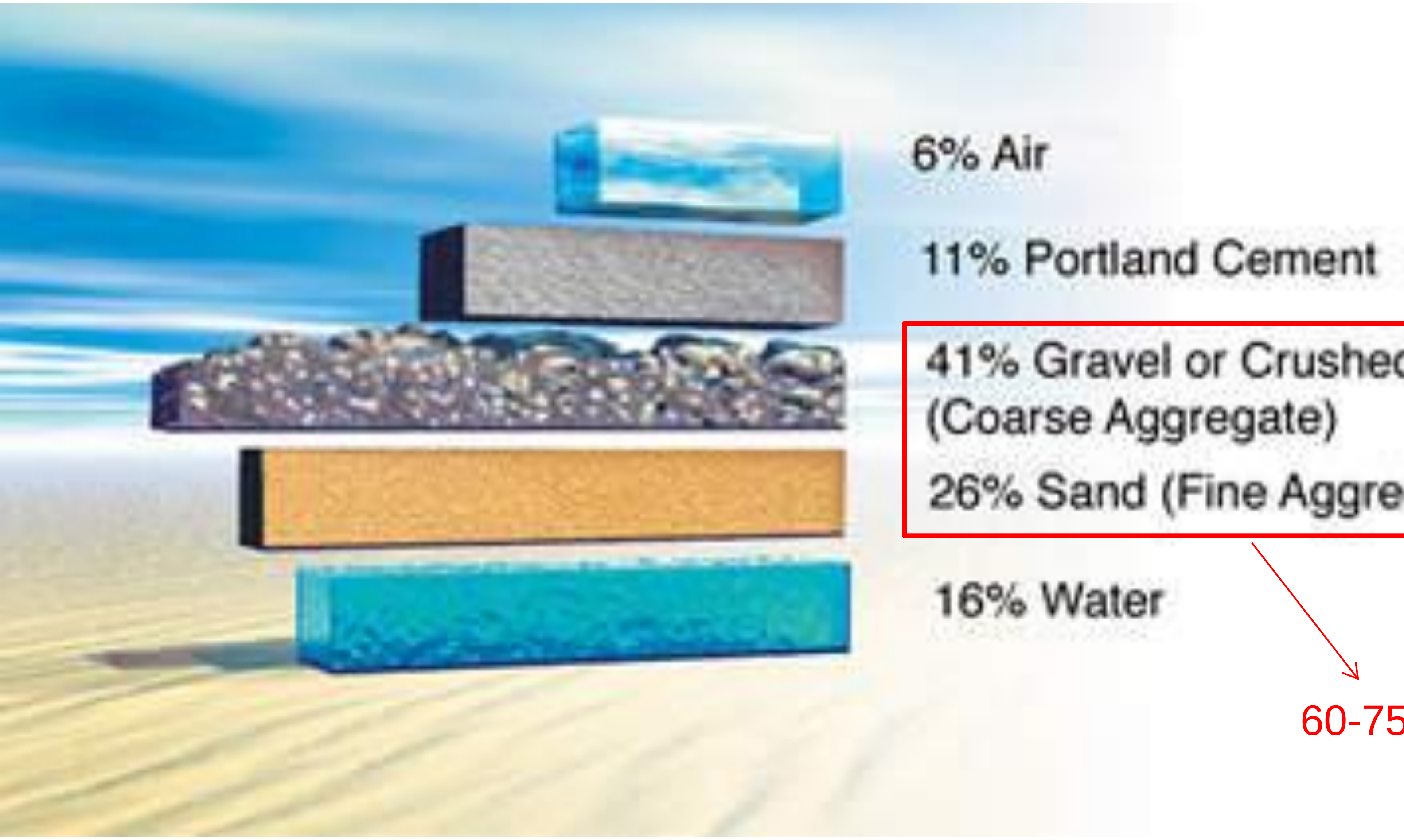
Taj Mahal - India

Aggregates for Concrete Mixes





Aggregate in Concrete



60-75%

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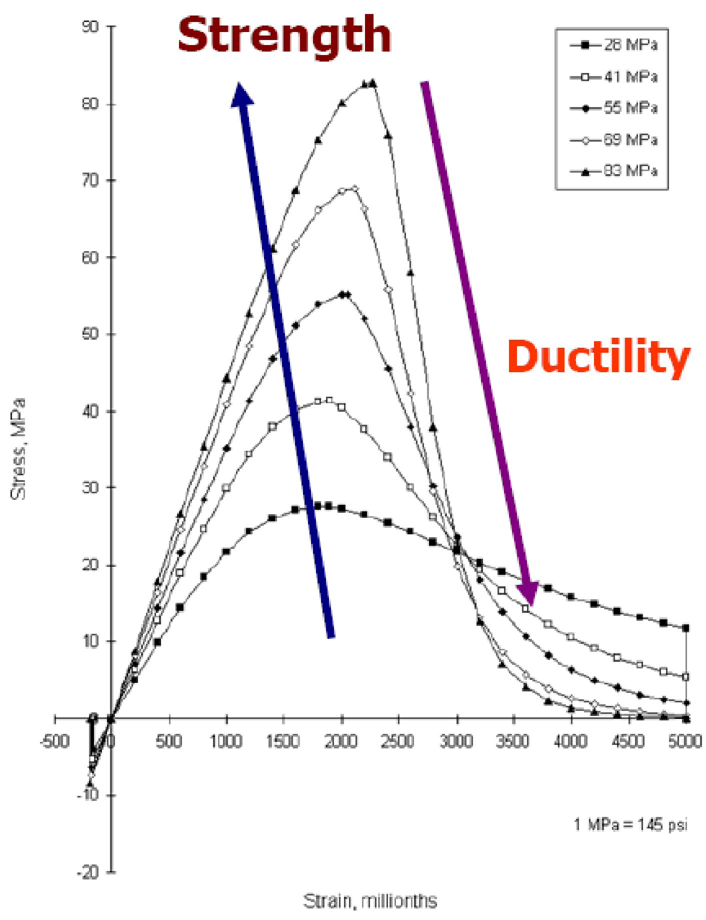
Source: PCA

Aggregate in Concrete

- Aggregate was originally viewed as an **inert** material. In fact, aggregate is not truly inert
- Aggregate is **cheaper** than cement
- Aggregate has higher **volume stability** and better **durability** than cement paste alone

Roles of Aggregates in Concrete

- **ECONOMICAL FILLER**
  - (60 - 80% BY VOLUME)
- **RESPONSIBLE FOR DUCTILITY**
  - AGGREGATE-CEMENT PASTE CRACKING
- **PROVIDES DIMENSIONAL STABILITY**
  - AGGREGATE – RIGID AND STRONG
  - CEMENT PASTE – RELATIVELY SOFT; SHRINKING, SWELL AND CREEP



Stress-strain curve for concrete

Concrete Properties VS Aggregate Properties

- Strength of concrete
  - Strength, Surface Texture, cleanness, Particle Shape, Maximum Size
- Shrinkage and Creep
  - Stiffness, Particle shape, Grading, Cleanness, Maximum size, Clay minerals
- Abrasion
  - Hardness

Natural strong aggregates (granite)

Lightweight weak aggregates (Expanded clay)

Classification of Aggregate: Size

- COARSE AGGREGATE
  - RIVER GRAVEL; BASALT, GRANITE, LIMESTONE, BLAST-FURANCE SLAG
- FINE AGGREGATE
  - RIVER SAND, QUARRY SAND, DUNE SAND, PIT SAND

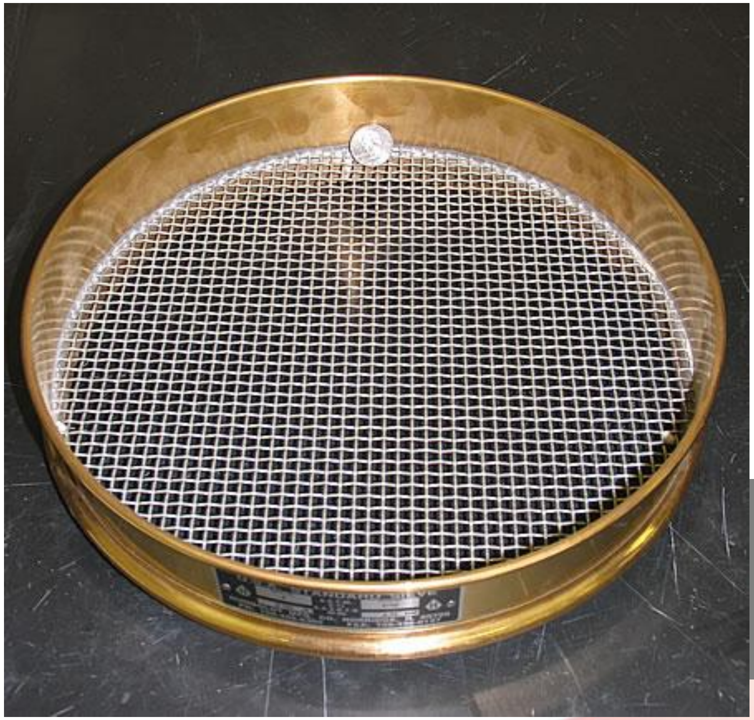
River gravel aggregate

Natural sand

Granite aggregate

Aggregate Sizes

- **Coarse** aggregate material retained on a sieve with 4.75 mm openings
- **Fine** aggregate material passing a sieve with 4.75 mm openings



- Maximum aggregate size – the largest sieve size that allows all the aggregates to pass
- Nominal maximum aggregate size – the first sieve to retain some aggregate, generally less than 10%

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Classification of Aggregate: Source

- **Natural**
  - Natural sand & gravel pits, river rock
  - Quarries (crushed)
  - Geological classification
    - Igneous: Basalt; Granite
    - Sedimentary: Limestone; Sandstone
    - Metamorphic: Marble; Quartzite

River gravel

Crushed rock

basalt

Limestone

granite

sandstone

Natural Aggregate Mining

Quarry

Sand from river deposit

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Crushed Aggregate Production

QUARRYING

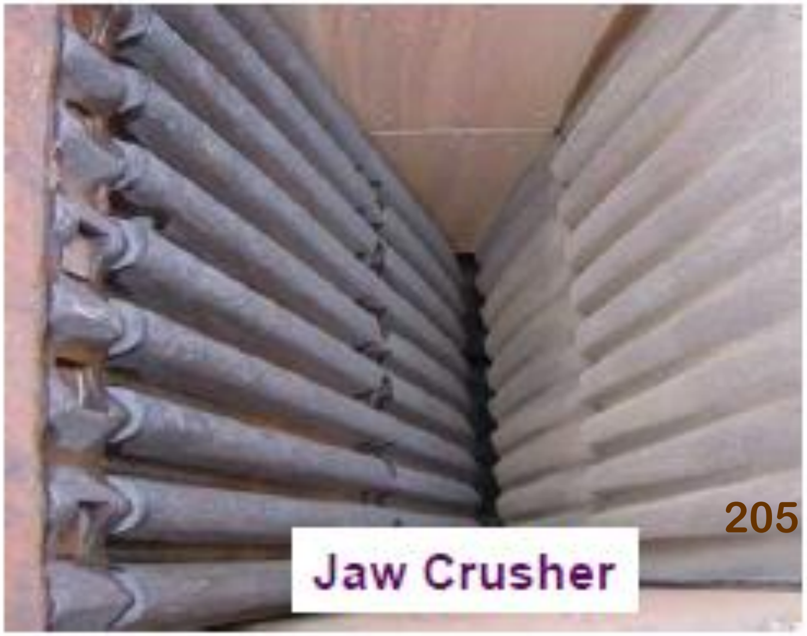
CRUSHING:

- PRIMARY : JAW CRUSHER
- SECONDARY: GYRATORY; ROLLER; IMPACT

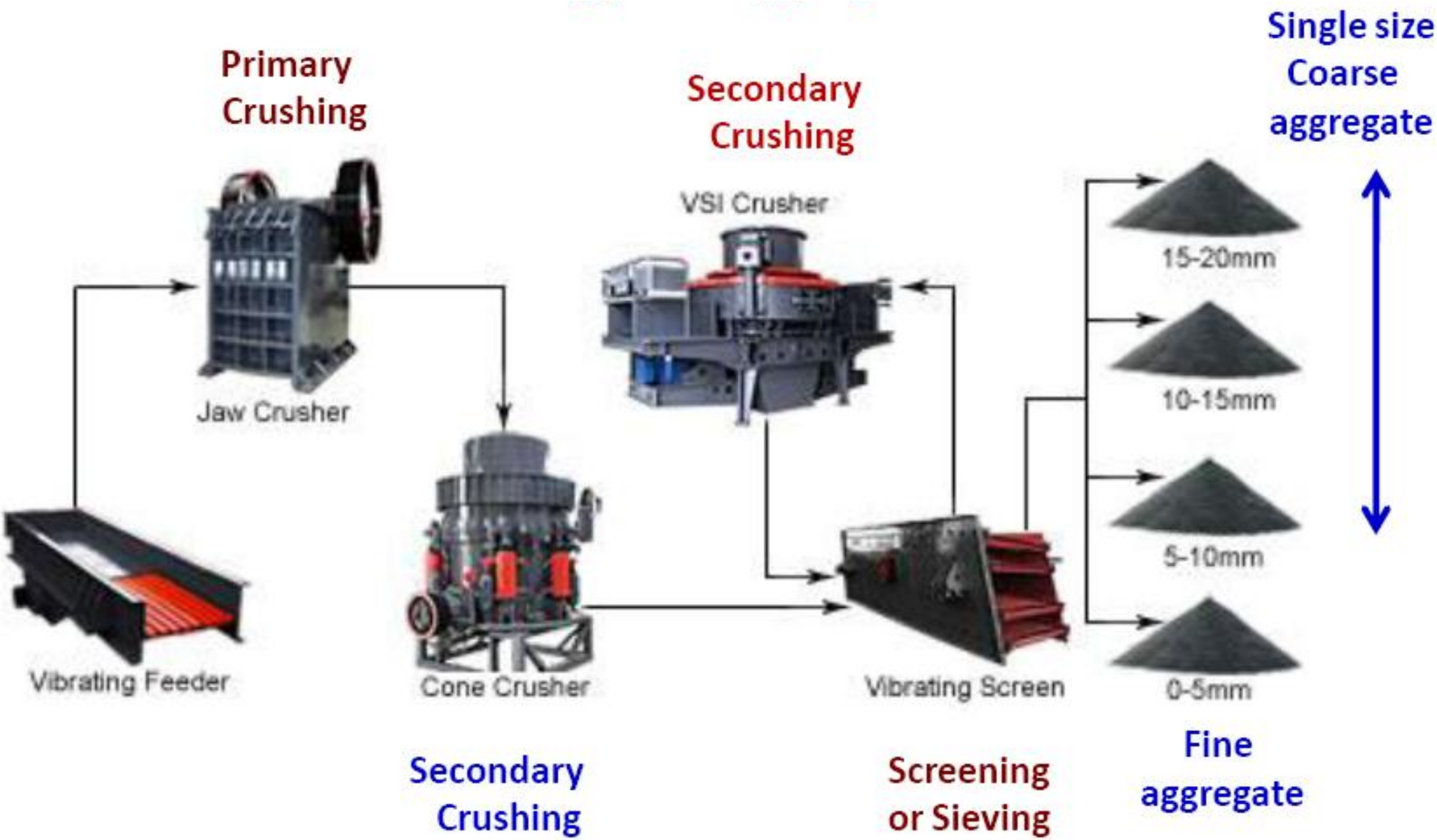
SCREENING

(SINGLE-SIZE PARTICLES)

- BY REJECTION
- BY SELECTION



Basalt Crushing Plant: Aggregate Production



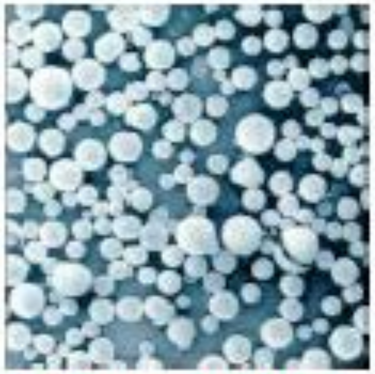
Classification of Aggregate: Source

Manufactured & recycled materials:

- Pulverized concrete & asphalt
- Steel mill slag
- Steel slugs
- Expanded shale
- Styrofoam


Recycled concrete aggregate


Expanded shale


Expanded polystyrene


Porous aggregate

Classification of Aggregate: Density

- Heavyweight aggregate
  - 4,000 – 8,500 kg/m^3
  - Provides effective and economical use of concrete for radiation shielding
- Normal
  - 2,300 – 2,500 kg/m^3
  - Suitable for normal concrete
- Lightweight aggregate
  - 350 – 1,100 kg/m^3
  - Concretes made with lightweight aggregates have good thermal insulation and fire resistance properties

Sampling Aggregates

- **Random** and **representative** of entire stockpile
  - Sample from entire width of conveyor belts at several locations
  - Sample from top, middle, and bottom of stockpile at several locations around stockpile diameter
  - Use larger sample for testing larger max. size
- Sample splitting or quartering
  - To reduce sample size from large stockpile to small 1-5 kg sample

Random sampling locations

Sample Splitter

Quartering

Aggregate Properties

- Aggregates' properties are used to determine if aggregate is suitable for a particular application and are needed for concrete mix design
  - Shape and texture
  - Soundness and durability
  - Hardness and abrasion resistance
  - Absorption
  - Specific gravity
  - Strength
  - Gradation
  - Cleanness and deleterious materials
  - Alkali-aggregate reactivity

Typical source properties

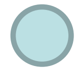
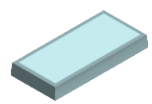
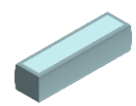
Needed for PCC mix design

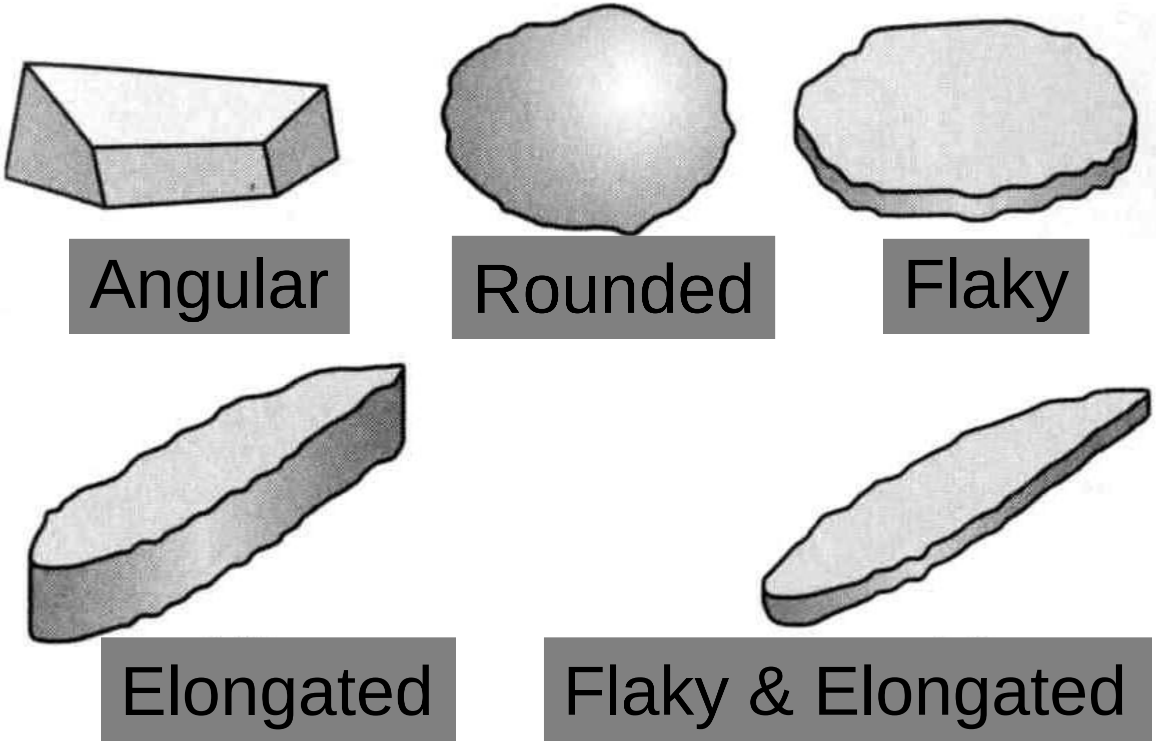
Aggregate Shape on Concrete Fresh Properties

- **HIGHER SURFACE TO VOLUME RATIO**
  - More cement paste required for coating aggregate surfaces
  - Less cement paste for lubrication and reduced workability of concrete
- **IRREGULAR PARTICLES**
  - Greater aggregate particles interaction
  - Reduced workability of concrete

Concrete is more workable with gravel aggregate compared to that with crushed aggregate, for a given mix proportion.

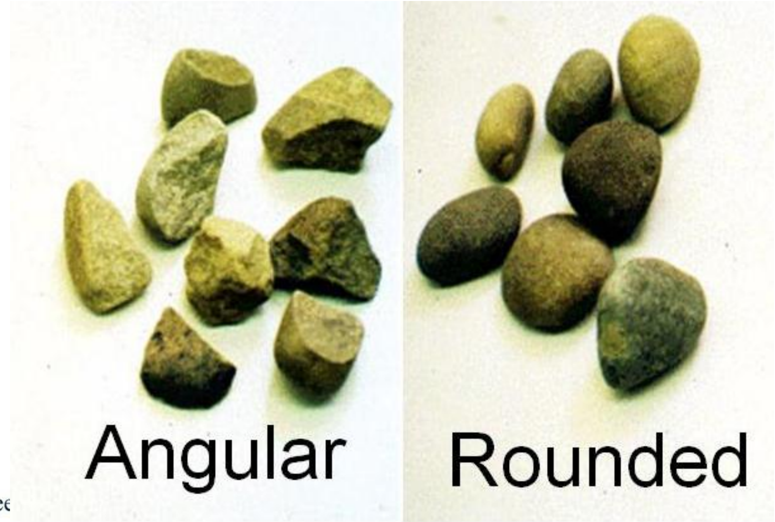
Particle Shapes of Aggregates

- **Rounded**: river gravel 
  - Better packing, lowest voids ratio 33%
  - Less interlocking between particles
- **Angular**: crushed rock 
  - Loose packing, higher voids ratio
  - Interlocking between particles is good
- **Flaky**: small thickness 
- **Elongated**: length considerable 
- **Flaky & elongated**: thin & long
  - Bad for concrete durability because of easy breakage and difficulty compacting
  - Should be restricted to 10-15% in concrete design


Angular
Rounded
Flaky
Elongated
Flaky & Elongated

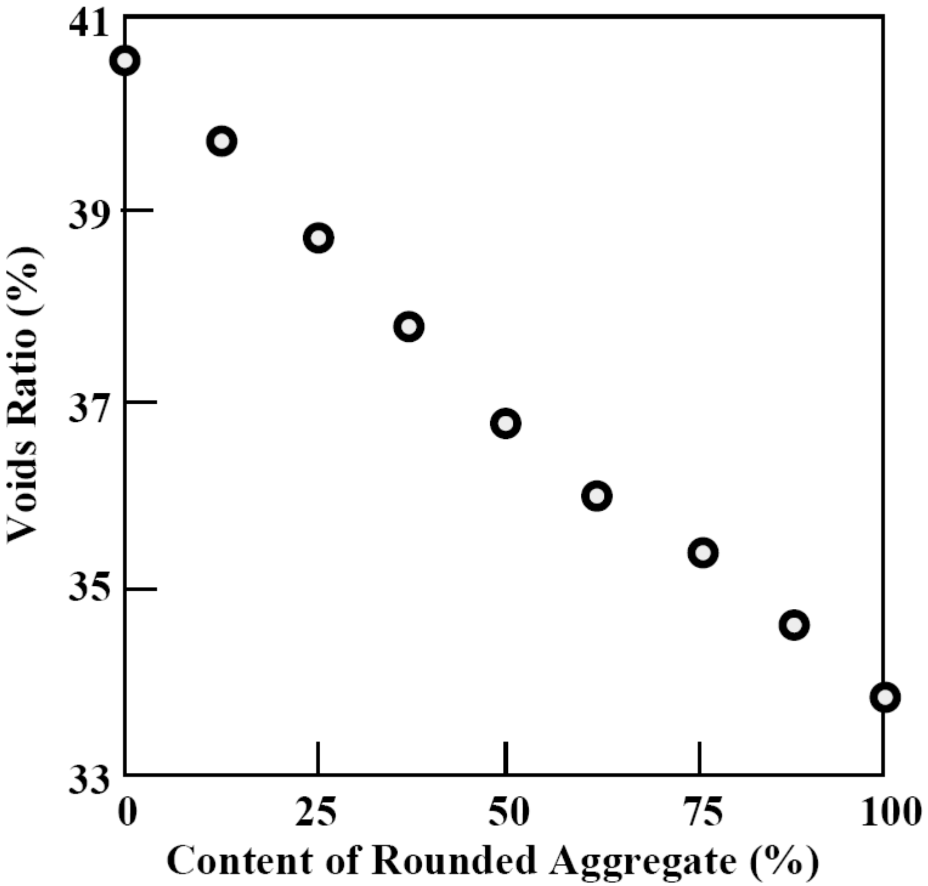

Flat Particles


Elongated Particles


Angular
Rounded

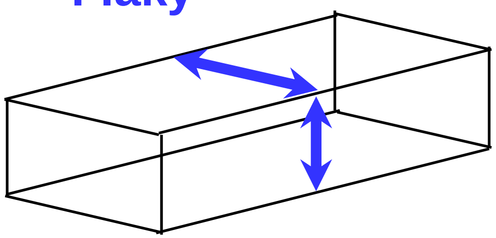
Effect of Particle Shape on Voids

- Sample consisted of mixture of two aggregates
  - Angular, and
  - Rounded
- Percentage of voids decreases with increasing rounded particles

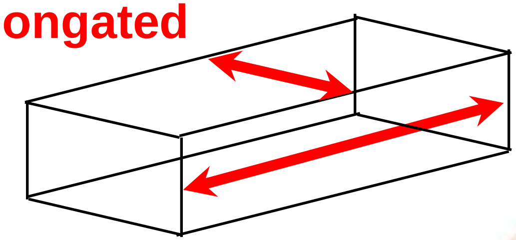


Particle Shape Characterization

- **Angularity number**
  - Voids ratio – 33
  - Higher the number, more angular the aggregate
  - The range for practical aggregate is between 0 (rounded) and 11 (angular)
- Particle is **flaky** if its smallest dimension (thickness) is less than 60% of the "middle" dimension



- Particle is **elongated** if its largest dimension (length) is more than 1.8 times of the "middle" dimension



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Flakiness Gauge:

Length Gauge:

Flaky Particles: Thickness less than 60% of nominal size

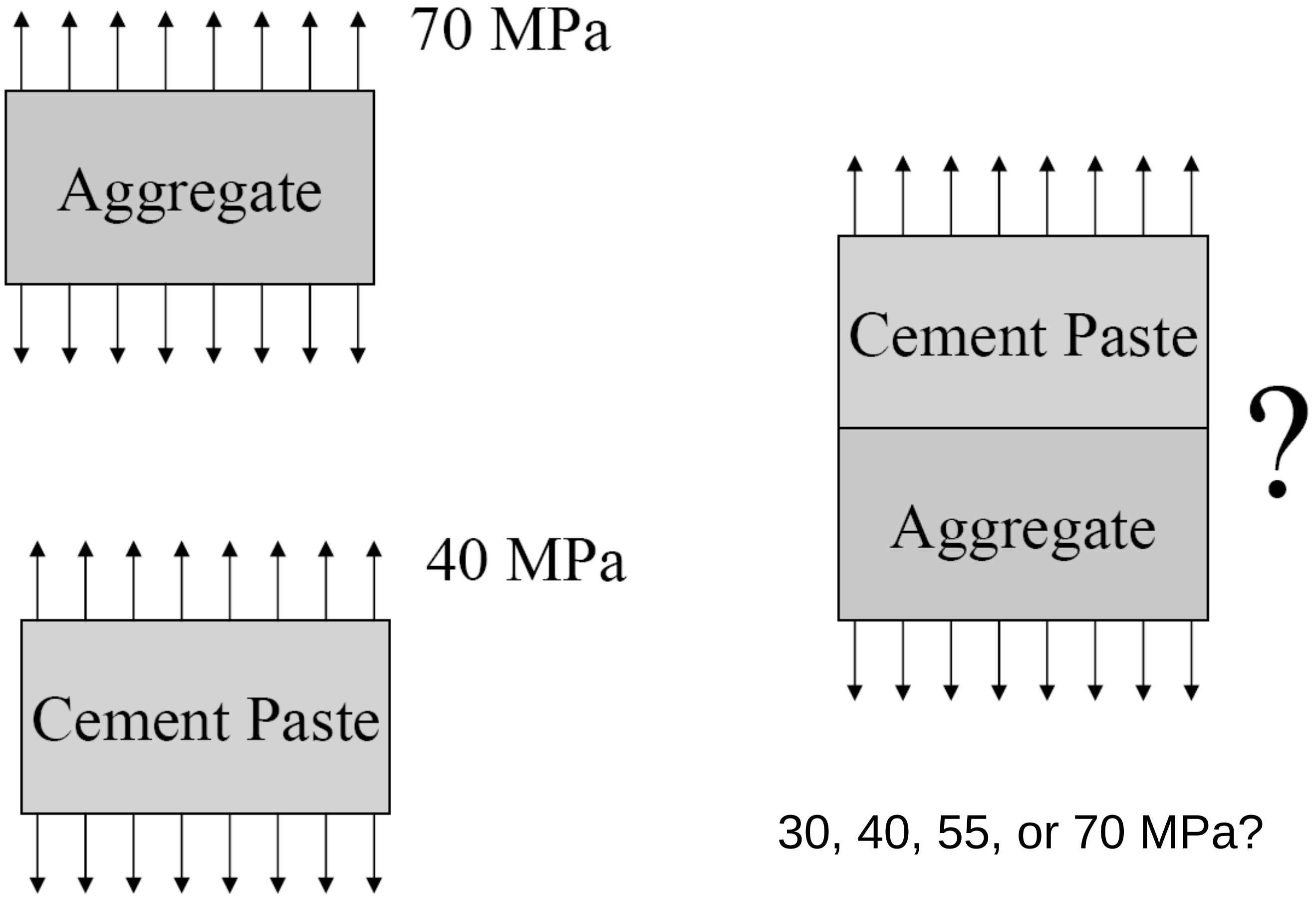
Elongated Particles: Length more than 1.80 times the nominal size

Surface Texture of Aggregate

- GLASSY:
  Volcanic Origin
- SMOOTH:
  River gravel
- GRANULAR:
  Sandstone
- ROUGH:
  Crushed
- CRYSTALLINE:
  Quartz
- HONEYCOMBED:
  Air-cooled slag

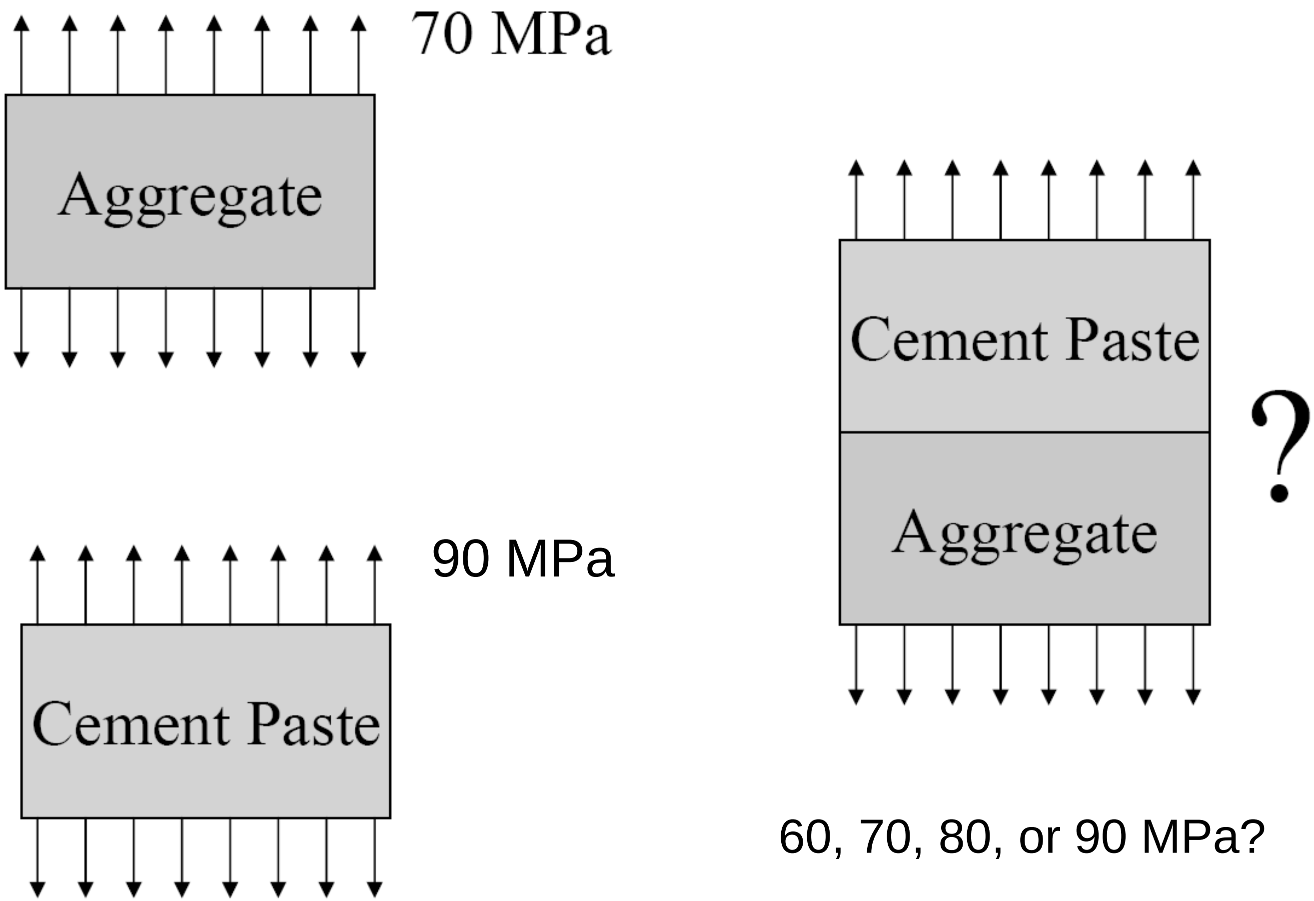
- PARENT ROCK
  - Hardness
  - Grain size
  - Pore structure
- DEGREE OF WEATHERING
- INCREASE ROUGHNESS
  - Reduces workability of concrete
  - Improves aggregate-paste bond strength

What is the Concrete Strength?



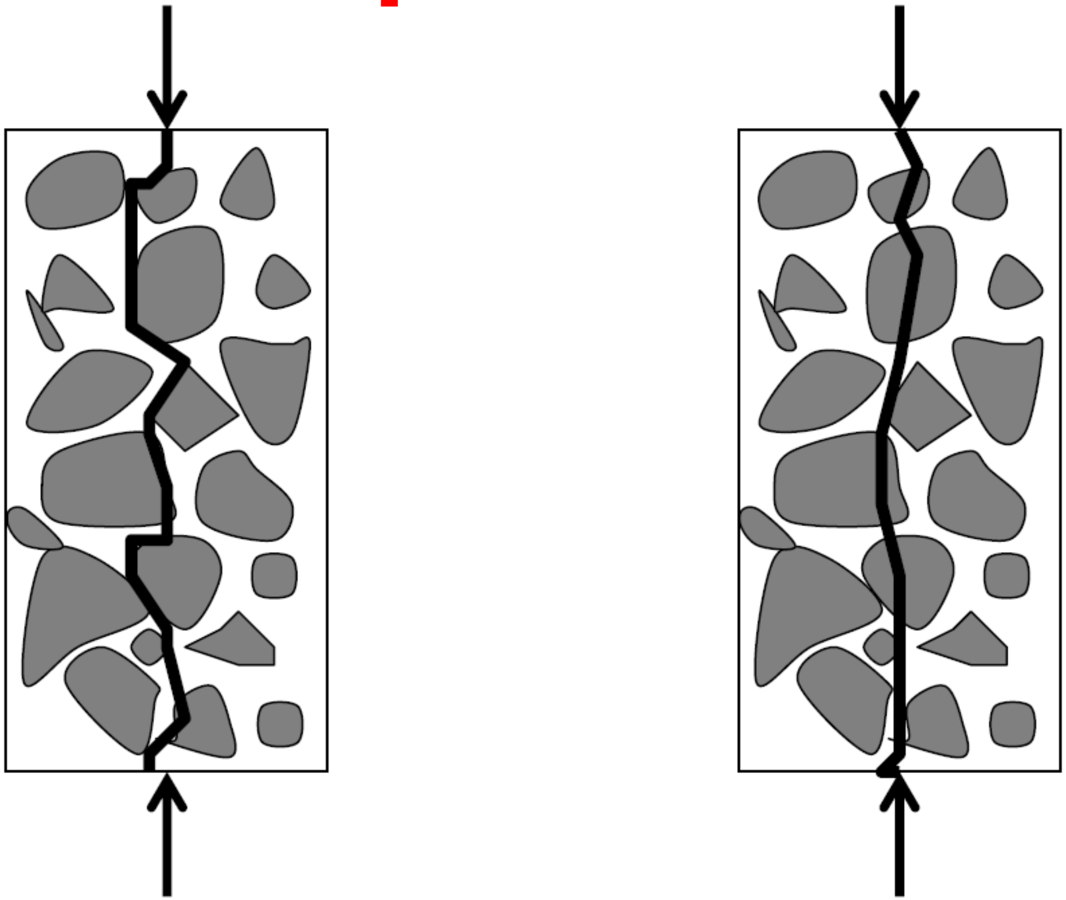
30, 40, 55, or 70 MPa?

What is the Concrete Strength?



60, 70, 80, or 90 MPa?

Failure Mode of Concrete in Compression



Normal Strength Concrete

High Strength Concrete

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Concrete Strength

- Concrete strength is dominated by the weakest component either the paste, aggregate, or interface
- For normal concrete, strength is dependent on bond between paste and aggregate, that is the interface
- For high strength concrete, strength may dependent on aggregate

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Aggregate Strength

- Strong aggregates alone cannot make strong concrete but strong aggregate are an essential requirement
- Aggregate strength is important in high-strength concrete and in the surface course on heavily traveled pavements

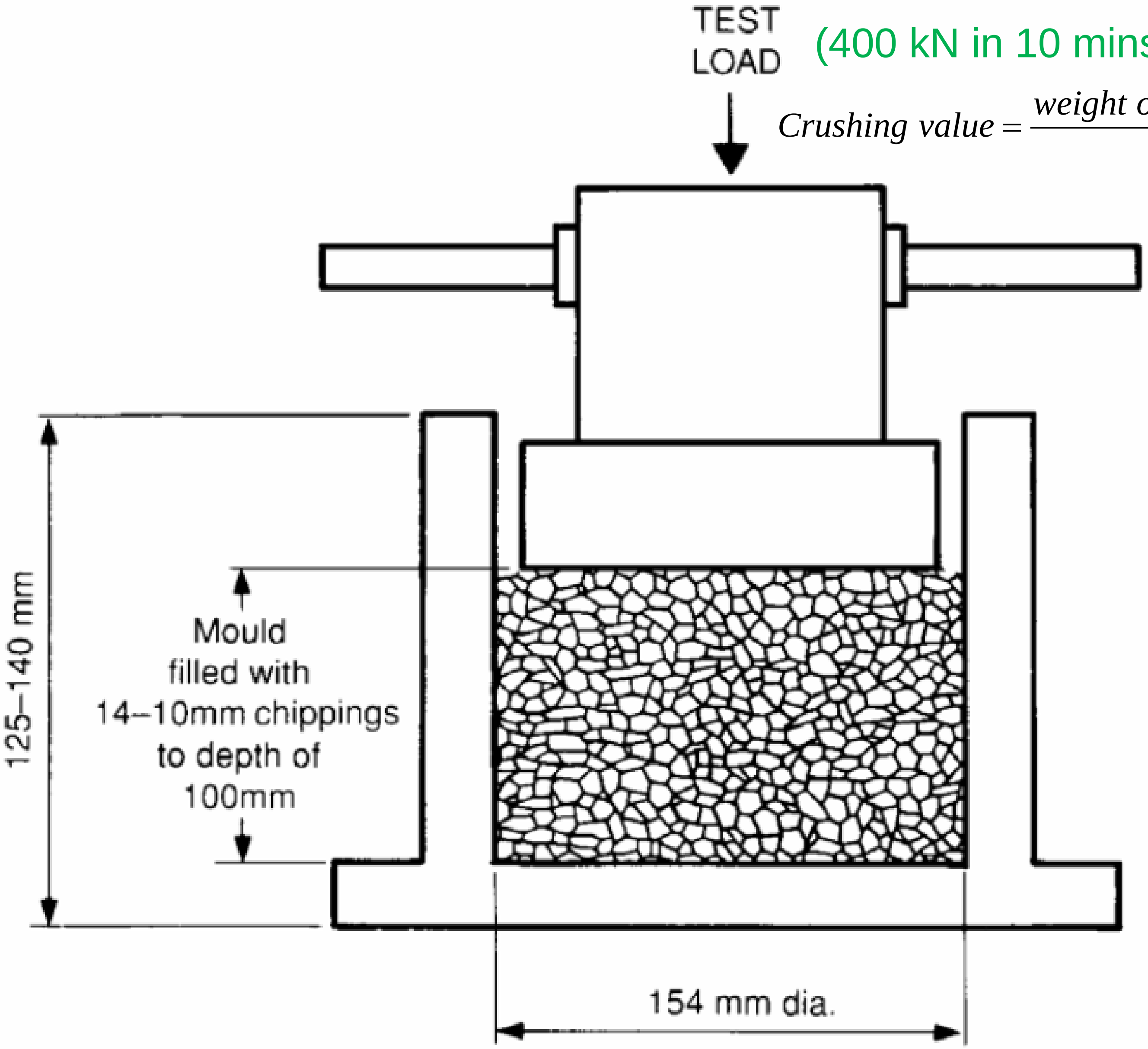
Strength of Aggregate

- It is difficult to test on single aggregate particle
- Unconfined compressive strength test of parent rock samples
  - It measures quality of parent rock rather than quality of aggregate as used in concrete
  - Result is affected by the presence of planes of weakness in the rock which may not be significant once the rock is comminuted to the size used in concrete
  - Rarely used

Crushing Test of Bulk Aggregate

(400 kN in 10 mins)

$$Crushing\ value = \frac{weight\ of\ material\ passing\ 2.36\ mm\ sieve}{total\ weight\ of\ sample}$$



For normal aggregate

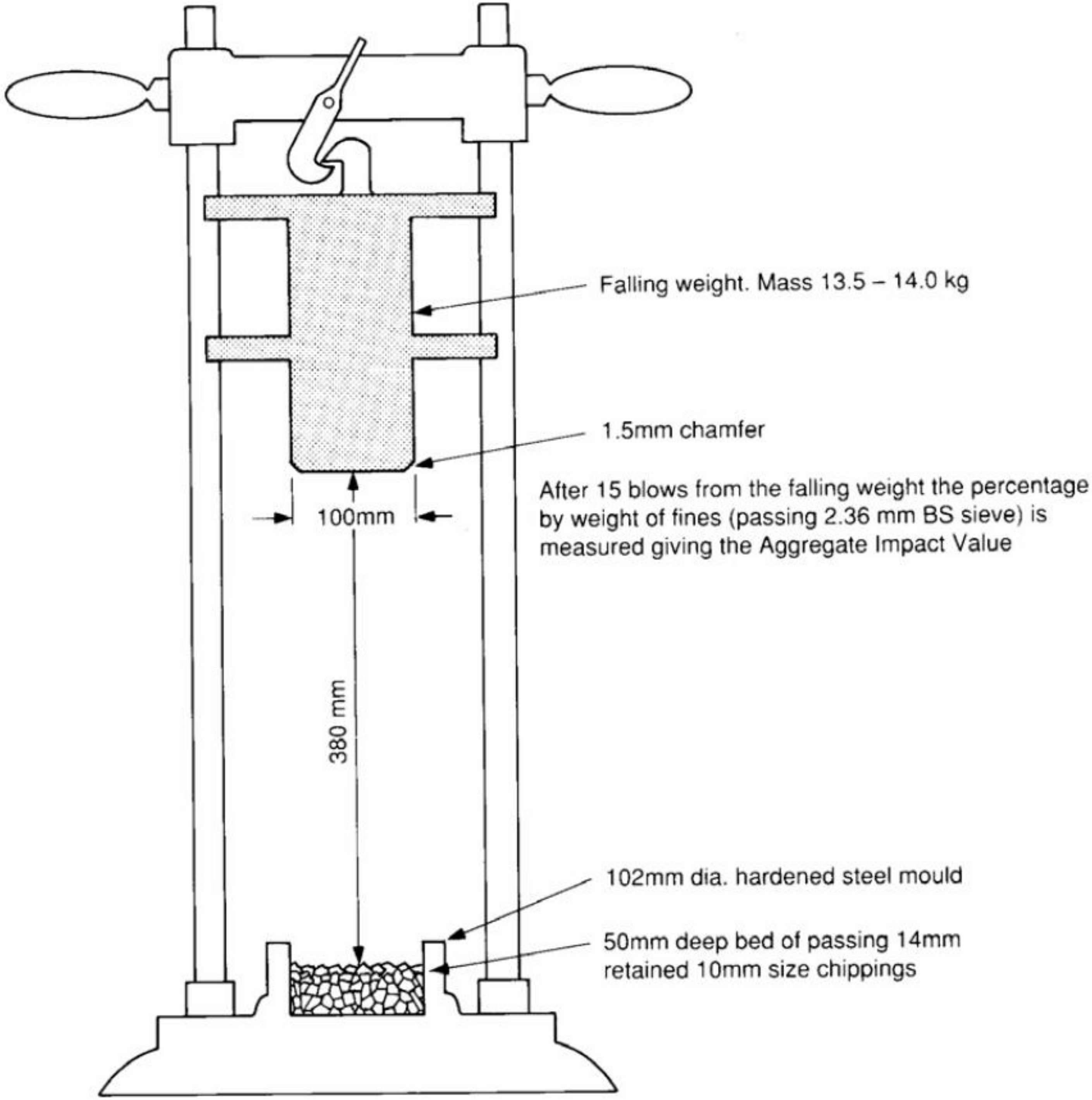
TEST LOAD

Aggregate Crushing Test
40 tonnes

10% Fines Test
A series of test loads between 40 tonnes and 1 tonne to interpolate the load which produces 10% of fines passing a 2.36mm sieve

For weak aggregate

Impact Value of Bulk Aggregate



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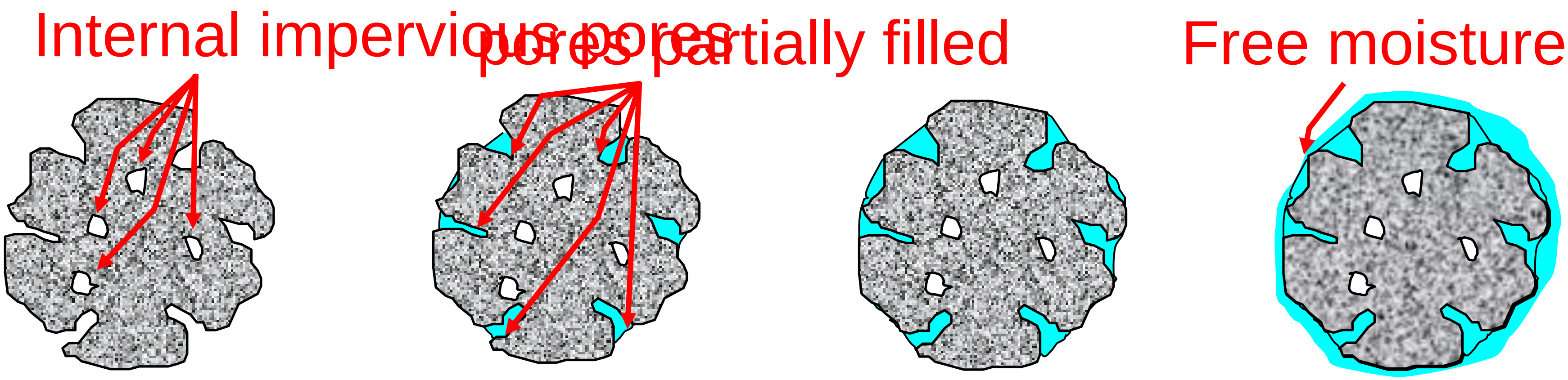
Absorption



Bone/oven dry – dried in oven to constant mass	Air dry – moisture condition state undefined	Saturated surface dry – moisture condition state undefined	Moist – moisture condition state undefined
W_{OD}	W_m	$W_{SSD}=W_{OD}+W_p$	W_m
	Moisture content	Absorption	Moisture content
	$M = \frac{W_m - W_{OD}}{W_{OD}}$	$\mathbf{A} = \frac{W_{SSD} - W_{OD}}{W_{OD}}$	$M = \frac{W_m - W_{OD}}{W_{OD}}$

Absorption is the moisture content when the aggregates are in the SSD condition

Free moisture is the moisture content in excess of the SSD condition.

Percent free moisture = M - A

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Important for proportioning concrete
negative free moisture – aggregates will absorb water
positive free moisture – aggregates will release water

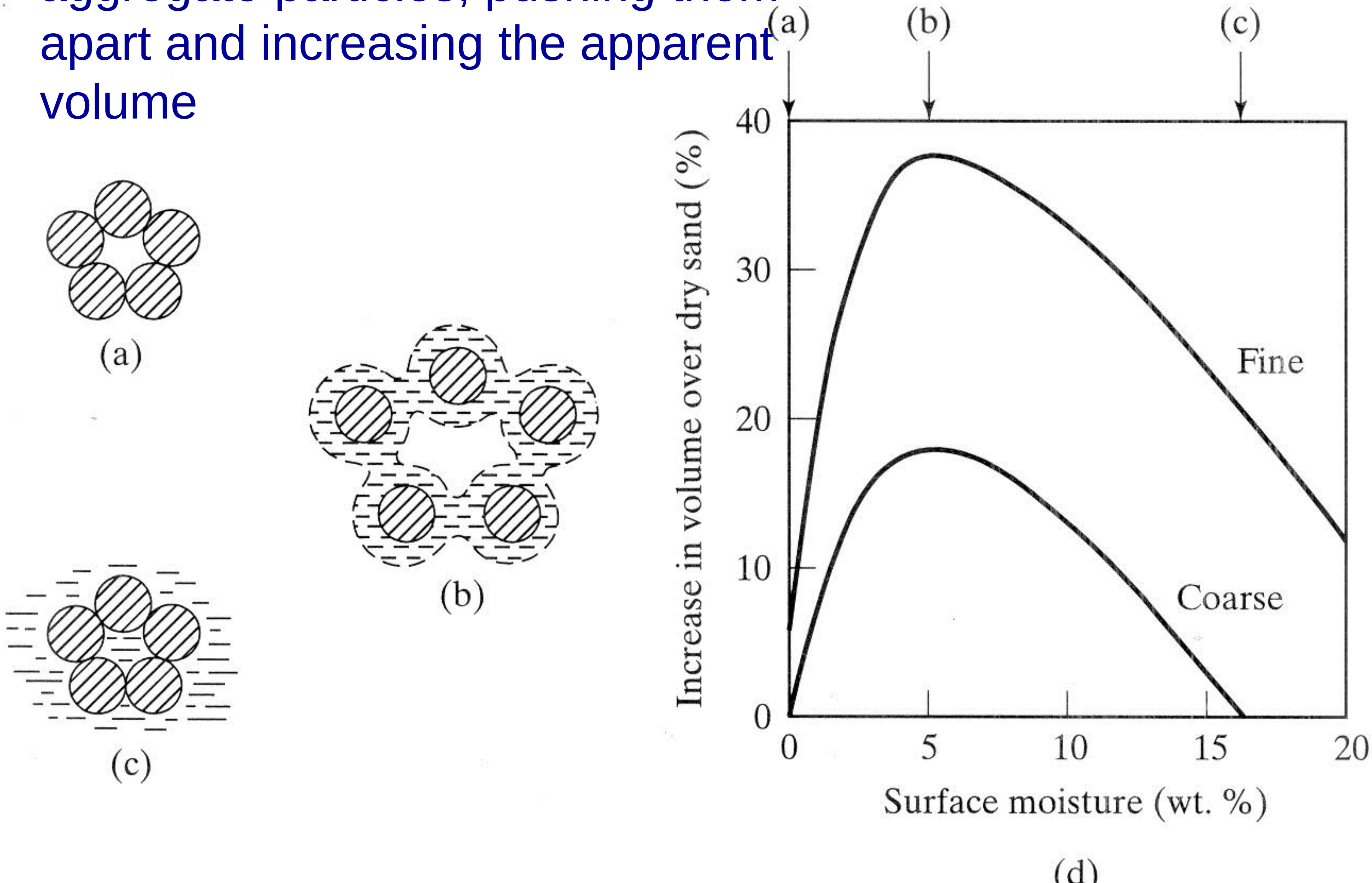
Example

- A sample of sand has the following properties:
  - Moist mass = 625.2 g
  - Oven dry mass = 589.9 g
  - Absorption = 1.6%

Determine: (a) total moisture content, and (b) free moisture content.

Bulking

- Formation of meniscus creates thicker films of water between aggregate particles, pushing them apart and increasing the apparent volume



Bulking

- Bulking can cause substantial errors in mix proportioning by volume
- For that reason, aggregate is batched by weight
- Coarse aggregates show much less bulking since particle size is large compared to thickness of water film and effect of meniscus formation is slight

Specific Gravity

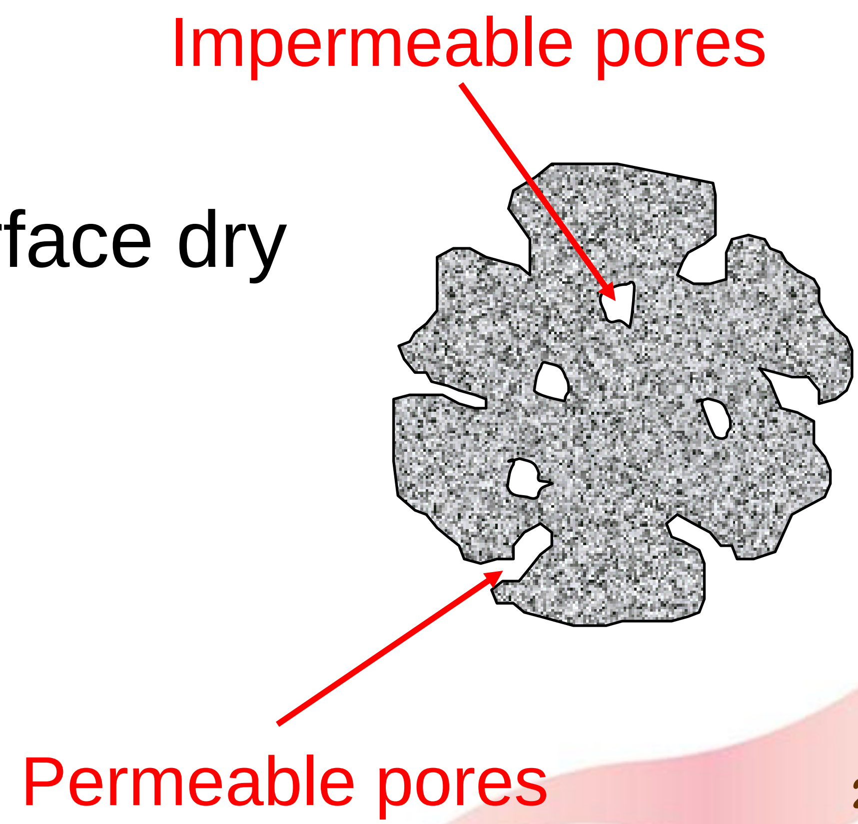
- Knowing density of aggregate is required in concrete **mix design** to establish weight-volume relationships
- Density is expressed as specific gravity
- Specific gravity (SG) is a dimensionless ratio relating density of aggregate to that of water

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

Density of water @ 4°C is 1000 kg/m^3

Effects of Voids in Aggregates

- Permeable pores in aggregates create multiple definitions of specific gravity
  - Apparent, ASG
  - Bulk-dry, BSG_{OD}
  - Bulk-saturated surface dry, BSG_{SSD}



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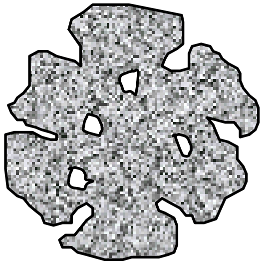
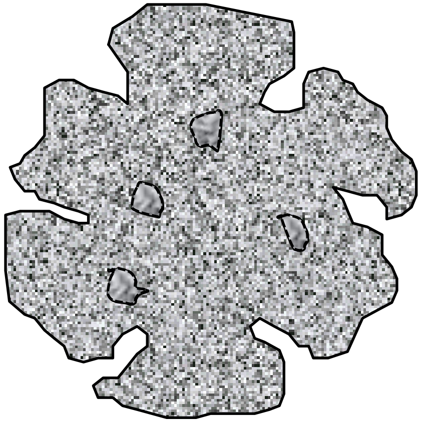
Apparent Specific Gravity



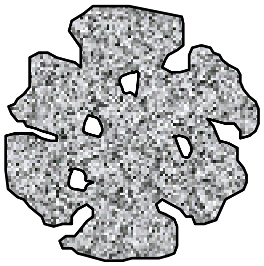
$$ASG = \frac{Dry\ weigth\ of\ \ Agg.}{Vol.of\ \ Agg. + impermeable\ \ pores} \bullet \frac{1}{\rho_w}$$



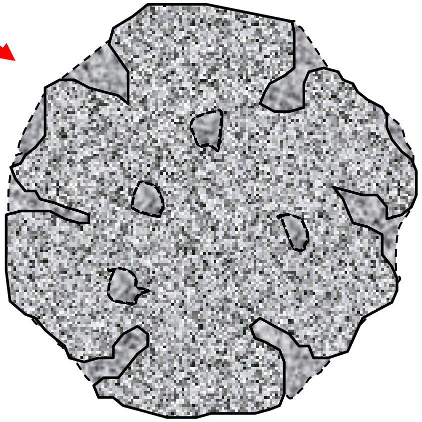
$$= \frac{W_{OD}}{(V_s + V_i)\rho_w}$$

Solid Impermeable pore

Bulk Specific Gravity, Oven Dry



$$BSG_{OD} = \frac{Dry\ weight\ of\ aggregate}{Vol.\ of\ Agg. + both\ permeable\ and\ impermeable\ pores} \bullet \frac{1}{\rho_w}$$



$$= \frac{W_{OD}}{(V_s + V_i + V_p)\rho_w}$$

$$= \frac{W_{OD}}{V_{SSD}\rho_w}$$

Permeable pore

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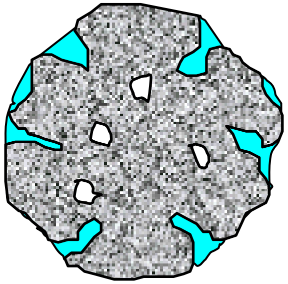
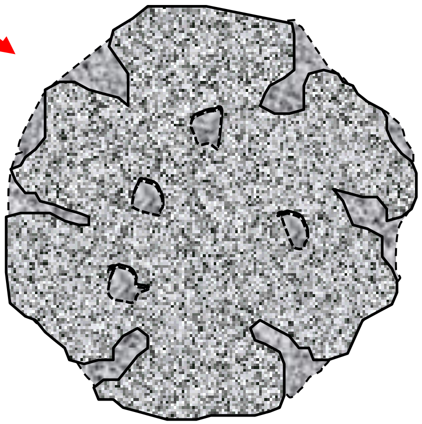
Bulk Specific Gravity, SSD



$$BSG_{SSD} = \frac{SSD\ weight\ of\ aggregate}{Vol.\ of\ Agg. + both\ permeable\ and\ impermeable\ pores} \bullet \frac{1}{\rho_w}$$



$$= \frac{W_{OD} + W_p}{(V_s + V_i + V_p)\rho_w}$$

$$= \frac{W_{SSD}}{V_{SSD}\rho_w}$$

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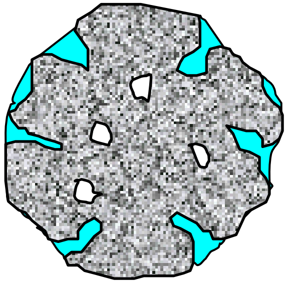
BSG_{SSD} for Concrete Mix Design

- BSG_{SSD} is often used as the reference state for mix design purpose



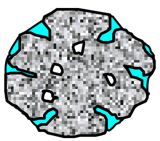
  - Water in permeable pores of aggregate does not participate in cement hydration
  - Effective volume that SSD aggregate occupies in concrete include permeable pores
  - If non-SSD aggregates are used in producing concrete based on BSG_{SSD} concrete mix design, the resulting water-to-cement ratio is different than the intended design
  - If non-SSD aggregates are expected to be used, corrections should to be taken into account [Refer to chapter on mix design]

Determination of SG and Absorption for Coarse Aggregate (ASTM C127)

- Sample of a coarse aggregate is soaked for 24 hours and rolled in a large absorbent cloth to remove all visible surface moisture to achieve the SSD condition
- Weighed suspended in water, W_w
- The sample is then dried to SSD condition again and weighed, W_{SSD}
- Finally, the sample is bond dried and weighed, W_{OD}

http://youtu.be/NlN3OgiMcms

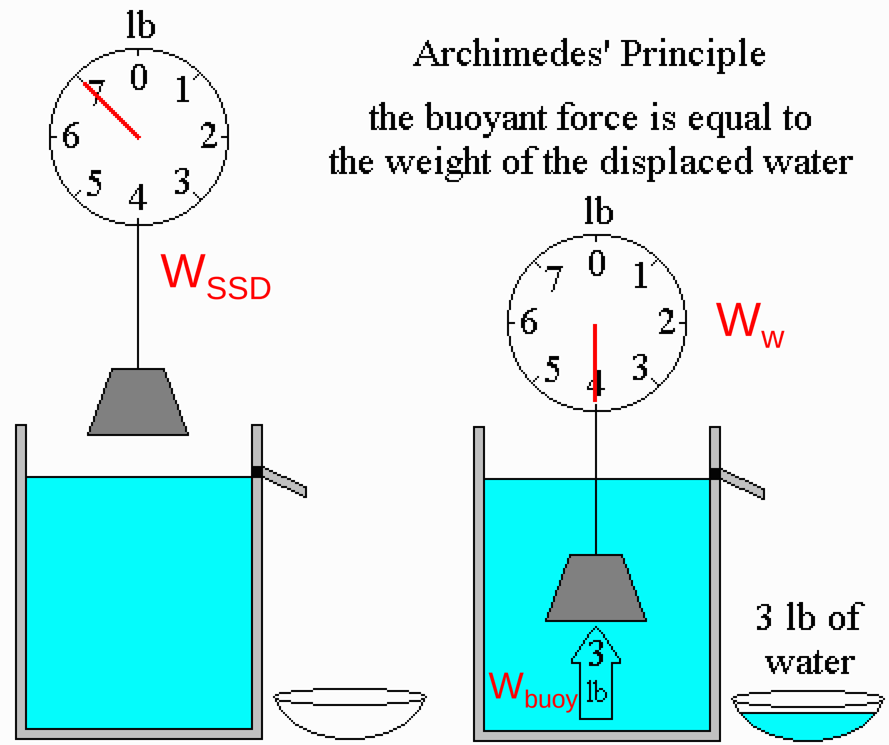
$$W_{buoy} = V_{SSD}\rho_w$$



$$W_w = W_{SSD} - W_{buoy} = W_{SSD} - V_{SSD}\rho_w$$

$$V_{SSD}\rho_w = W_{SSD} - W_w$$

$$\therefore BSG_{SSD} = \frac{W_{SSD}}{V_{SSD}\rho_w} = \frac{W_{SSD}}{W_{SSD} - W_w}$$



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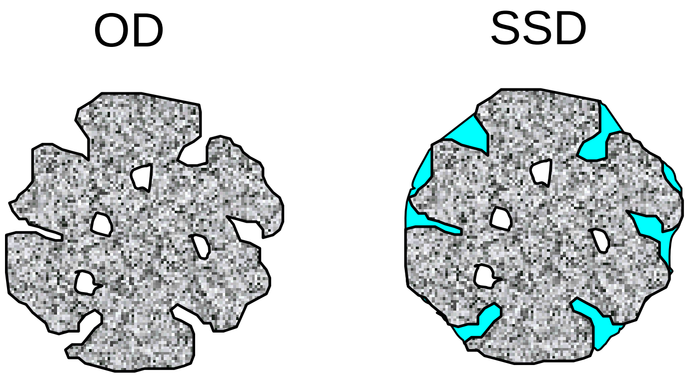
$$BSG_{SSD} = \frac{W_{SSD}}{V_{SSD}\rho_w} = \frac{W_{SSD}}{W_{SSD} - W_w}$$

$$BSG_{OD} = \frac{W_{OD}}{V_{SSD}\rho_w} = \frac{W_{OD}}{W_{SSD} - W_w}$$

$$ASG = \frac{W_{OD}}{(V_{SSD} - V_p)\rho_w} = \frac{W_{OD}}{(W_{SSD} - W_w) - W_p} = \frac{W_{OD}}{W_{OD} - W_w}$$

$$Absorption\,(\%) = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100$$



Example

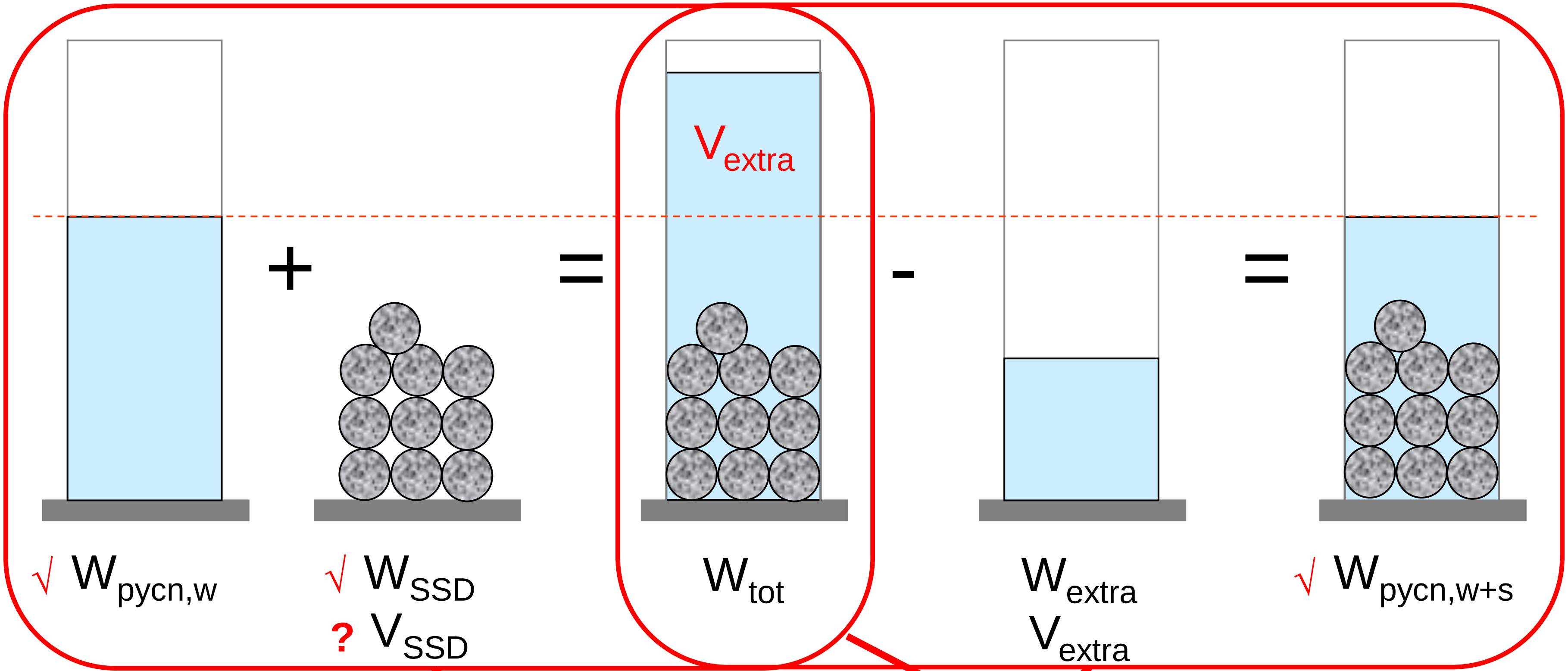
- A sample of coarse aggregate weighs 5360 g when oven dry, 5455 g when saturated surface-dry, and 3338 g submerged. What is the bulk specific gravity (SSD)? What is absorption capacity?

Example

- A 1050-g sample from the stockpile of the same aggregate as in the previous example weighted 637 g when immersed in water. Calculate the free moisture content of the aggregate in the stockpile.

Determination of SG and Absorption for Fine Aggregate (ASTM C128)

- Sample of a fine aggregate is soaked for 24 hours to achieve SSD condition
- A 500-g SSD sample (W_{SSD}) is planed in **pycnometer**, a constant volume flask
- Water is added to the constant volume mark on the pycnometer and weighed, $W_{pyc,w+s}$
- Remove the sample and water from the pycnometer and re-fill the pycnometer with water only to the same volume mark and weighed, $W_{pyc,w}$
- The sample is then bond dried and weighed, W_{OD}



$$V_{SSD} = V_{extra}$$

$$V_{SSD}\rho_w = V_{extra}\rho_w = W_{extra} = W_{tot} - W_{pycn,w+s} = W_{pycn,w} + W_{SSDs} - W_{pycn,w+s}$$

$$\therefore BSG_{SSD} = \frac{W_{SSD}}{V_{SSD}\rho_w} = \frac{W_{SSD}}{W_{pycn,w} + W_{SSD} - W_{pycn,w+s}}$$

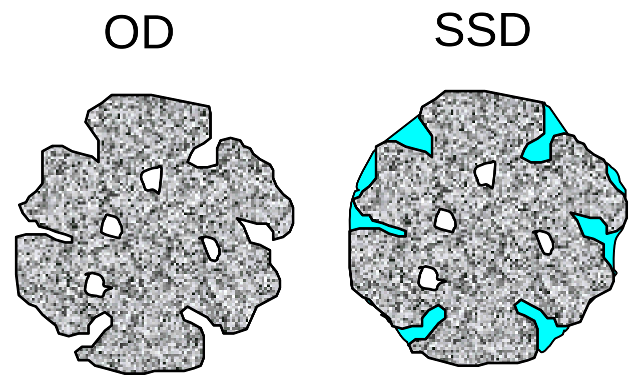
$$BSG_{SSD} = \frac{W_{SSD}}{V_{SSD}\rho_w} = \frac{W_{SSD}}{W_{pycn,w} + W_{SSD} - W_{pycn,w+s}}$$

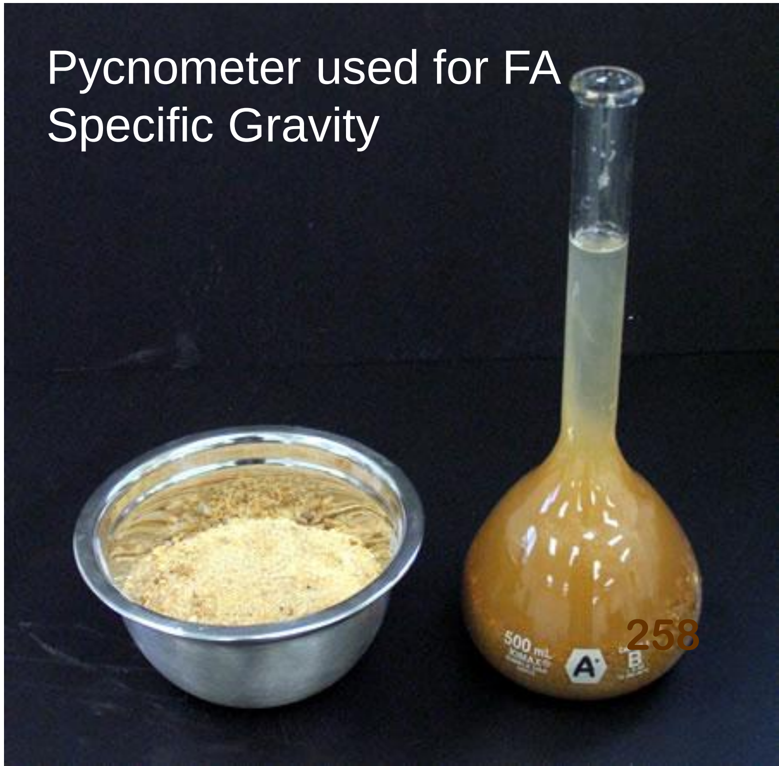
$$BSG_{OD} = \frac{W_{OD}}{V_{SSD}\rho_w} = \frac{W_{OD}}{W_{pycn,w} + W_{SSD} - W_{pycn,w+s}}$$

$$ASG = \frac{W_{OD}}{(V_{SSD} - V_p)\rho_w} = \frac{W_{OD}}{(W_{pycn,w} + W_{SSD} - W_{pycn,w+s}) - W_p}$$

$$= \frac{W_{OD}}{W_{pycn,w} + W_{OD} - W_{pycn,w+s}}$$

$$Absorption\,(\%) = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100$$





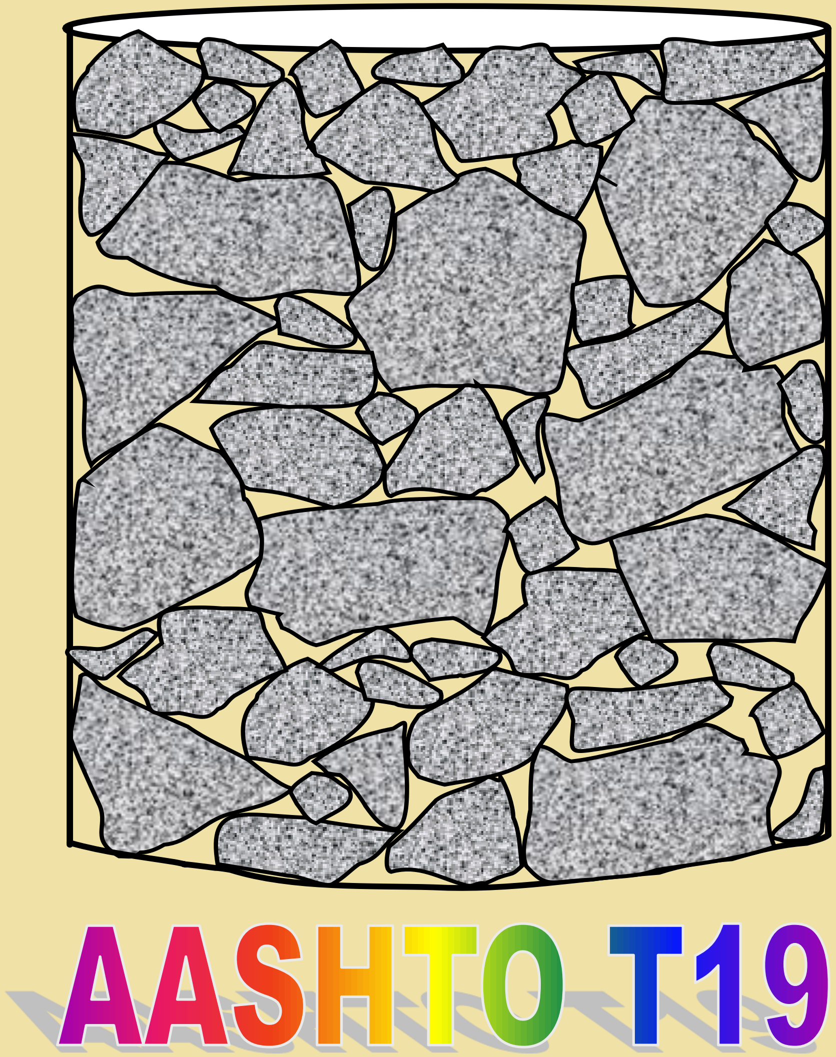
Example

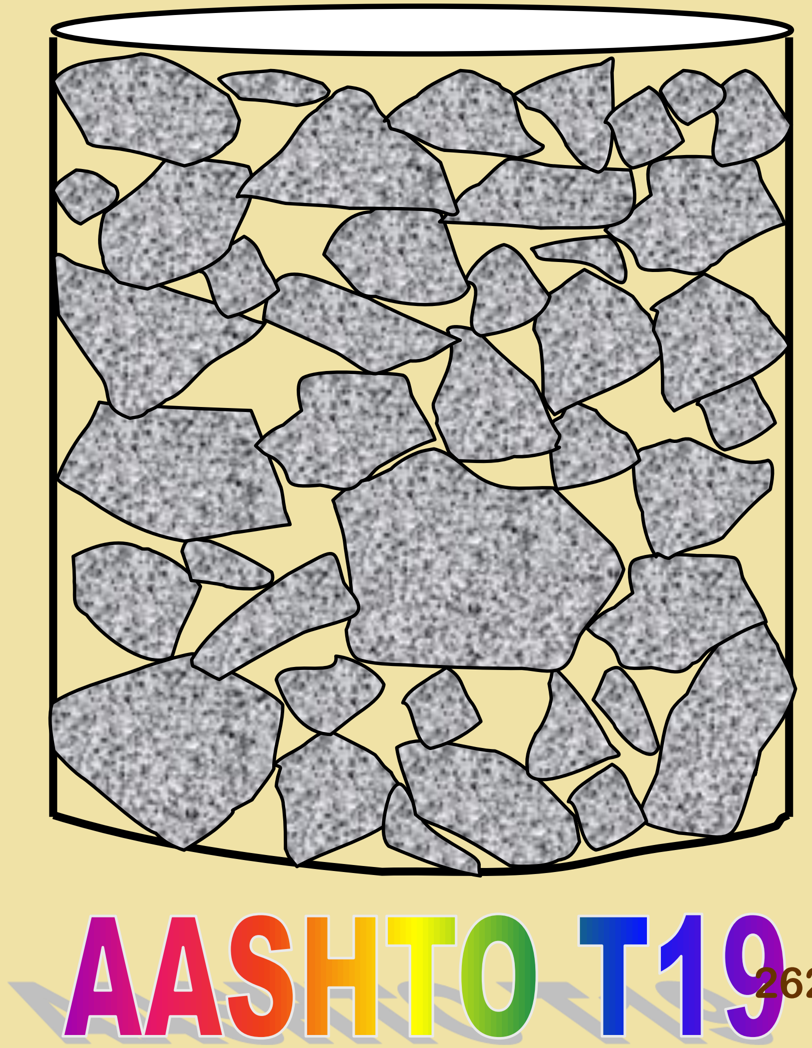
- A sample of fine aggregate weights 500 g when SSD and 492.6 g when OD. A flask weighing 35.3 g empty weighs 537.6 g when filled with water and 846.2 g when filled with the aggregate sample and water. What are the bulk specific gravity (SSD) and absorption capacity?

Bulk Unit Weight & Voids in Aggregates

- Sometimes we need to know the mass or weight of aggregate required to fill a volume, e.g. the volume of coarse aggregate in a cubic yard of concrete, for the proportioning of concrete
- **Bulk unit weight** or bulk density is the weight of aggregate required to fill a "unit" volume. Typical units are cubic meters and cubic feet
- **Voids in aggregate** is the percentage of voids between aggregate particles

Test on Aggregate Bulk Unit Weight (ASTM C29)





Example

Coarse aggregate is placed in a rigid bucket and rodded with a tamping rod to determine its unit weight. The following data are obtained:

- Volume of bucket = 0.01 m^3
- Weight of empty bucket = 8.4 kg
- Weight of bucket filled with dry rodded coarse aggregate = 25.4 kg

(a) Calculate the dry-rodded unit weight

(b) If the oven-dried bulk specific gravity of the aggregate is 2.63, calculate the percent voids in the aggregate

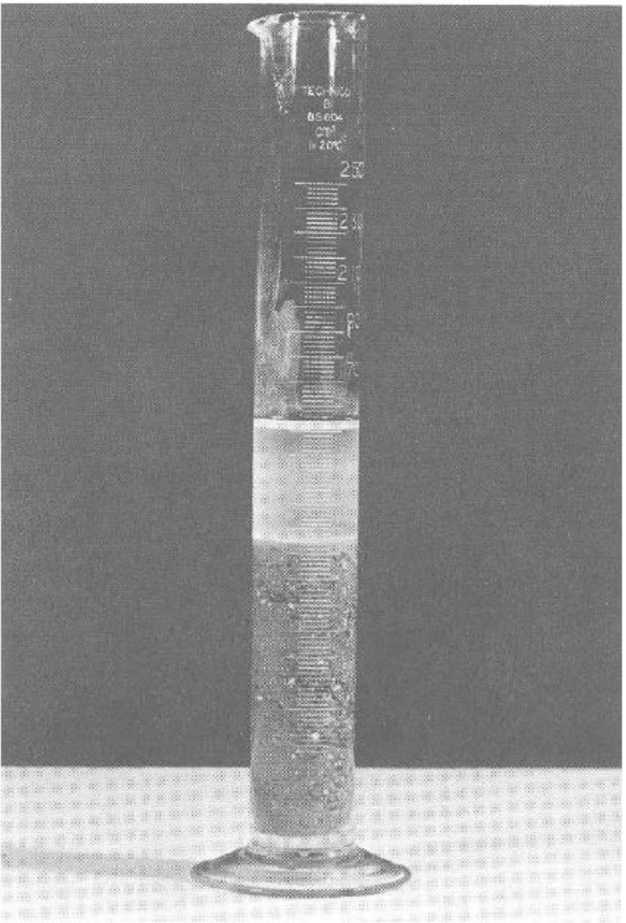
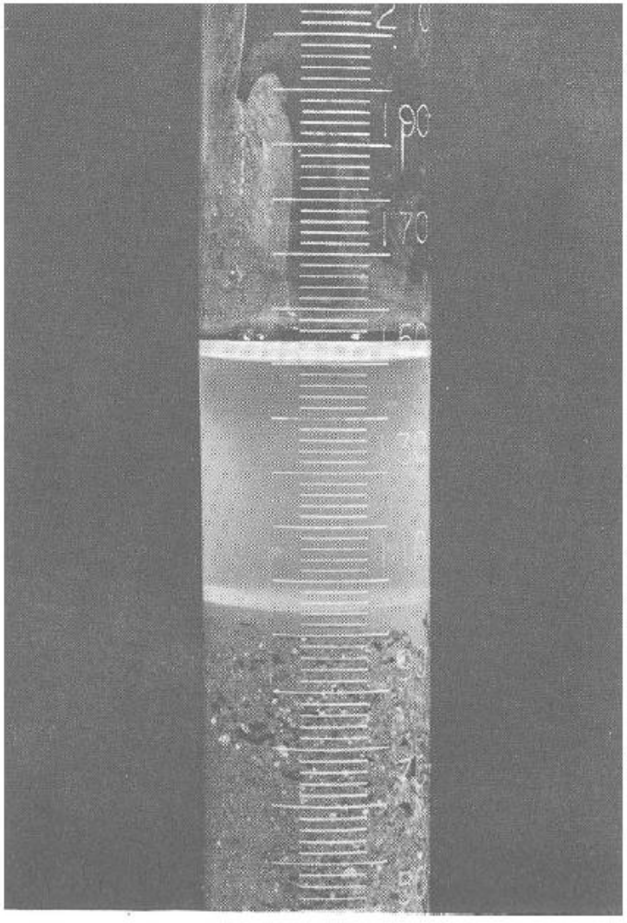
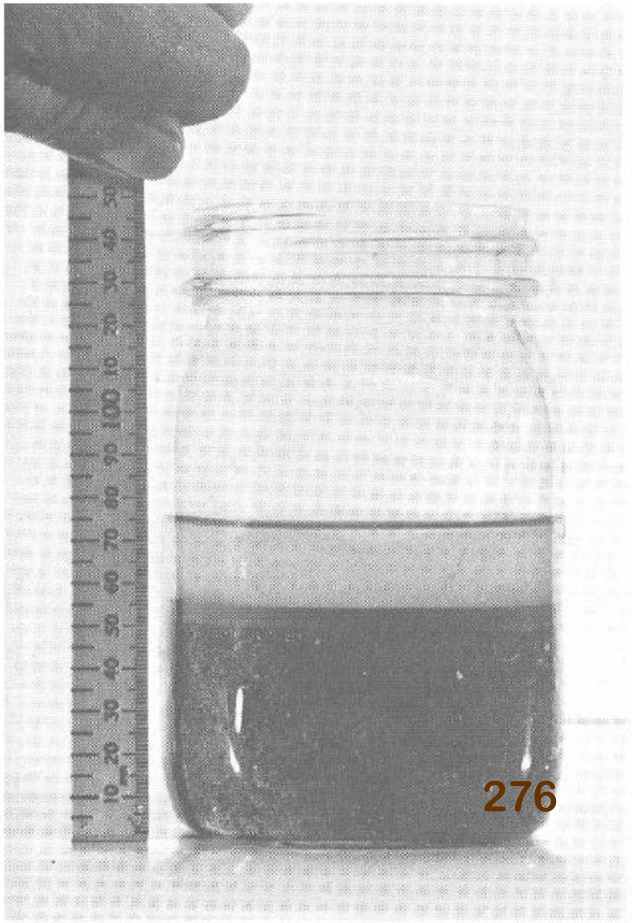
Cleanness and Deleterious Materials

- **Deleterious Substances:** Aggregate contaminated by materials that adversely affects the quality of concrete

Substance	Harmful Effect
Organic impurities	Delay setting and hardening, may reduce strength gain, may cause deterioration
Minus 0.075 mm (No.200)	Weaken bond, may increase water requirement
Coal, lignite or other low-density materials	Reduce durability, may cause popouts or stains
Clay lumps and friable particles	Popouts, reduce durability and wear resistance
Soft particles	Reduce durability and wear resistance, popouts

Silt Test for Sand

- Silt content = (height of silt layer / height of sand)
- Silt content should not be more than 8%

Soundness & Durability

Resist weathering

- water freezing in voids fractures & disintegrates aggregates
- Test method uses "salt solution" to simulate freezing (ASTM C88)

Prepare sample
minimum mass
specified gradation

Soak 16 hrs – dry 4 hrs
Repeat cycle 5 times

Measure gradation

$$Loss = \left(\frac{M_B - M_A}{M_B} \right) 100$$

Hardness & Abrasion Resistance

- Resist load damage
  - During construction
  - Traffic loads
- Los Angeles abrasion test (ASTM C131, C535)

•Prepare sample
•Minimum mass original
•Specified gradation

•Charge drum w/ sample
•Steel spheres
•500 revolutions

•Sieve

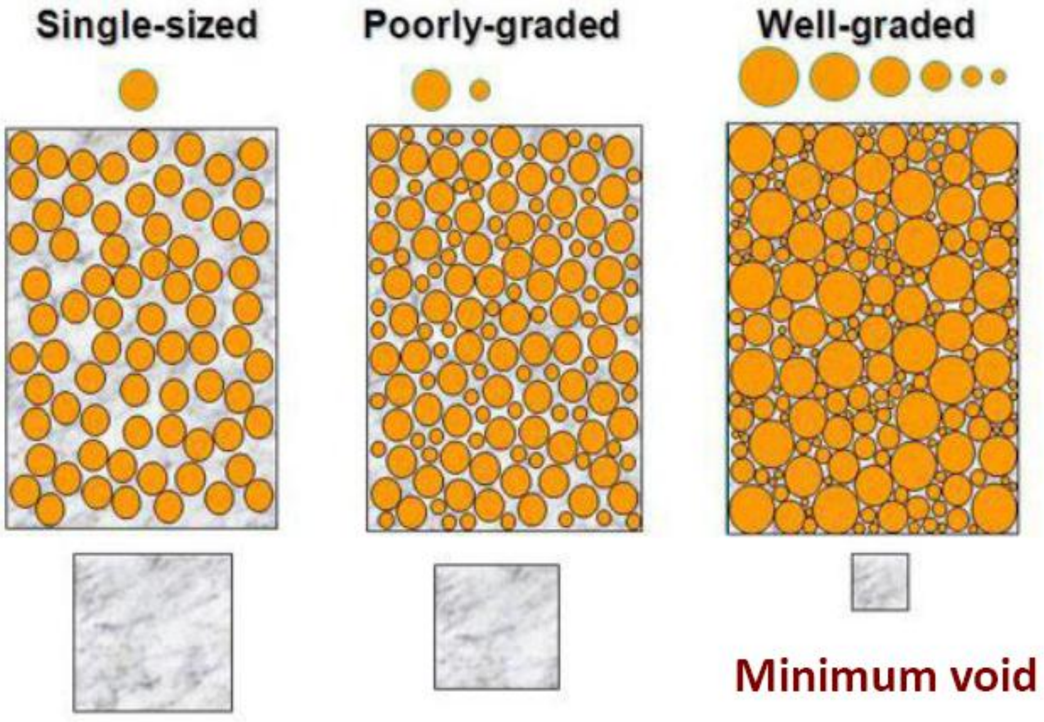
$$Loss = \left(\frac{M_{original} - M_{final}}{M_{original}} \right) \times 100$$

Alkali-Aggregate Reactivity

- **Alkali-silica reaction:** Silica in some agg. reacts with the alkalis (Na_2O, K_2O) in Portland Cement (especially in warm, humid climates)
  - Excessive expansion
  - Cracking
  - Spalling
- **Alkali-carbonate reaction:** Carbonates in aggregate can also react to a lesser extent
- Minimizing reactivity if a reactive aggregate must be used
  - Type II cement – minimizes alkali content of P.C.
  - Keep concrete as dry as possible
  - Fly Ash, GGBS, silica fume reduce alkali reactivity
  - Sweetening – add 30% crushed limestone to the aggregate

Gradation

- Gradation is an important attribute to produce economical concrete
  - Max. density (i.e. min. voids)
  - Min. cement content



Void content of aggregate:

: Particle size distribution

: Maximum aggregate size

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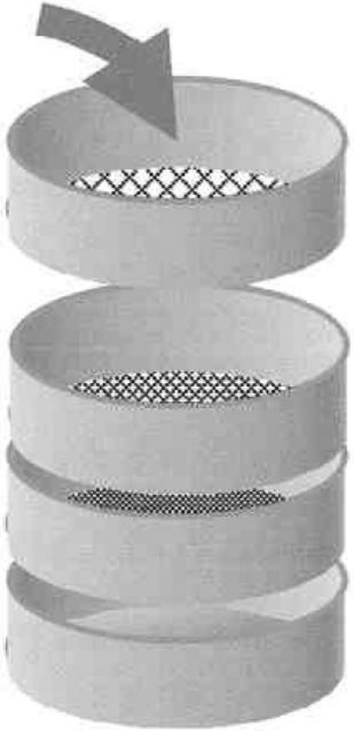
Sieve Analysis for Gradation

- **Gradation**: Particle size distribution of aggregate
- **Sieve Analysis**: Process of dividing aggregate into fractions of same particle size in order to determine gradation of aggregate
  - Standard coarse sieves: 37.5mm; 19mm; 9.5mm; 4.75mm
  - Standard fine sieves: 4.75mm; 2.36mm; 1.18mm; 0.60mm; 0.30mm; 0.15mm
- **Grading Curve**: Usually described by the cumulative percentage of aggregates that either pass through or retained by a specific sieve size

Aggregates are poured into the test sieves, which are placed in order of decreasing aperture size from top to bottom.



Sieve Analysis for Fine Aggregate Sample & Fineness Modulus

Sieve size (mm)	No.	Weight retained (g)	% retained	Cumulative % retained	Cumulative % passing
4.75	4	0	0	0	100
2.36	8	241.9	11.9	11.9	88.1
1.18	16	388.9	19.1	31.0	69.0
0.60	30	505.5	24.9	55.9	44.1
0.30	50	543.4	26.7	82.6	17.4
0.15	100	340.8	16.8	99.4	0.6
Pan		11.3	0.6	100	0
Total		2031.8	100		

$$FM = \frac{11.9 + 31.0 + 55.9 + 82.6 + 99.4}{100} = \frac{280.8}{100} = 2.81$$

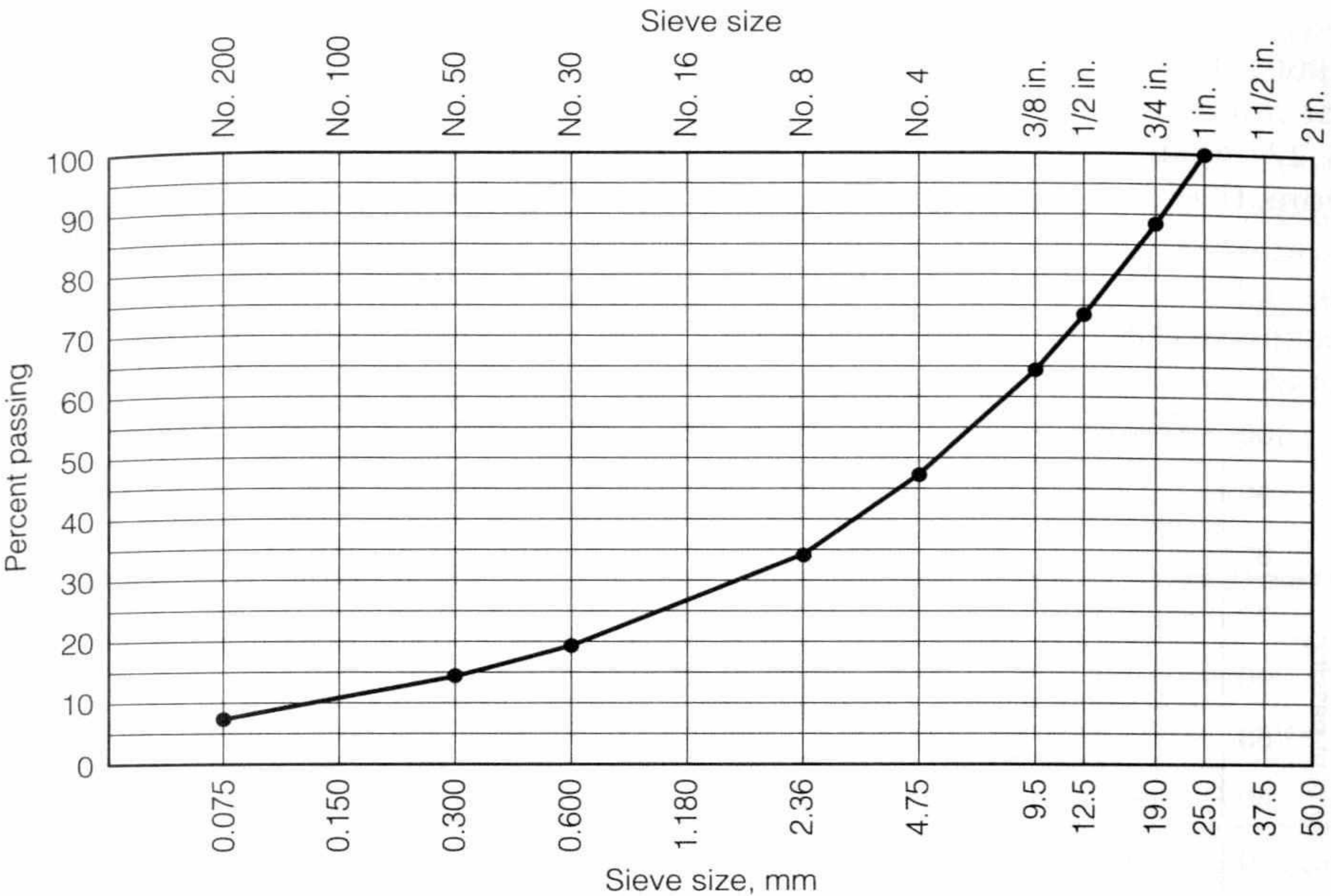
Fineness Modulus

- A measure of gradation fineness
- FM = ∑ (Cumulative % retained on standard sieves up to 0.15 mm) / 100

$$FM = \sum R_i \Big/ 100$$

- FM cannot be representative of a distribution, i.e. two different grading curves can have same FMs
- Higher FM, coarser aggregate
- Lower FM is not economical

Semi Log Grading Graph



Example

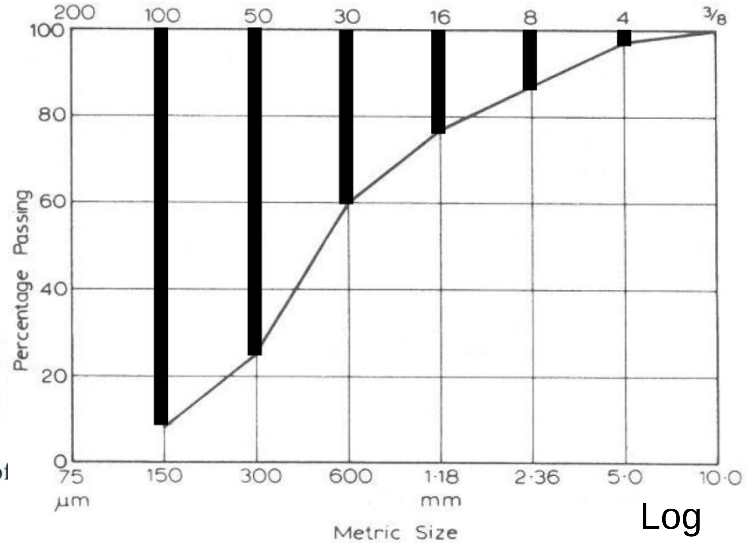
- The following results were obtained from the sieve analysis of fine aggregate sample

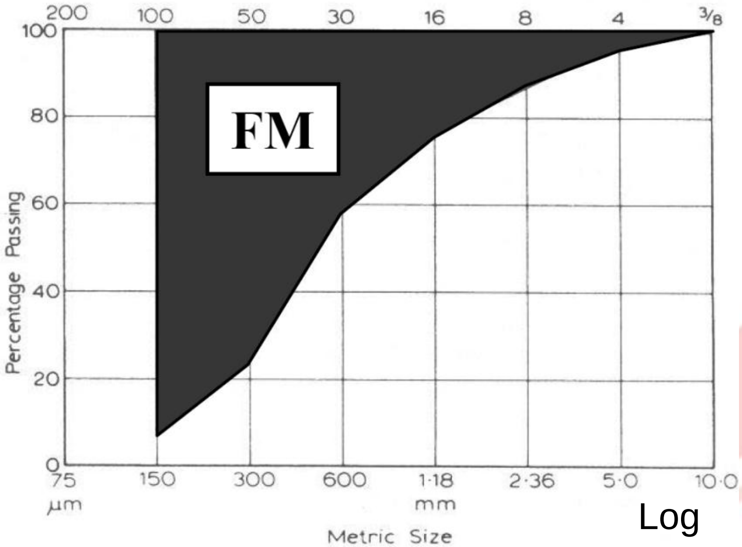
Sieve size (mm)	9.5	4.75	2.36	1.18	0.60	0.30	0.15	Pan
Retained (g)	0	6	31	30	59	107	53	21

  - Draw the grading curve for the fine aggregate
  - Determine the fineness modulus of the fine aggregate

Solution

Sieve size BS (ASTM)	Mass retained, g	% retained	Cumulative % retained	Cumulative % passing
9.50 mm (3/8 in.)	0	0.0	0	100
4.75 mm (No. 4)	6	2.0	2	98
2.36 mm (No. 8)	31	10.1	12	88
1.18 mm (No. 16)	30	9.8	22	78
600 μm (No. 30)	59	19.2	41	59
300 μm (No. 50)	107	34.9	76	24
150 μm (No. 100)	53	17.3	93	7
< 150 μm	21	6.8	---	---
Total	307		246	
FM			2.46	





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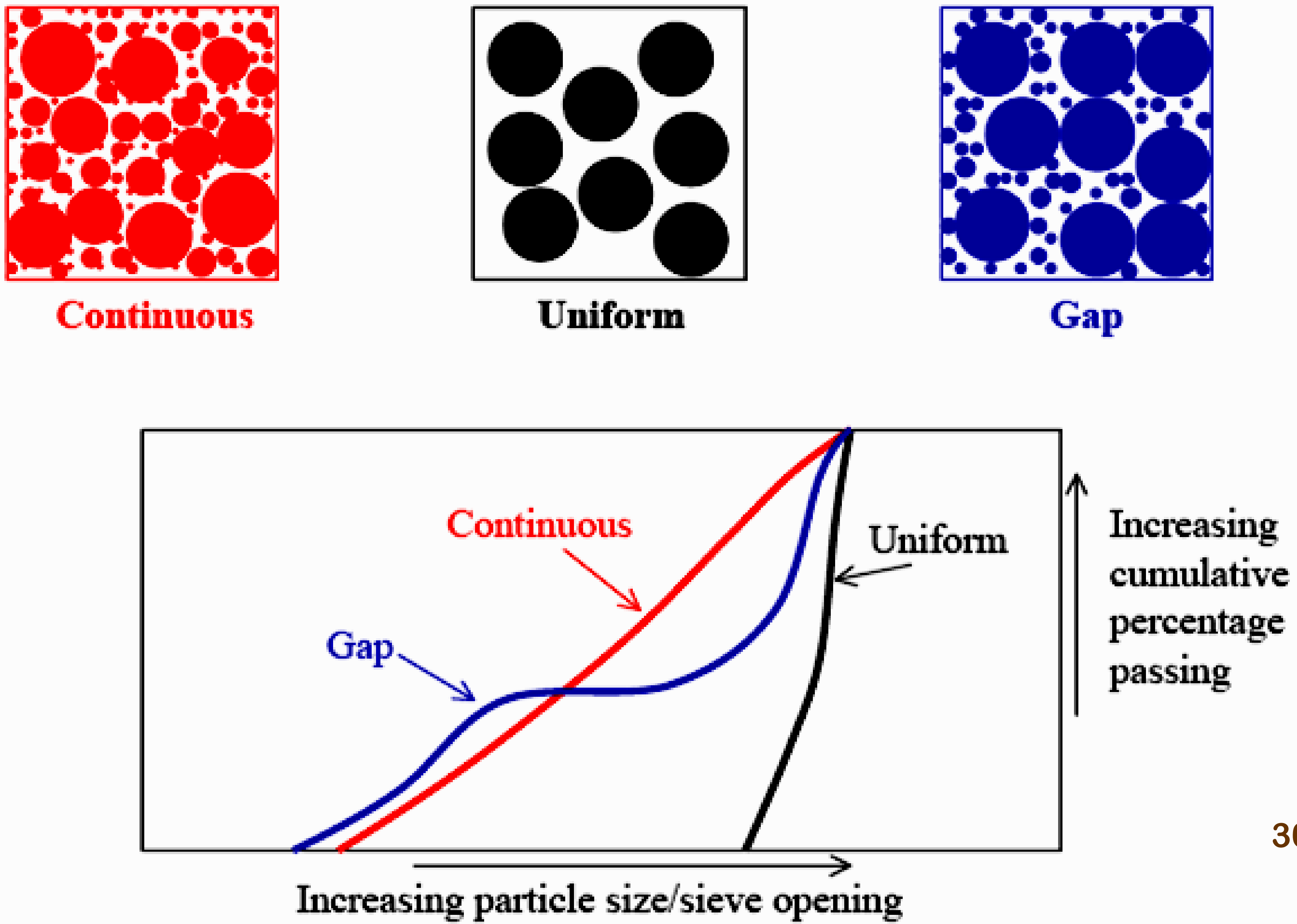
Schematic Representations of Different Agg. Gradation



Types of Gradation

Continuous (Well graded, dense)

- Has a good mix of all particle sizes which means the aggregates use most of the volume and less cement is needed

One-size gradation (Uniform)

- All same size = nearly vertical curve

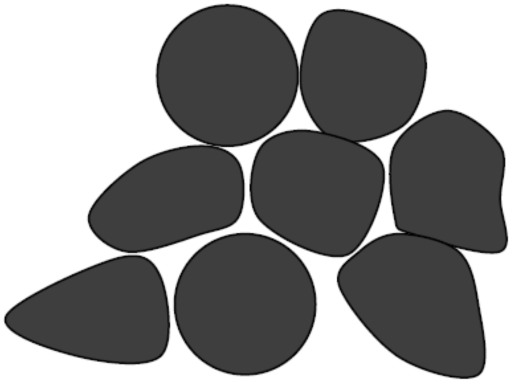
Gap-graded

- Missing some sizes = nearly horizontal section of curve

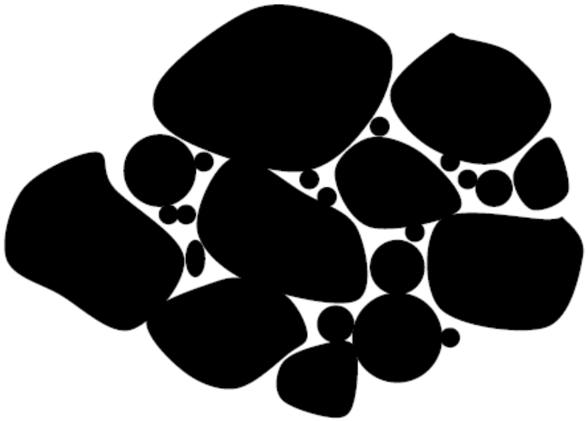
Open-Graded

- Missing small aggregates which fill in holes between larger ones
- Lower part of curve is skewed toward large sizes

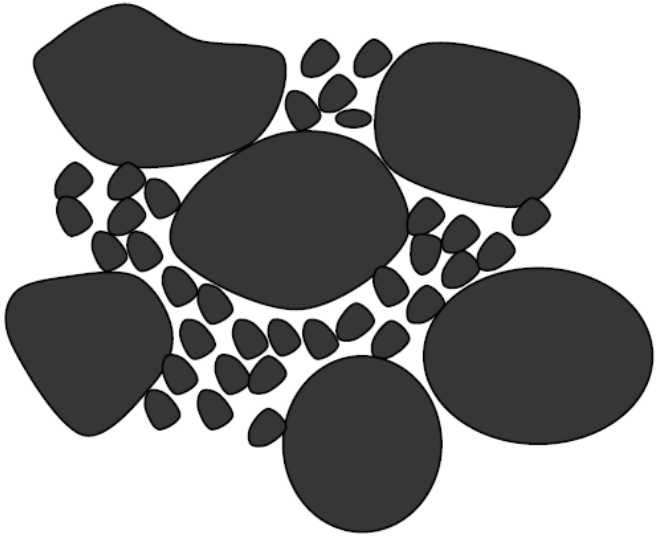
Well-graded Aggregate: Increased Concrete Density and Shearing Strength



Uniform size aggregate:
1. Friction at few points of contact
2. Poor interlocking
3. High percentage of voids

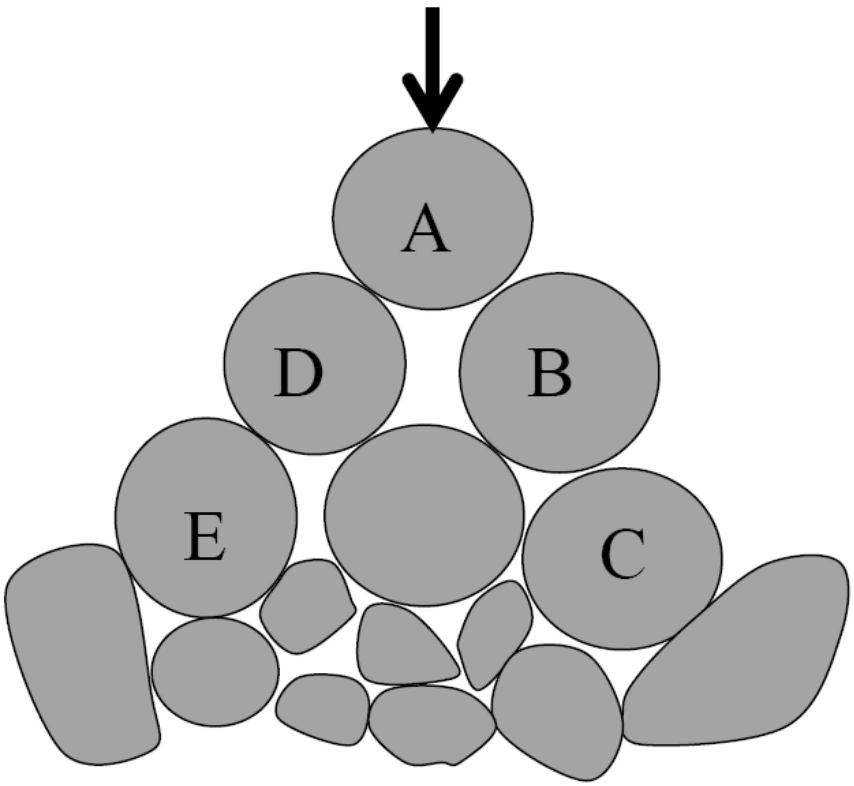


Well-graded aggregate:
1. Friction at many points of contact
2. Excellent interlocking
3. Very few voids

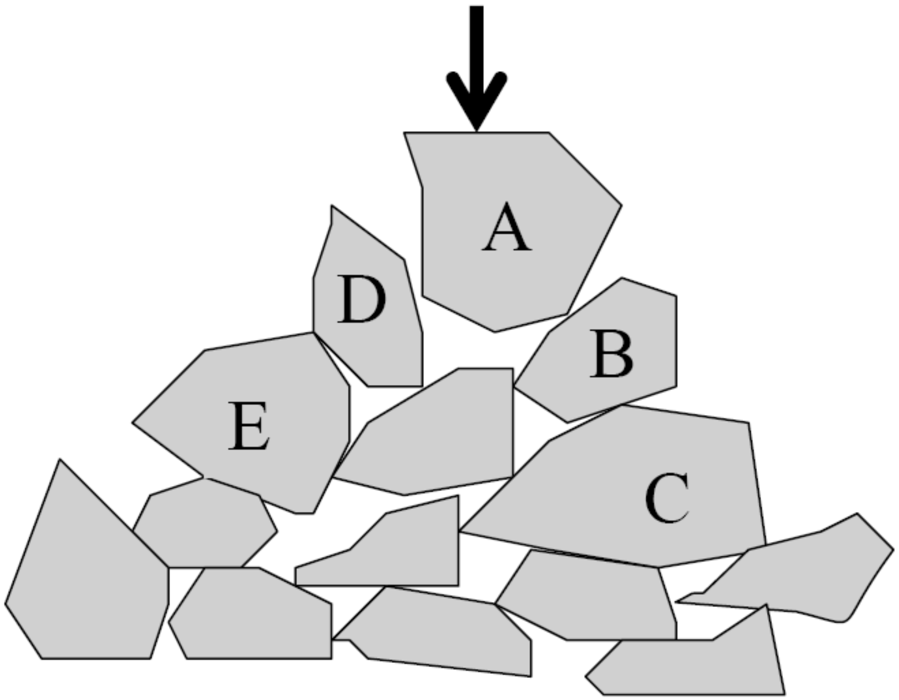


Gap-graded aggregate:
1. Friction at many points of contact
2. God interlocking
3. Few voids

Friction and Interlocking



Rounded particles



Angular particles

Grading Requirements

- Grading of granular materials to produce dense packing
  - Max. density
  - Min. voids
  - Min. cement content
  - Economic consideration
- It was found, however, aggregate graded to give max. density makes a harsh and somewhat unworkable mix

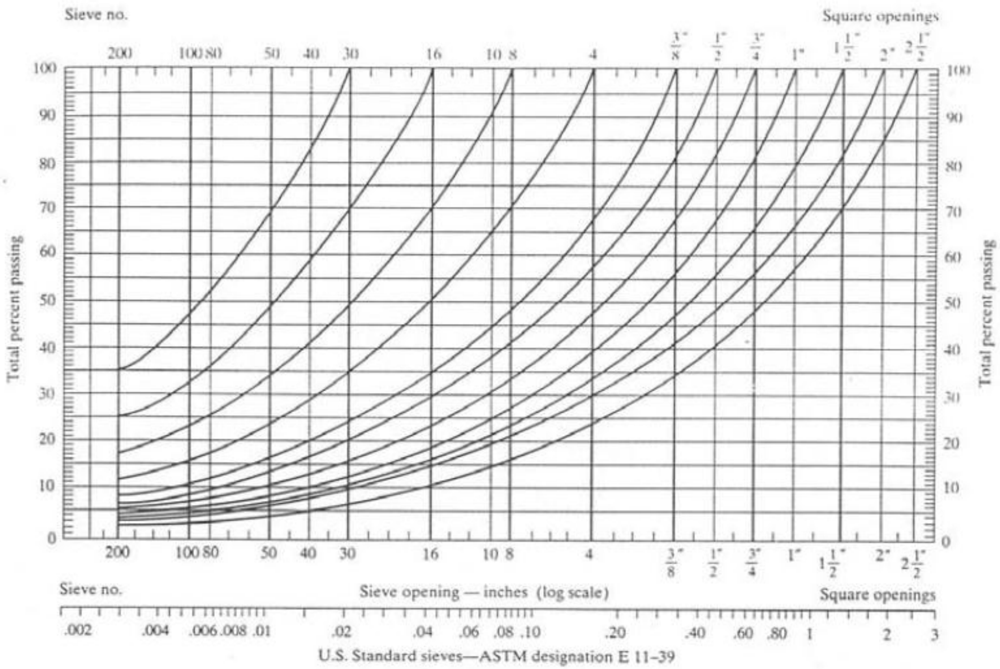
Fuller Thompson Max. Density

$$p_i = \left(\frac{d_i}{D}\right)^{0.50}$$

p_i = percent passing i^{th} sieve
d_i = opening size of i^{th} sieve
D = max. particle size

Fuller, W.B. and Thompson, S.E., “The Law of Proportioning Concrete,” Transactions of the ASCE, v.159, 1907

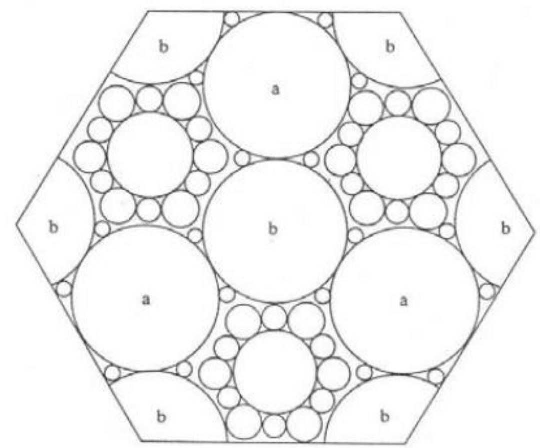
Fuller Thompson Max. Density



(a)

Minimum Void!

The aggregate graded to give maximum density makes a harsh and somewhat unworkable mix.



(b)

Figure 10.4
Densely graded aggregate: (a) Fuller-Thompson maximum density (minimum voids content) gradation curves; (b) schematic description of the concepts of dense grading.

Modified Fuller Thompson Max. Density

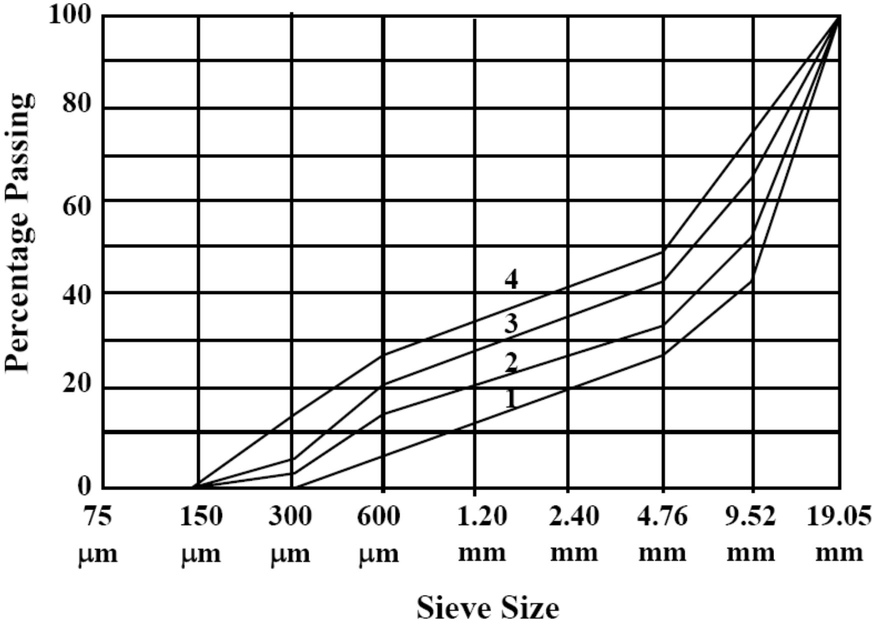
- In 1962, FHWA published a modified version of Fuller's equation with a different exponent

$$p_i = \left(\frac{d_i}{D}\right)^{0.45}$$

p_i = percent passing ith sieve
d_i = opening size of ith sieve
D = max. particle size

Practical Gradings

- Curve No. 1 represents coarsest grading
  - Comparatively workable
  - Make sure no segregation occur
- Curve No. 4 represents a fine grading
  - Cohesive but not very workable



Road Note No. 4 type grading curves for 19.05 mm aggregate

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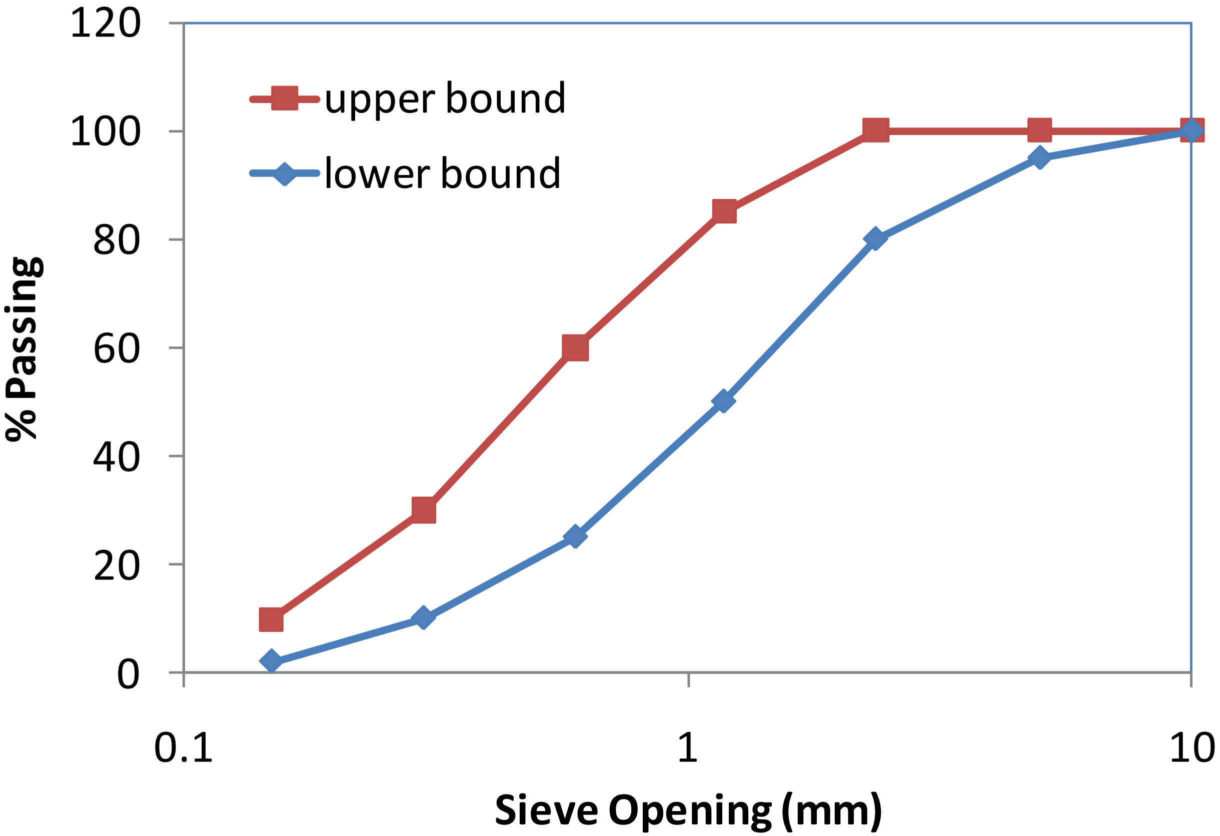
Grading Requirement for Fine Aggregate (ASTM C33)



Sieve	Percent Passing
9.5 mm (3/8)	100
4.75 mm (No. 4)	95–100
2.36 mm (No. 8)	80–100
1.18 mm (No. 16)	50–85
0.60 mm (No. 30)	25–60
0.30 mm (No. 50)	10–30
0.15 mm (No. 100)	2–10

Grading Requirement for Fine Aggregate (BS 882)

- BS 882:1992 requires any fine aggregate to satisfy overall grading limits of the following table and also one of three additional grading limits of the same table

Sieve size		Percentage by mass passing sieves				
		BS 882:1992				ASTM C33-93
BS	ASTM No.	Overall grading	Coarse grading	Medium grading	Fine grading	
10.0 mm	3/18 in.	100				100
5.0 mm	3/16 in.	89-100				95-100
2.36 mm	8	60-100	60-100	65-100	80-100	80-100
1.18 mm	16	30-100	30-90	45-100	70-100	50-85
600 μm	30	15-100	15-54	25-80	55-100	25-60
300 μm	50	5-70	5-40	5-48	5-70	10-30
150 μm	100	0-15*				2-10

* For crushed stone fine aggregate, the permissible limit is increased to 20% except for heavy duty floors

Grading Requirement for Coarse Aggregate (ASTM C33)

Sieve size	Percentage by mass passing sieves		
	Nominal size of graded aggregate		
mm	37.5 to 4.75 mm	19.0 to 4.75 mm	12.5 to 4.75 mm
75.0	---	---	---
63.0	---	---	---
50.0	100	---	---
37.5	95-100	---	---
25.0	---	100	---
19.0	35-70	90-100	100
12.5	---	---	90-100
9.5	10-30	20-55	40-70
4.75	0-5	0-10	0-15
2.36	---	0-5	0-5

Grading Requirement for Coarse Aggregate (BS 882)

Sieve size	Percentage by mass passing BS sieves		
	Nominal size of graded aggregate		
mm	40 to 5 mm	20 to 5 mm	14 to 5 mm
50.0	100	---	---
37.5	90-100	100	---
20.0	35-70	90-100	100
14.0	25-55	40-80	90-100
10.0	10-40	30-60	50-85
5.0	0-5	0-10	0-10
2.36	---	---	---

Grading Limits for Maximum Aggregate Size

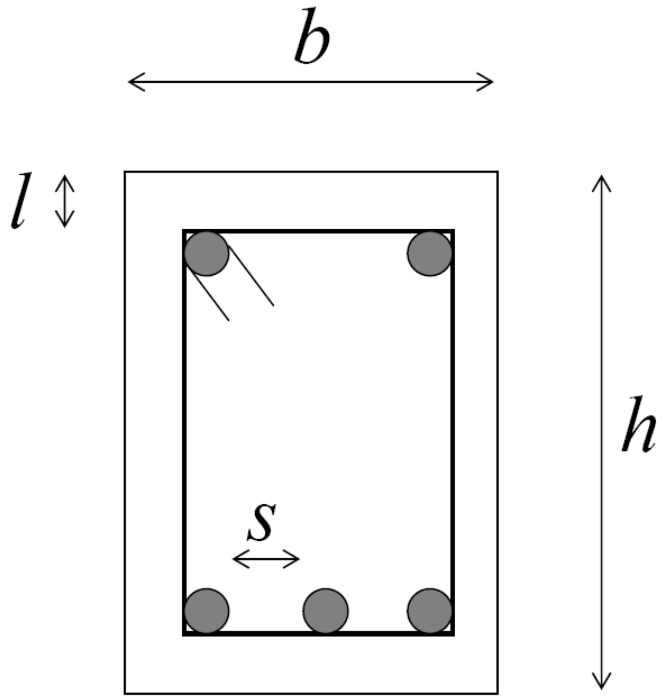
- Aggregate size is limited depending upon size of mixing, and processing and placing equipment

$$d = \text{max. size of aggregate}$$

$$d < 0.25\, b \text{ (or } 0.2\, b\text{)}$$

$$d < s - 5 \text{ mm (or } 3/4\, s\text{)}$$

$$d < l - 5 \text{ mm (or } 3/4\, l\text{)}$$

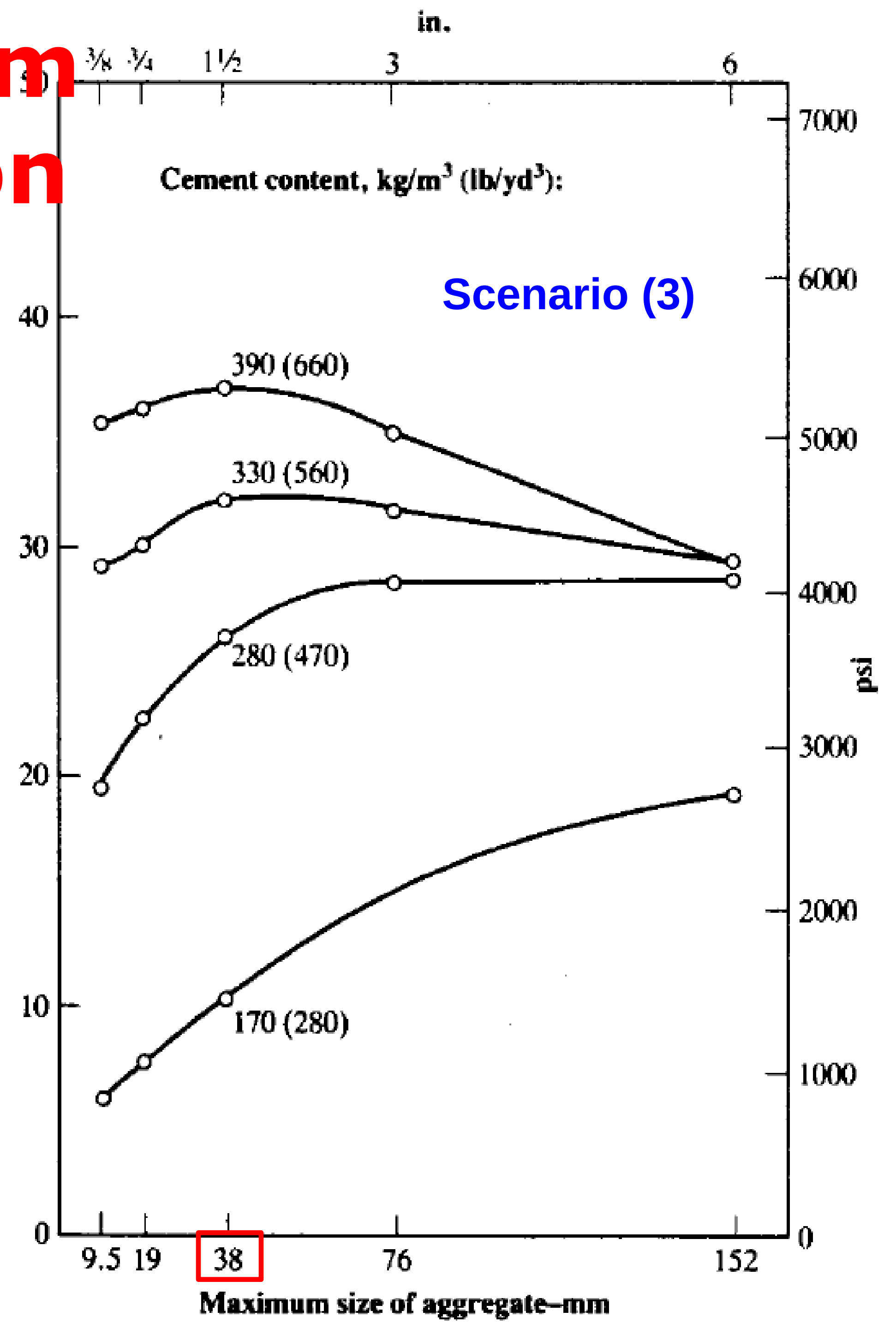


Increased Maximum Aggregate Size Can…

- Scenario (1): Reduce water content, for specified workability
- Scenario (2): Lower cement content, for specified workability and w/c
  - Reduced total heat of hydration
- Scenario (3): Lower w/c, for specified workability and cement content → Increased strength

Effect of Maximum Aggregate Size on Compressive Strength

- Increased particle size
  - Reduced w/c → f_c' (+)
  - Lower bond area
    - Less ITZ → f_c' (+)
    - Increased internal stresses between aggregate/paste interface → f_c' (-)
- For any given strength of concrete, there is an optimum maximum size of aggregate
  - In general, aggregates in HSC is less than 10 mm



Recycled Concrete Aggregates

Recycled aggregate particles:
Natural + Attached Mortar

- High absorption
- Low mechanical resistance
- Contamination (??)

Aggregate Property	Granite (Natural)	Recycled concrete agg.	SS 31
Water Absorption (%)	1.0	5.0	-
Flakiness Index (%)	15.7	12.6	< 40.0
Elongation Index (%)	23.8	17.4	-
Los Angels Abrasion (%)	28.3	33.1	< 50.0
Impact Value (%)	19.6	22.0	< 25.0

RCA concrete properties compared to control concrete

- Reduced compressive strength, modulus of elasticity
- Increased drying shrinkage, permeability
- RCA quality variation - Minimum effect on concrete quality

ADMIXTURE

Definition of Admixture

A material other than water, aggregate, cement and reinforcing fibres that is used in concrete as an ingredient, and added to the batch immediately before or during mixing

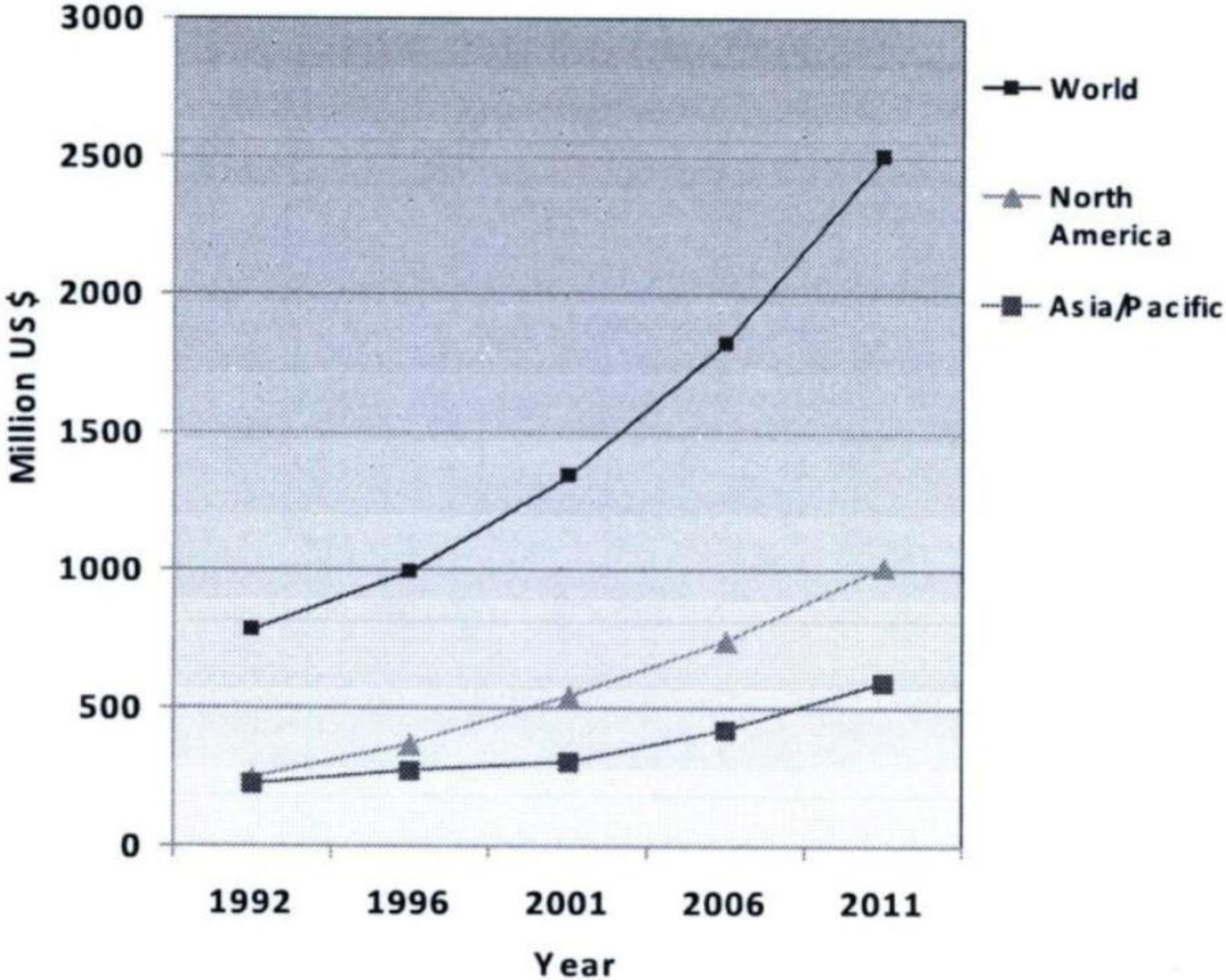
Why they are used?

- **To modify properties of fresh & hardened concrete**
- **To ensure the quality of concrete during mixing, transporting, placing & curing**
- **To overcome certain unexpected emergencies during concrete operations**

Admixtures

- Classification
  - Chemical admixtures
  - Mineral admixtures
- Admixtures exclude essential concrete ingredients
- They should be used cautiously and for good reason

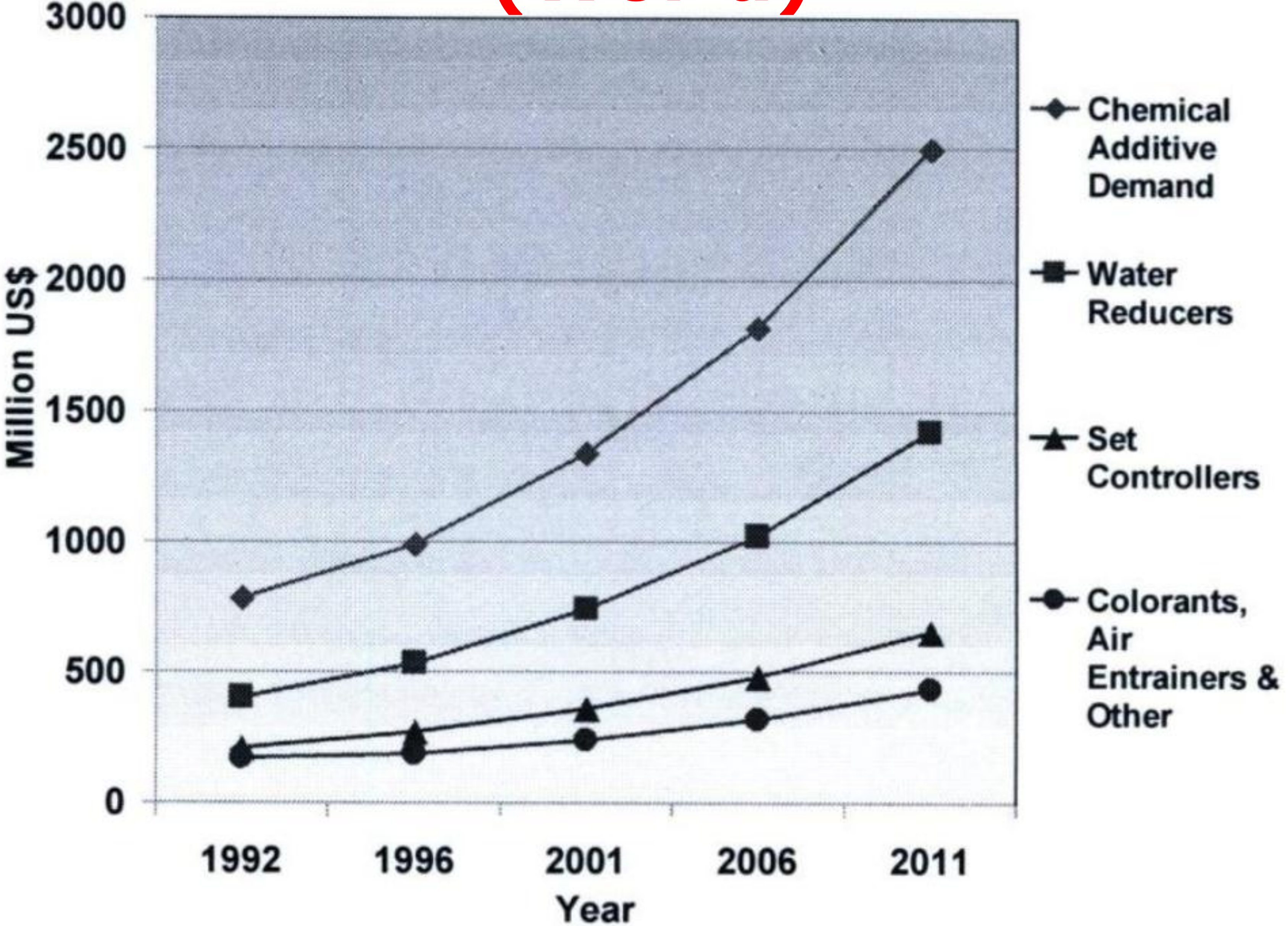
Trends in Consumption of Chemical Admixtures



Chemical Admixtures for Concrete

- Commonly used to improve properties of fresh and hardened concrete
- Materials that are added in small amounts to the concrete (usually no larger than 5% by weight of cement) and dissolved in mixing water
- Types of admixtures
  - Air-entraining admixtures (ASTM C 260)
  - Water-reducing admixtures (ASTM C 494 and 1017)
    - Water reducers
    - Superplasticizers
  - Set-controlling admixtures (ASTM C 494)
    - Accelerators
    - Retarders
  - Miscellaneous admixtures

Admixture Consumption by Type (World)



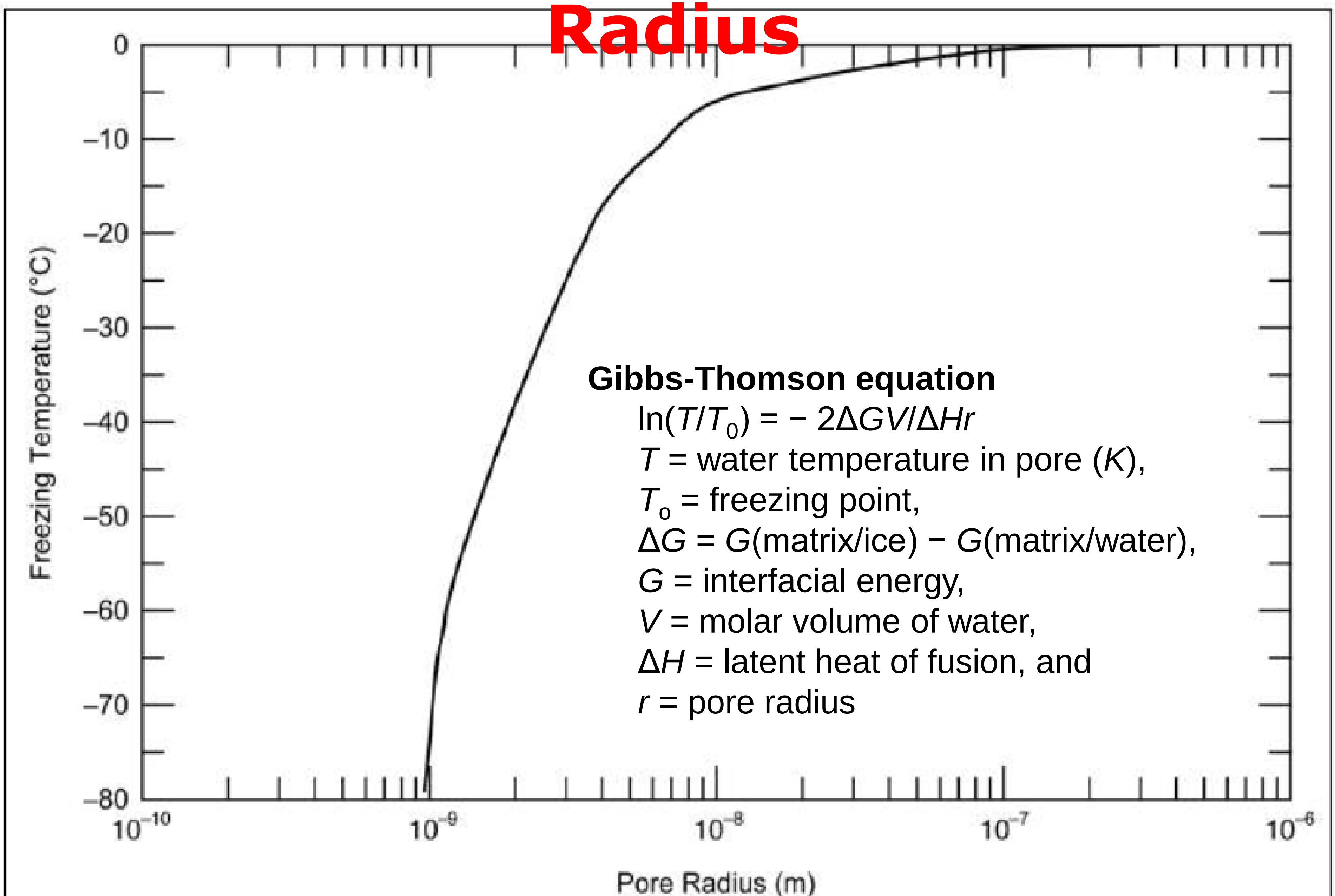
Air-entraining Admixtures

- These admixtures produce tiny, dispersed air bubbles (0.05 to 1.25 mm) into the concrete
  - Water expands 9% as it freezes causing internal stress that cracks the hardened cement paste and greatly reduces durability
  - Air entrainer provides space for the water to go as it expands
- Recommended for **all concrete exposed to freezing**
- **Improve workability**, resistance to freeze-thaw cycles, de-icing chemicals, sulfates, & alkalis-silica reaction
- Decreases strength (1% air causes 5% loss in strength) but can be compensated with **lower w/c ratio**

Concrete Freeze-thaw Damage Mechanism: The Osmotic Pressure Theory (Powers)

- Freezing temperature of the water depends on the size of the pore (lower for smaller pores)
- Capillary pores shall freeze first and water moves from the gel pores to the capillary pores according to the laws of thermodynamic (diffusion from high to low free energy) and the theory of osmosis (diffusion along concentration gradients)
  - Supercooled water (water < 0^oC) has higher free energy than ice
  - Concentration of the remaining unfrozen pore solution increases

Freezing Temperature vs Pore Radius



Gibbs-Thomson equation

$\ln(T/T_0) = -2\Delta G V/\Delta H r$

T = water temperature in pore (K),

T_o = freezing point,

ΔG = G(matrix/ice) − G(matrix/water),

G = interfacial energy,

V = molar volume of water,

ΔH = latent heat of fusion, and

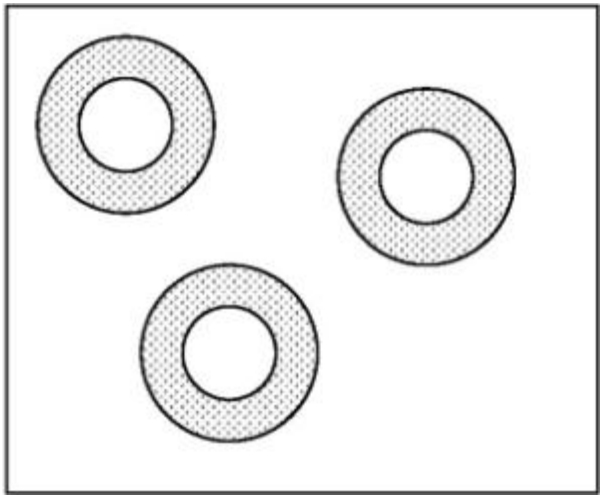
r = pore radius

Concrete Freeze-thaw Damage Mechanism: The Osmotic Pressure Theory (Powers)

- If sufficient water flow from gel to capillaries and freezes, the capillary will become full an pressure will develop.
- Excessive pressure buildup causes cracking and damage the concrete

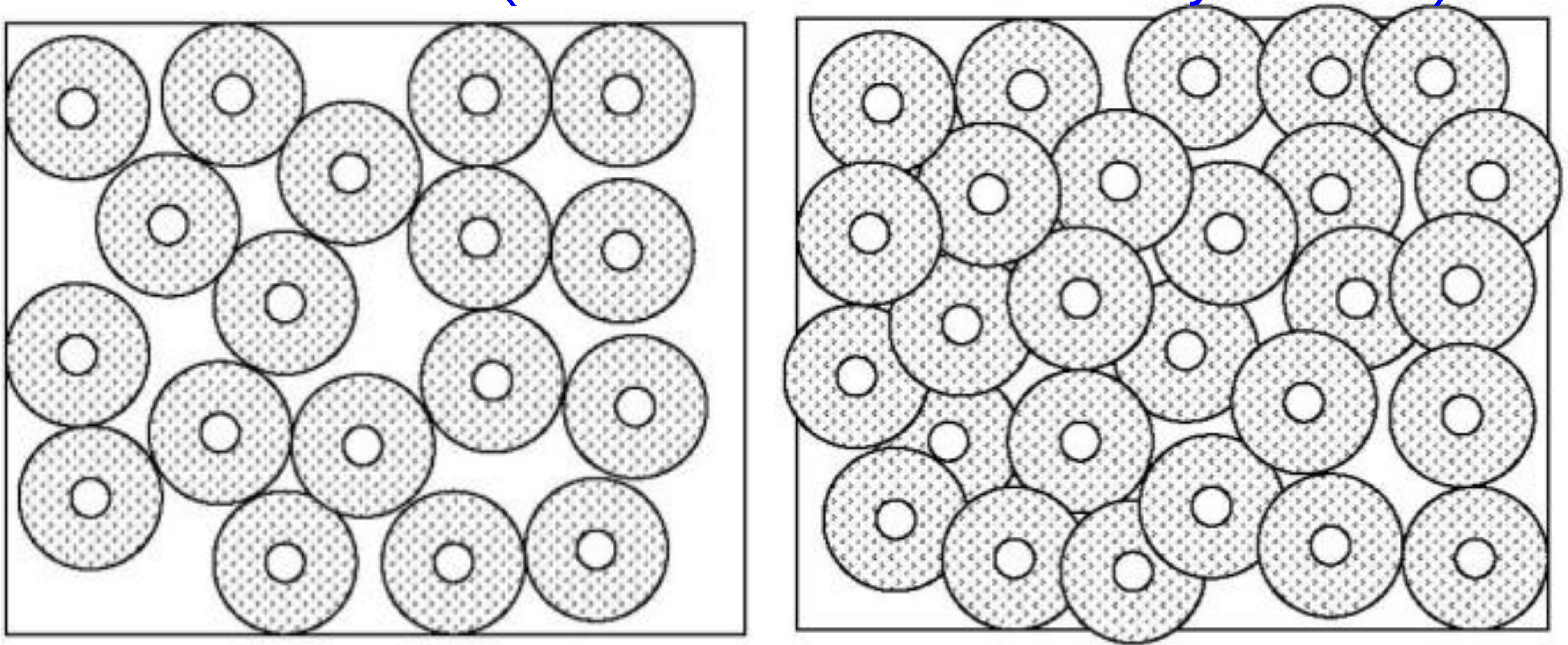
Role of Air Voids

- Upon freezing
  - Controlled air voids with a size bigger than the capillaries
  - Any water in the air bubbles will begin to freeze at a temperature close to 0^oC that allows the processes of osmosis and desorption, reducing the level of saturation in the adjacent cement paste
  - The air voids act as “safety valves” drawing water from the cement paste and serving as reservoir
- Upon thawing
  - The water in the air voids returns to the cement paste because of the higher surface tension in the smaller capillaries and pores



Spacing Factor

- The distance of air voids must not be too great if osmotic pressure is to be relieved; hence the requirement of a critical spacing factor
- Spacing factor: average distance from any point in the paste to the edge of the nearest void, should not exceed 0.2 mm (~9% of air entrainment by volume)



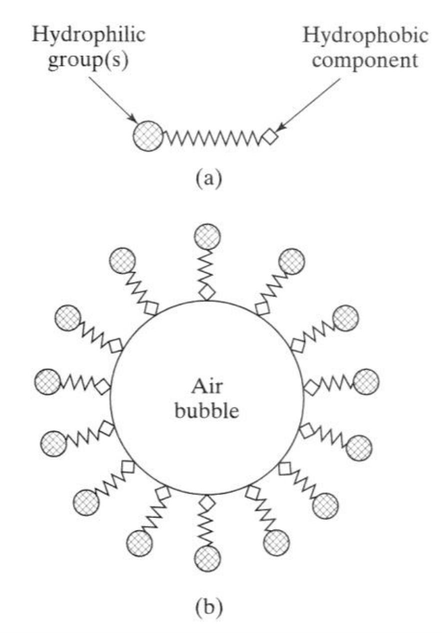
Frost Damage of Concrete

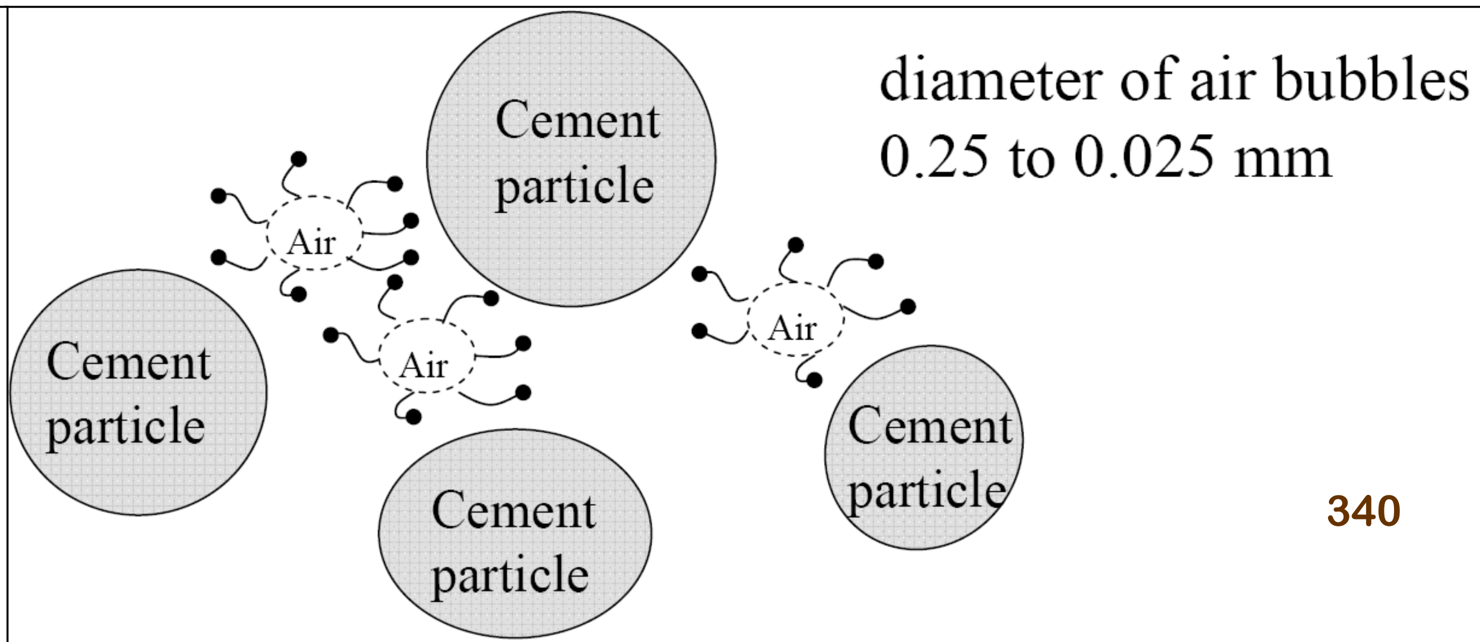
- Concrete can be damaged during freezing and thawing cycles
- Air-entrained concrete have much improved frost resistance

Wang, K., et al. Investigation into Freezing-Thawing Durability of Low Permeability Concrete with and without Air Entraining Agent, IDOT report, 2009

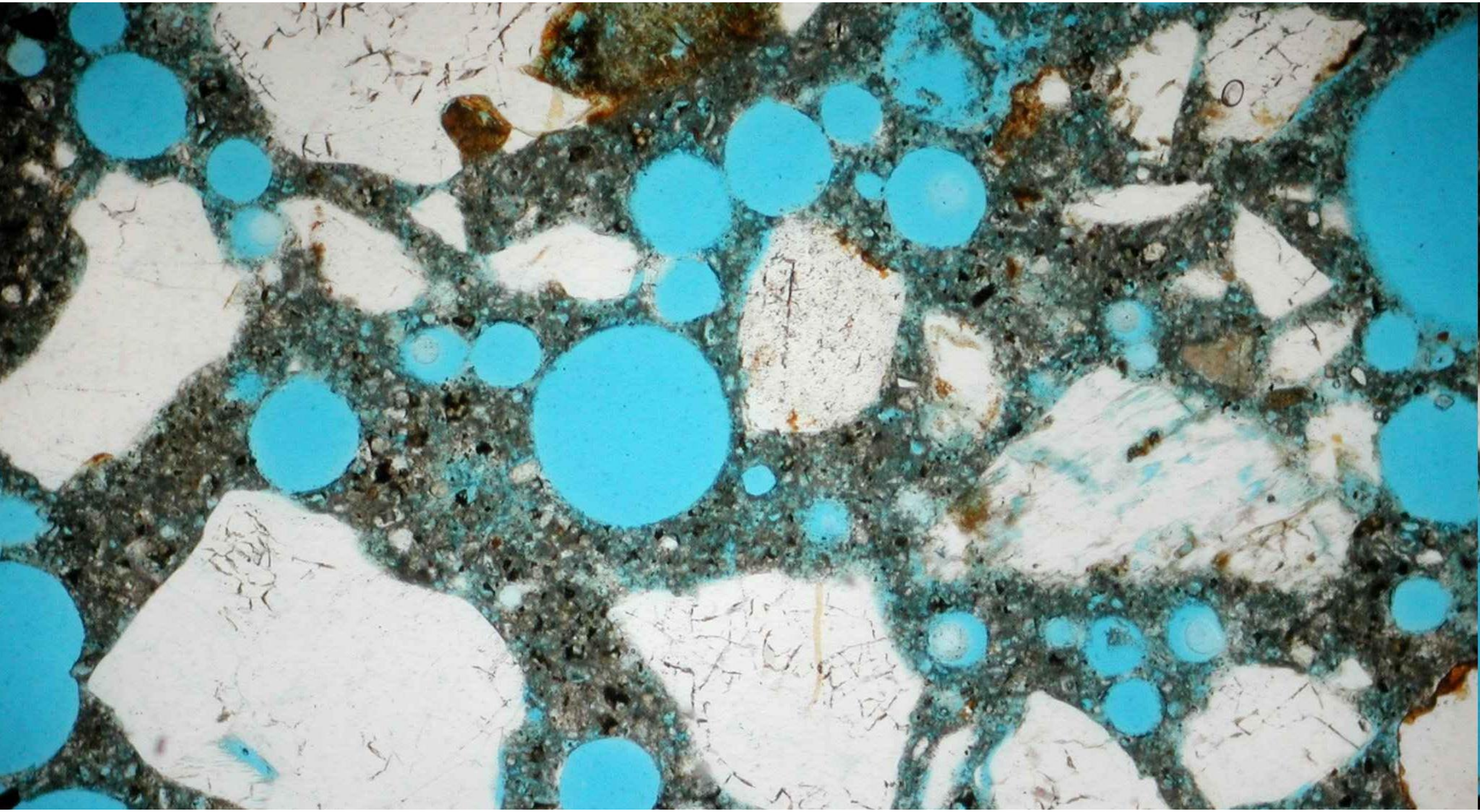
Mechanism of Air Entraining

- Air-entraining admixtures are surface-active agents which acts at the air-water interface, causing water to foam during mixing, similar to *detergents*
- The fine foam remains stable until it is “locked” into the cement paste during hardening





Thin section of concrete with air voids dyed blue

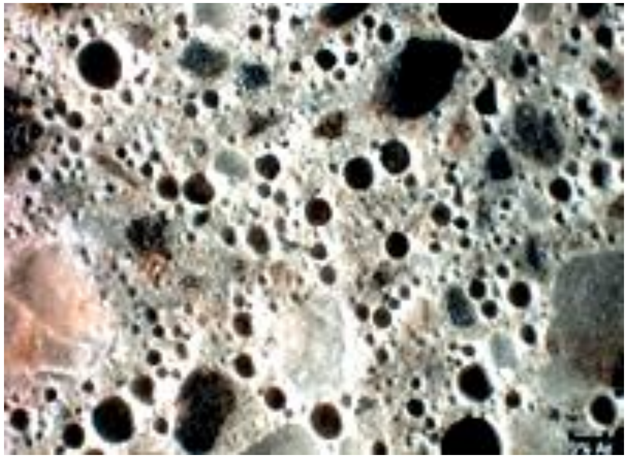


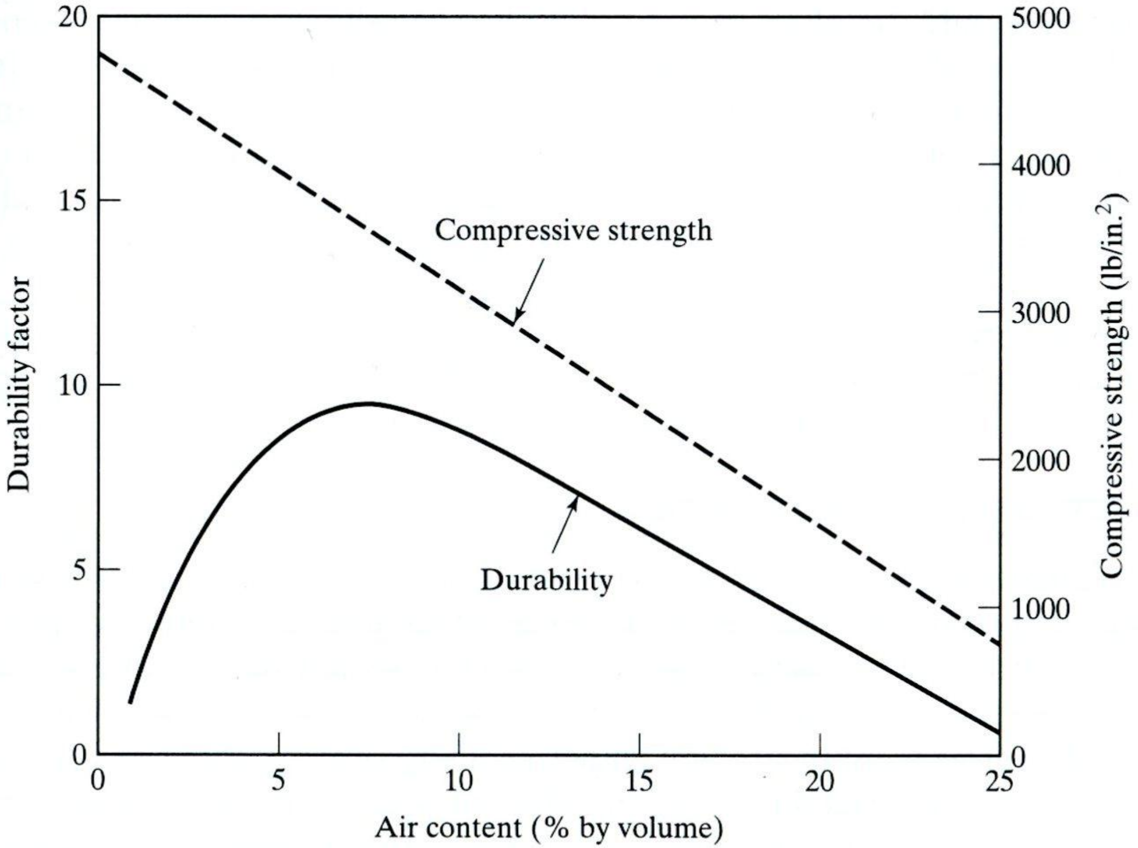
Different from entrapped air which is harmful larger bubbles

- **Frost resistance improves with decreasing void size**
- **Small voids reduce strength less than large ones**

Disadvantages of Using Air-entraining Admixtures

- Loss in strength (for each 1% of air causes 5% loss in strength)





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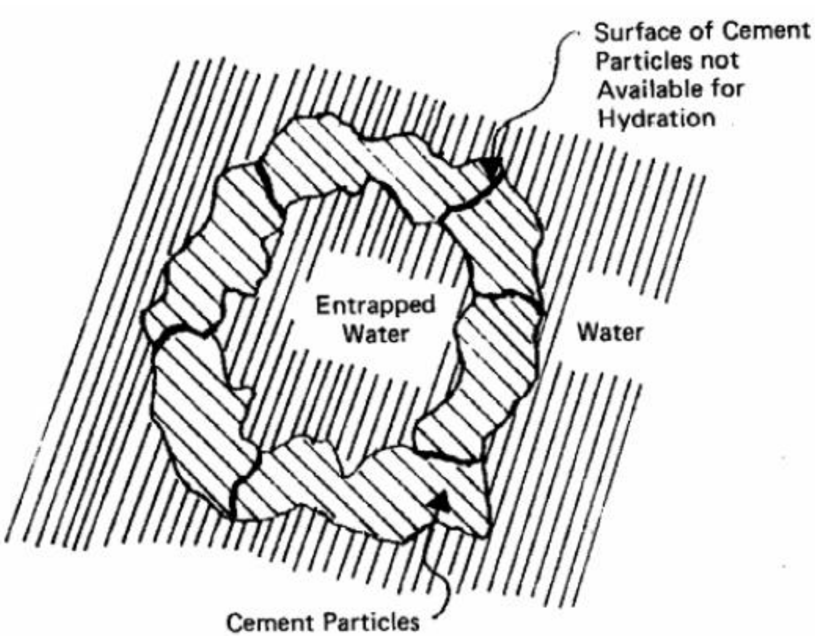
Water Reducers (Normal and Mid-Range)

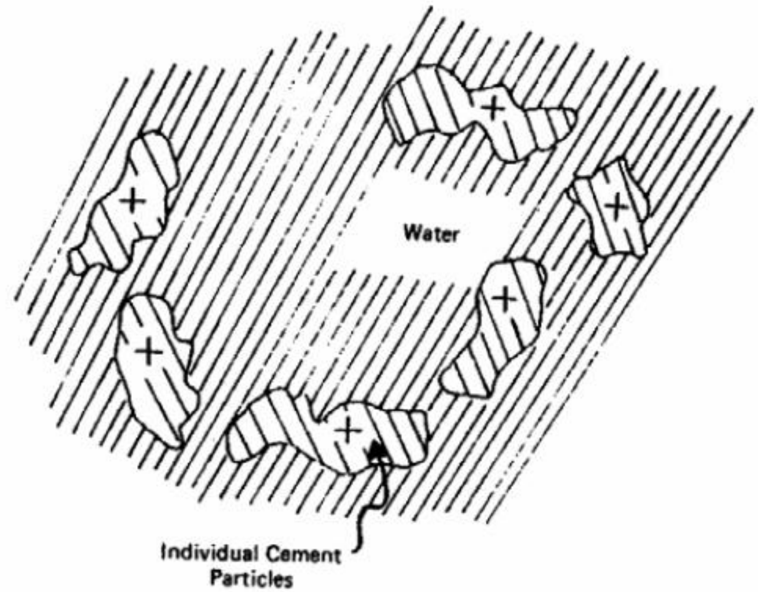
- These admixtures lower the water required (8-12% reduction) to attain a given slump
- Use to
  - Improve workability at same w/c ratio
  - Increase strength at same workability
  - Reduce cost at same w/c ratio and workability

(Source: Hewlett 1978)	Cement content (kg/m3)	Water/Cement Ratio	Slump (mm)	Compressive Strength (MPa)	
				7 day	28 day
Base mix	300	0.62	50	25	37
Improve workability	300	0.62	100	26	38
Increase strength	300	0.56	50	34	46
Reduce costs	270	0.62	50	25.5	37.5

Mechanism of Water Reduction



Cement particles in the absence of dispersing agent



Effect of dispersant on the cement-water mixture

Addition of water reducer results in:

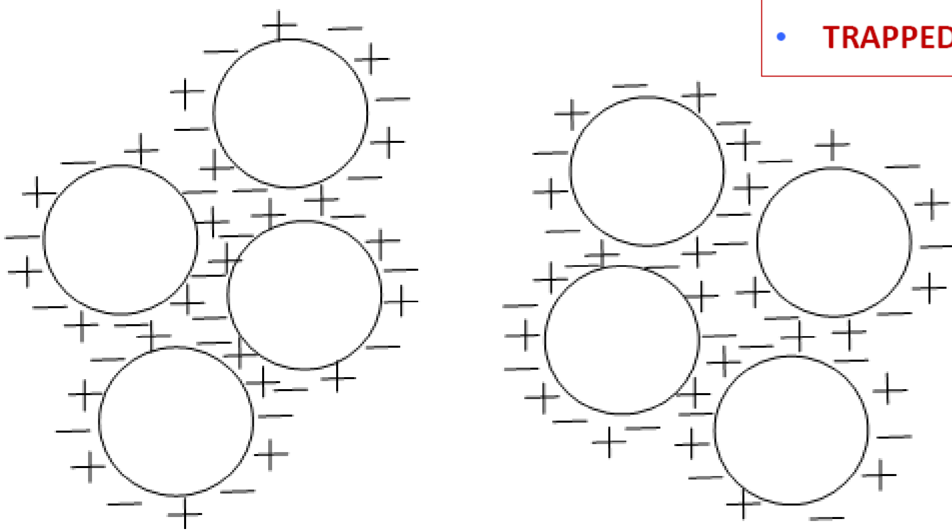
- Liberating water entrapped by surrounding cement particles so that it can contribute to fluidity of concrete
- Making additional surfaces of cement particles available for early hydration

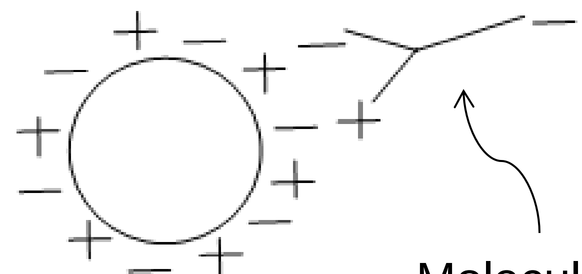
Source: "Concrete Admixture" by Dodson, V.H.

Mechanism of Water Reduction

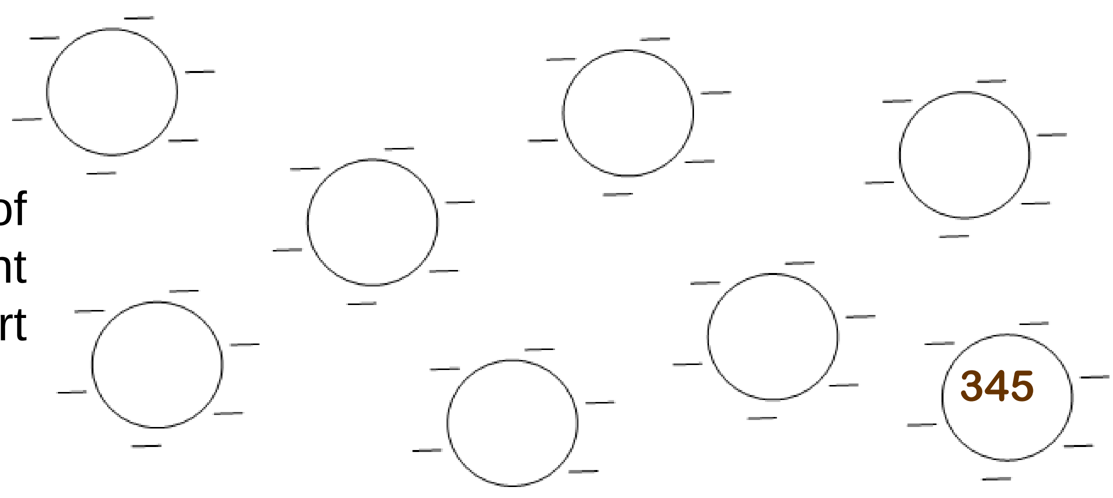
- CEMENT PARTICLES WITH EITHER +VE OR –VE ELECTROSTATIC CHARGE
- WATER TRAPPED WITHIN CEMENT PARTICLE GROUP
- WATER-REDUCER PROVIDE EQUAL POLARITY TO CEMENT PARTICLES
- CEMENT PARTICLES GET DISPERSED
- TRAPPED WATER RELAESED THUS INCREASING WORKABILITY

Without Water Reducer: Unlike charges attract, causing cluster of cement grains or flocculate





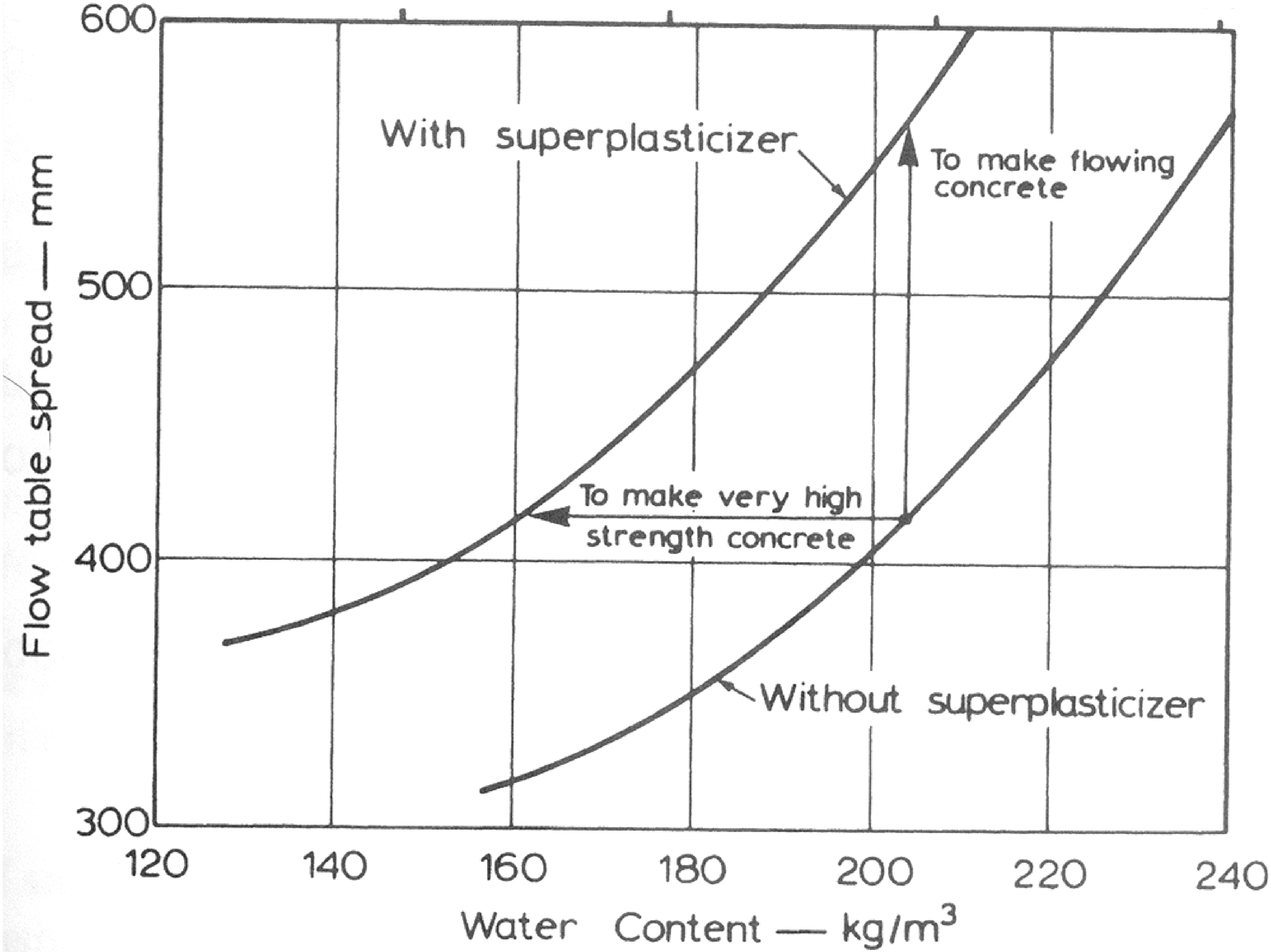
Molecule of Water Reducer



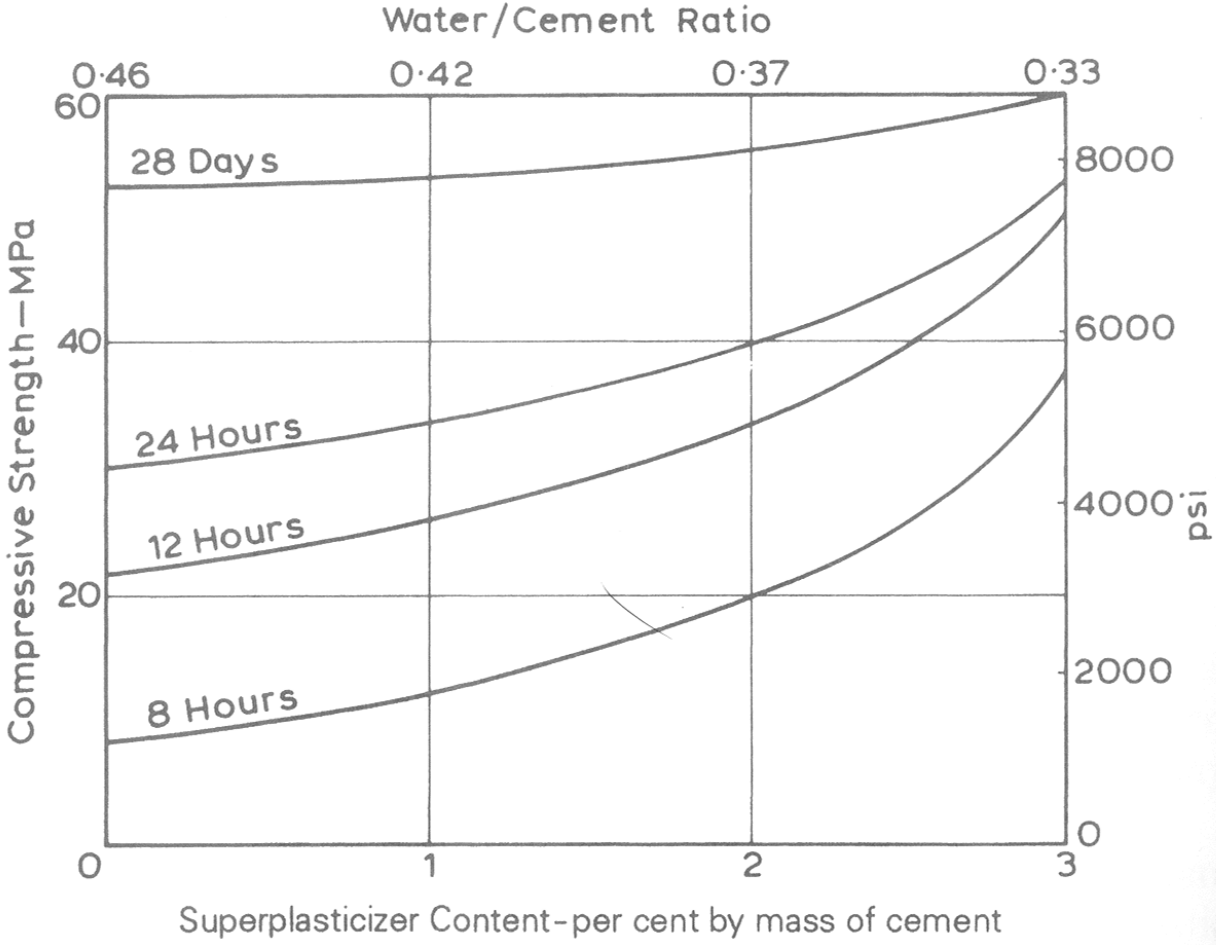
With Water Reducer: Repulsion of like charges pushes the cement grains apart

Superplasticizers (High-Range Water Reducers)

- These are a more recent and more effective type of water reducer (12-40% reduction)
- Used to produce flowing concrete in situations where placing in inaccessible locations or where very rapid placing is required
- Also used to produce very-high strength concrete, using normal workability but a very low w/c


600
500
400
300
Flow table spread — mm
With superplasticizer
To make flowing concrete
To make very high strength concrete
Without superplasticizer
120
140
160
180
200
220
240
Water Content — kg/m3

Superplasticizers



- SP increases the 24-hour strength by 50 to 75% (i.e., accelerator)
- Greater increase occurs at earlier ages

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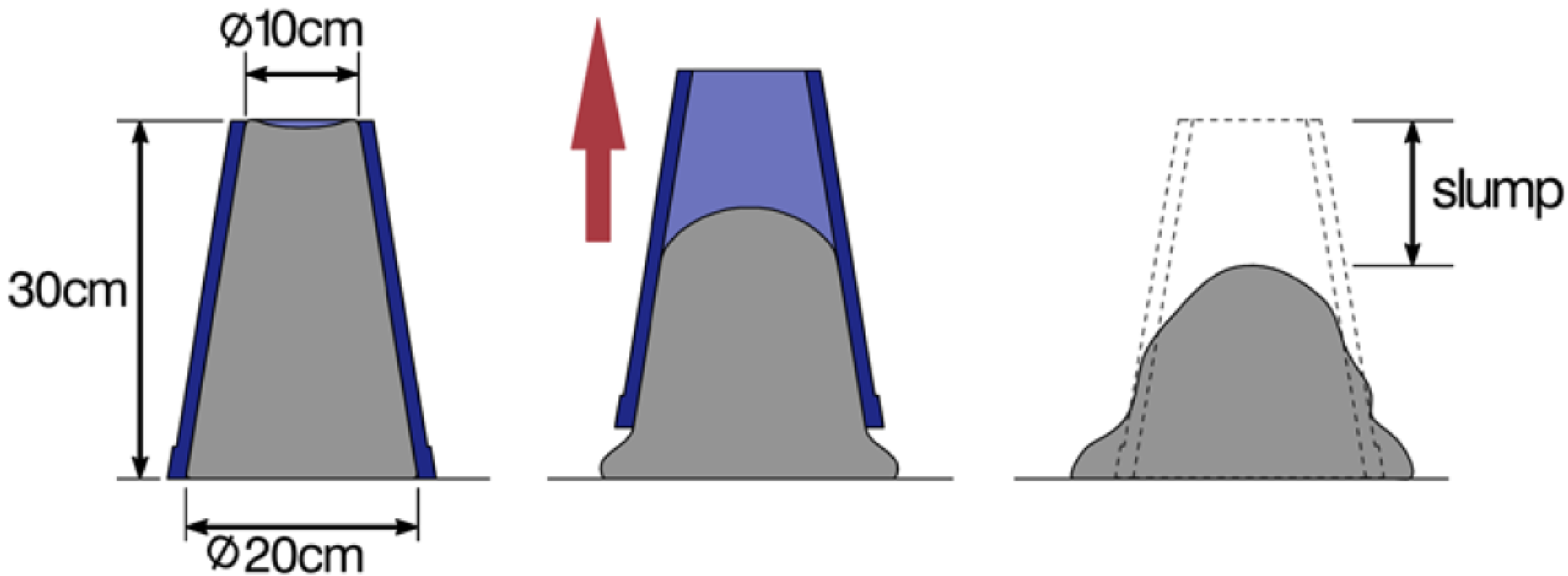
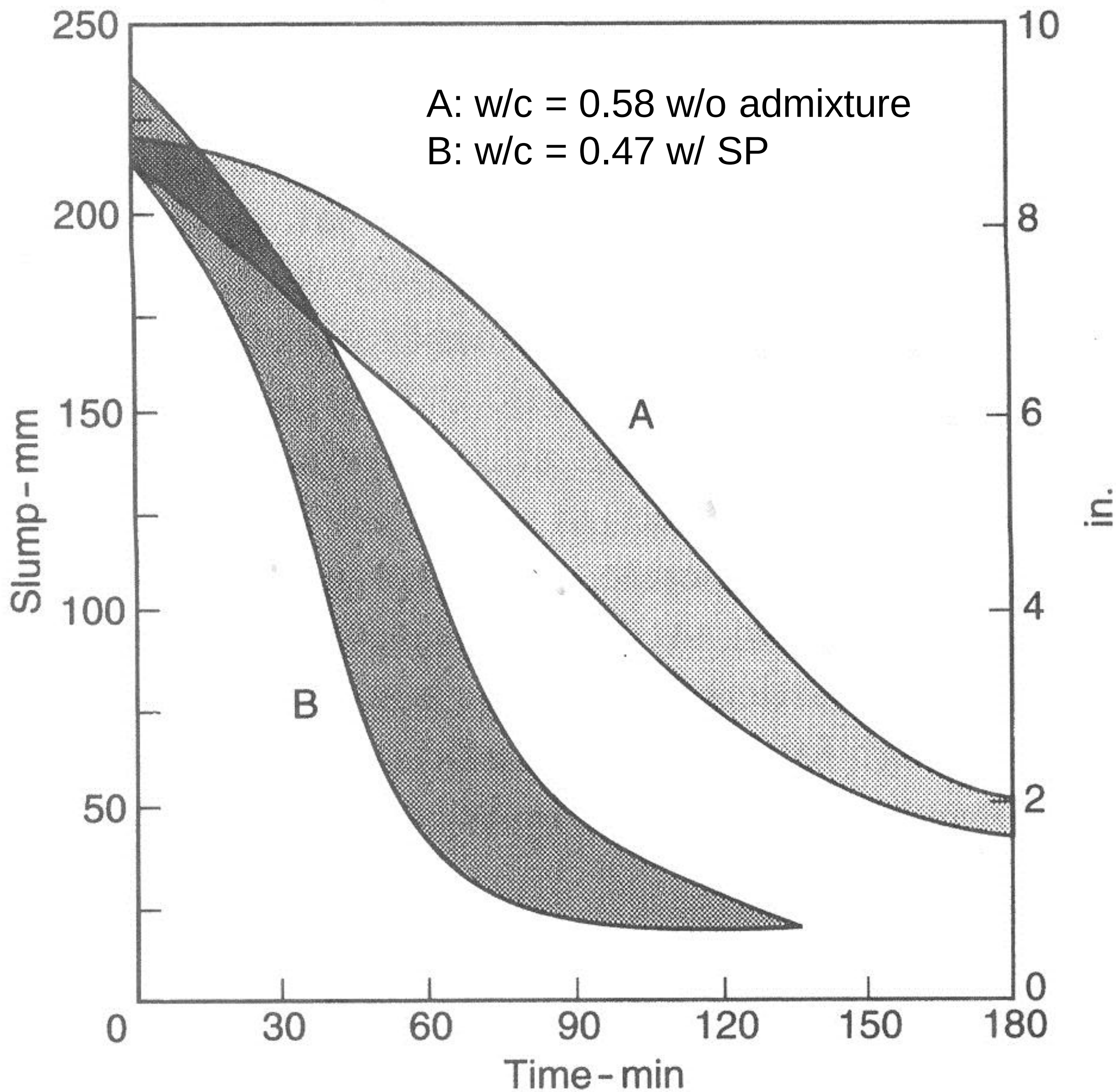
Other concerns with the use of superplasticizers

- Shorter working period (< 45 min.)
- Rapid slump loss
- Increase bleeding
- Segregation of concrete (mix design ??)



Slump Loss



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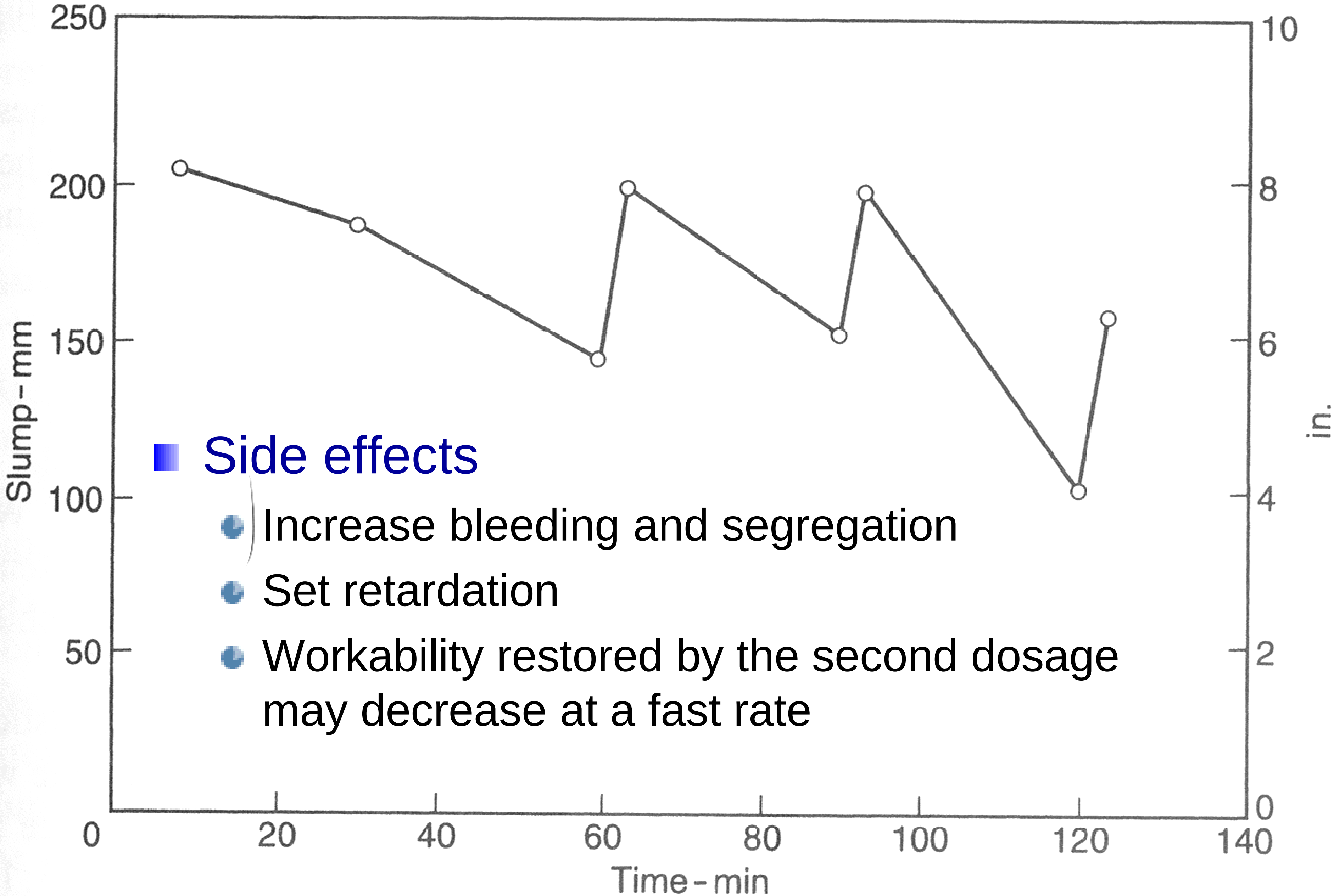
Repeated Re-dosage



- Side effects
  - Increase bleeding and segregation
  - Set retardation
  - Workability restored by the second dosage may decrease at a fast rate

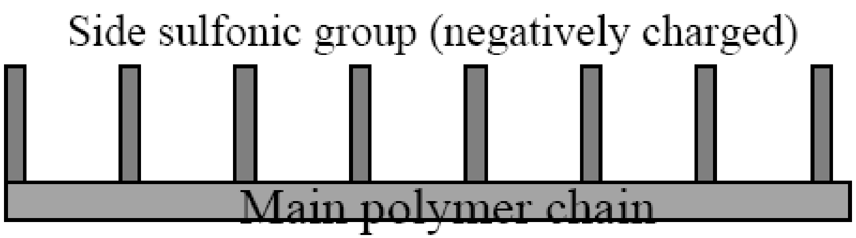
Superplasticizers

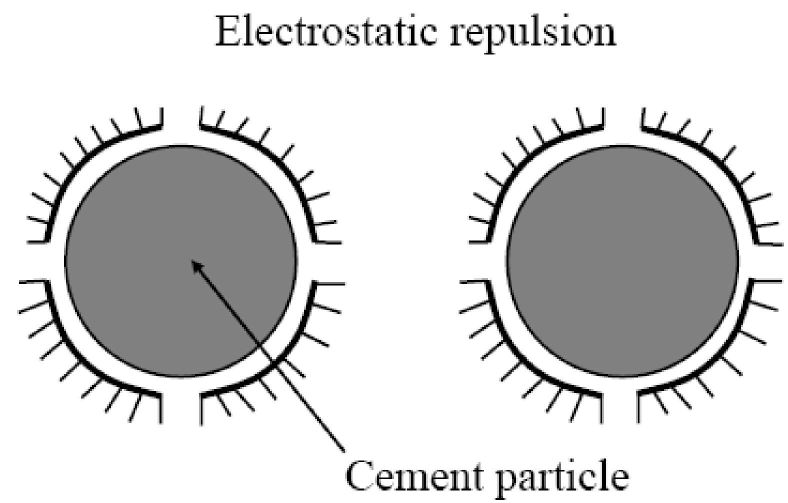
ASTM C 494 type F, G

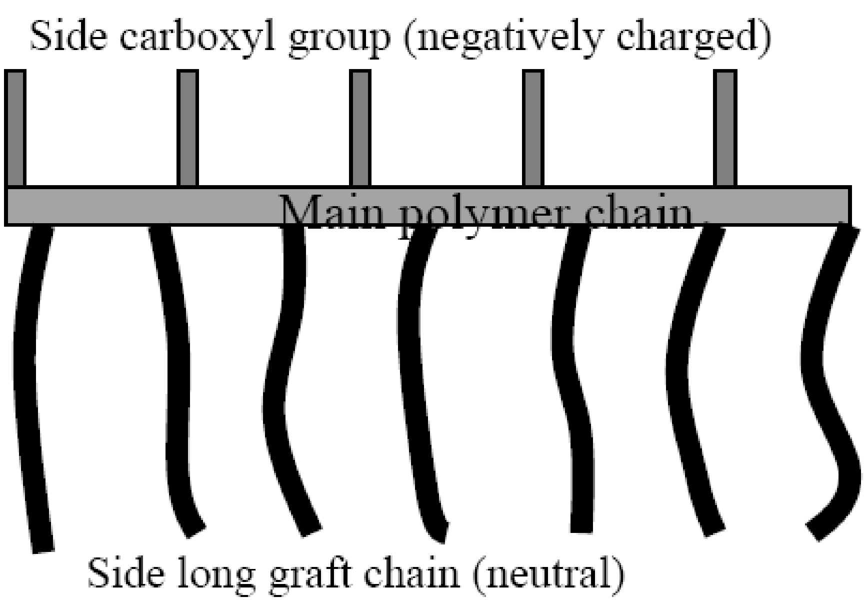
JIS A 6204

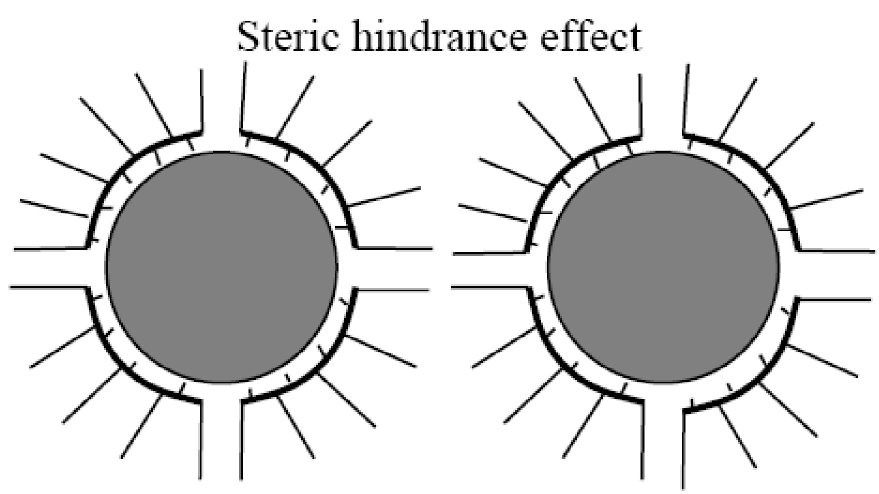
- 1st generation: Naphthalene Sulfonate
- 2nd generation: Melamine Sulfonate
- 3rd generation: Napthalene Sulfonate + Reactive Polymer
- 4th generation: Polycarboxylate (Copolymer)

Sulfonated Polymer and Copolymer Superplasticizers



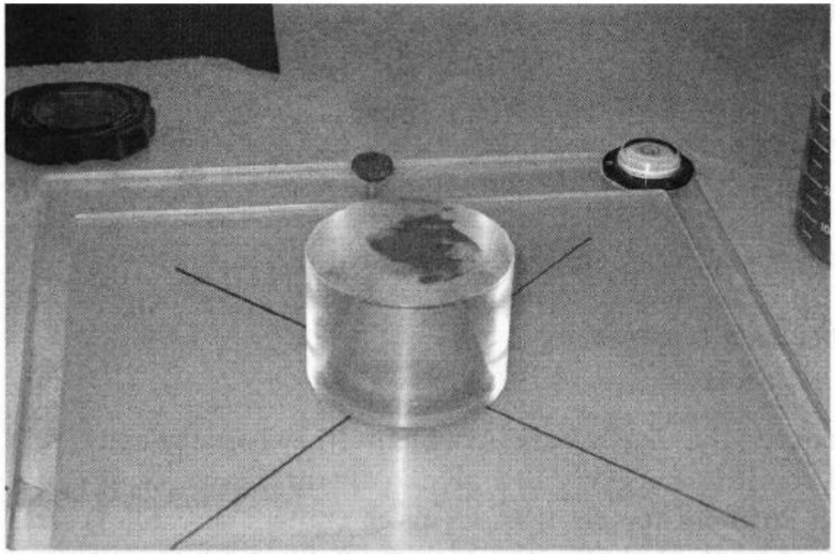


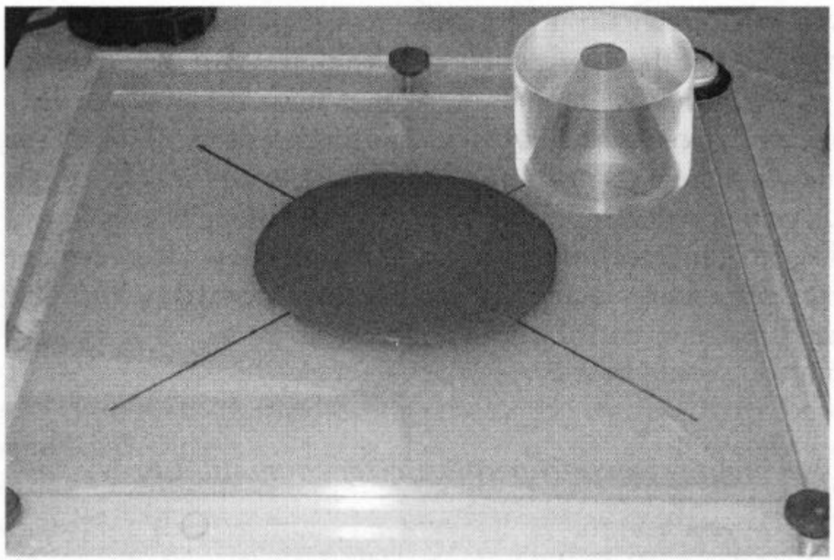




Superplasticizer-cement Compatibility

- Find optimum dosage for particular cement
- A high C_3A content in cement reduces the effectiveness of a given dosage of the superplasticizer
- The finer the cement, the higher the dosage of a superplasticizer required to obtain a given workability





Evaluation of Cement/Superplasticizers Compatibility and Robustness

Two simple comparative tests on 0.35 w/c paste at a constant temperature

1. **Mini slump test (static mode)**
2. **Marsh cone test (dynamic mode)**

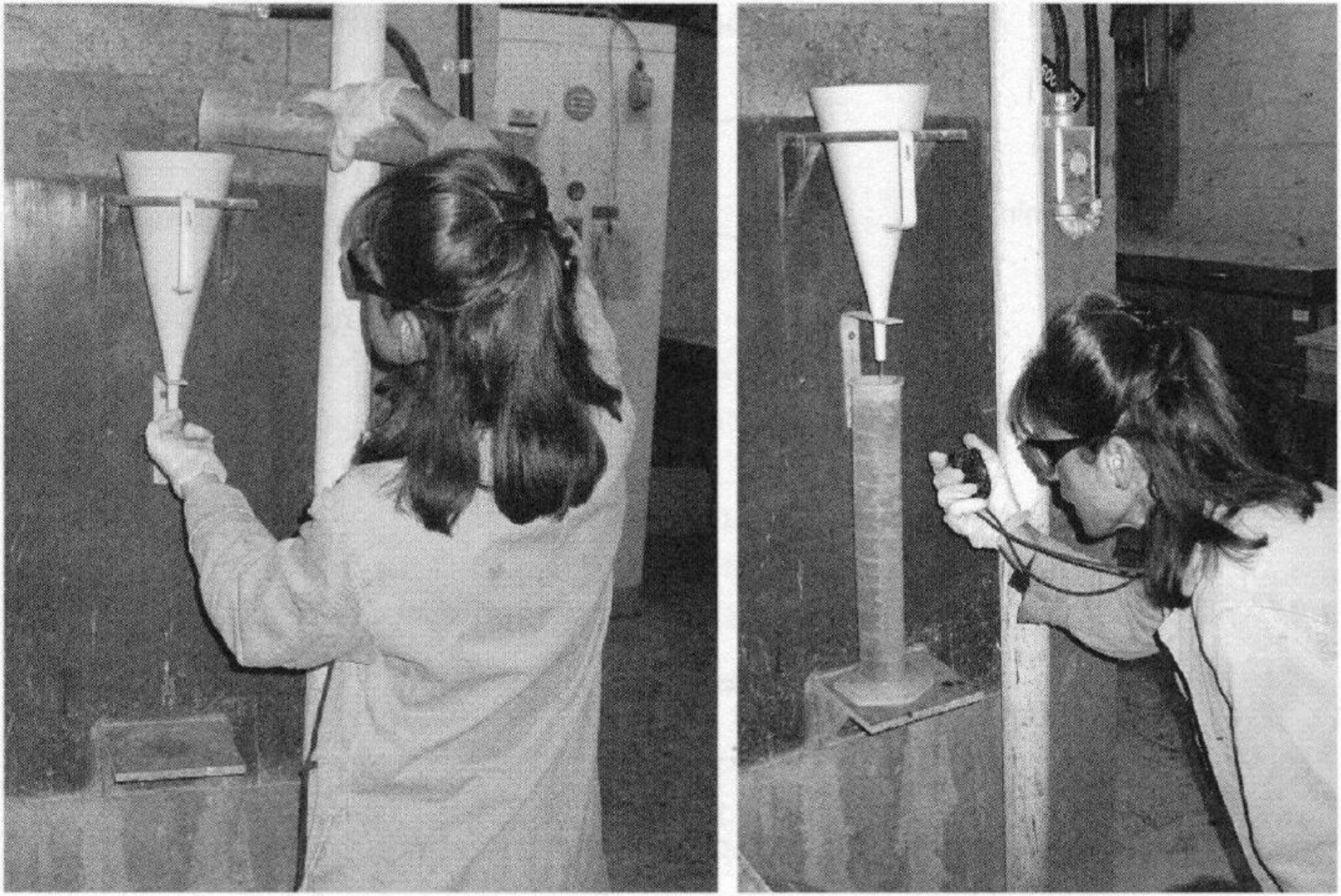
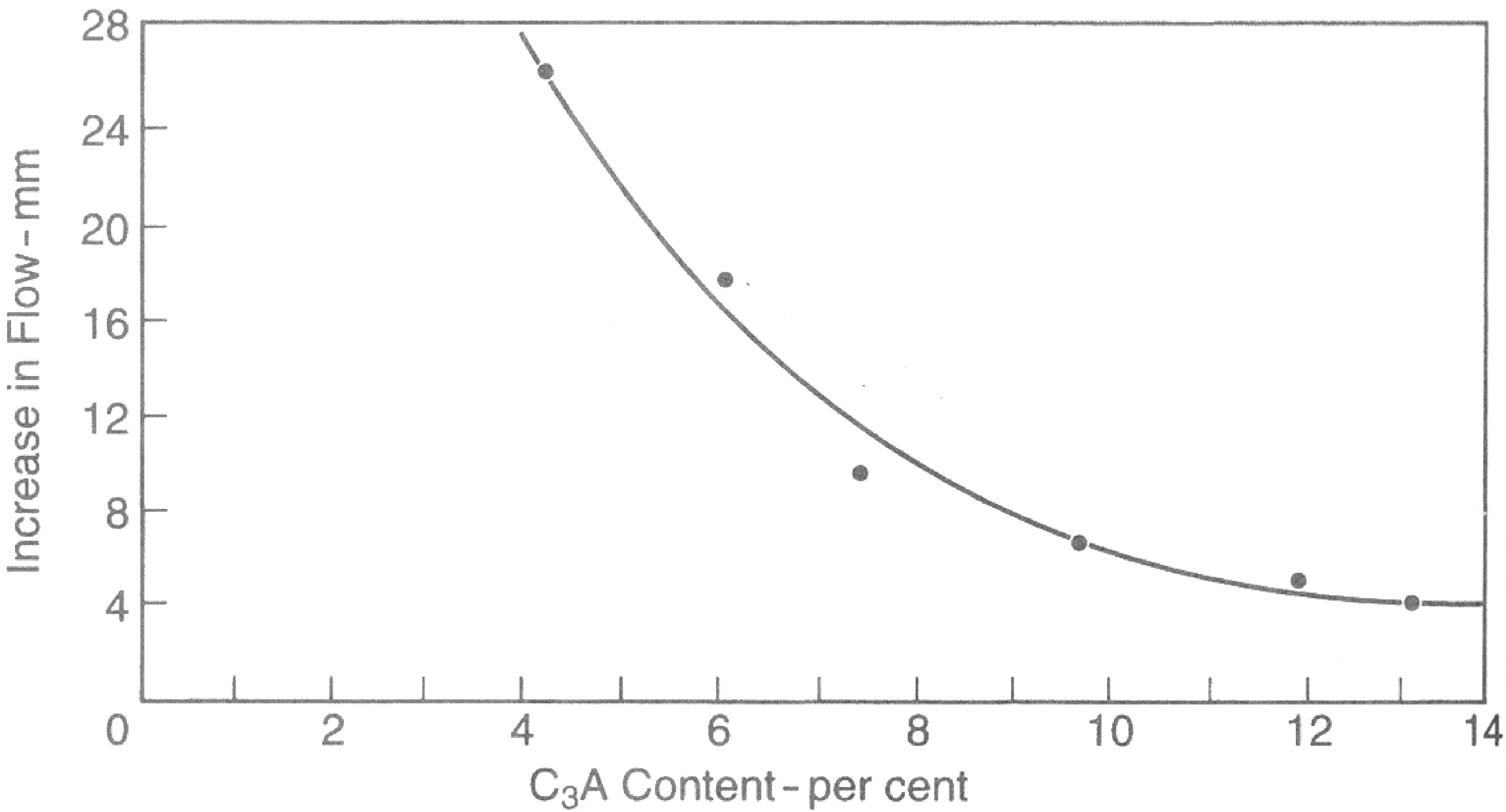
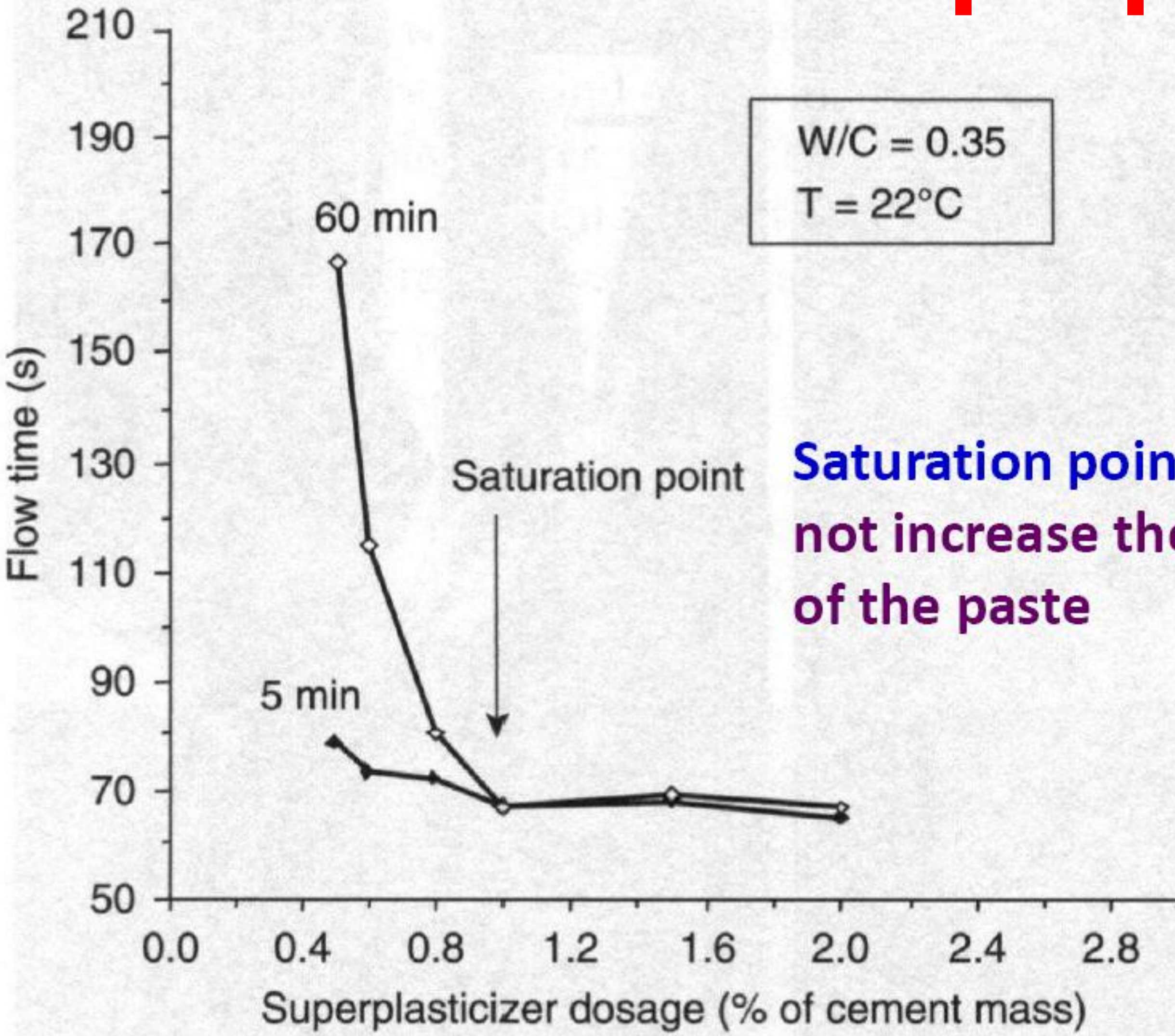


Figure 7.11 Marsh cone test. Reproduced from *Binders for Durable and Sustainable Concrete*, Aïtcin 2008. (Courtesy of Taylor & Francis).

Effect of C_3A in Cement on Mortar Flowability @ A Given Dosage of Water Reducer



Saturation of Superplasticizer



Saturation point: Higher dosage does not increase the rheological properties of the paste

Figure 7.12 Flow time as a function of the superplasticizer dosage. Reproduced from *Binders for Durable and Sustainable Concrete*, Aïtcin 2008. (Courtesy of Taylor & Francis).

Saturation Point vs Cement Type

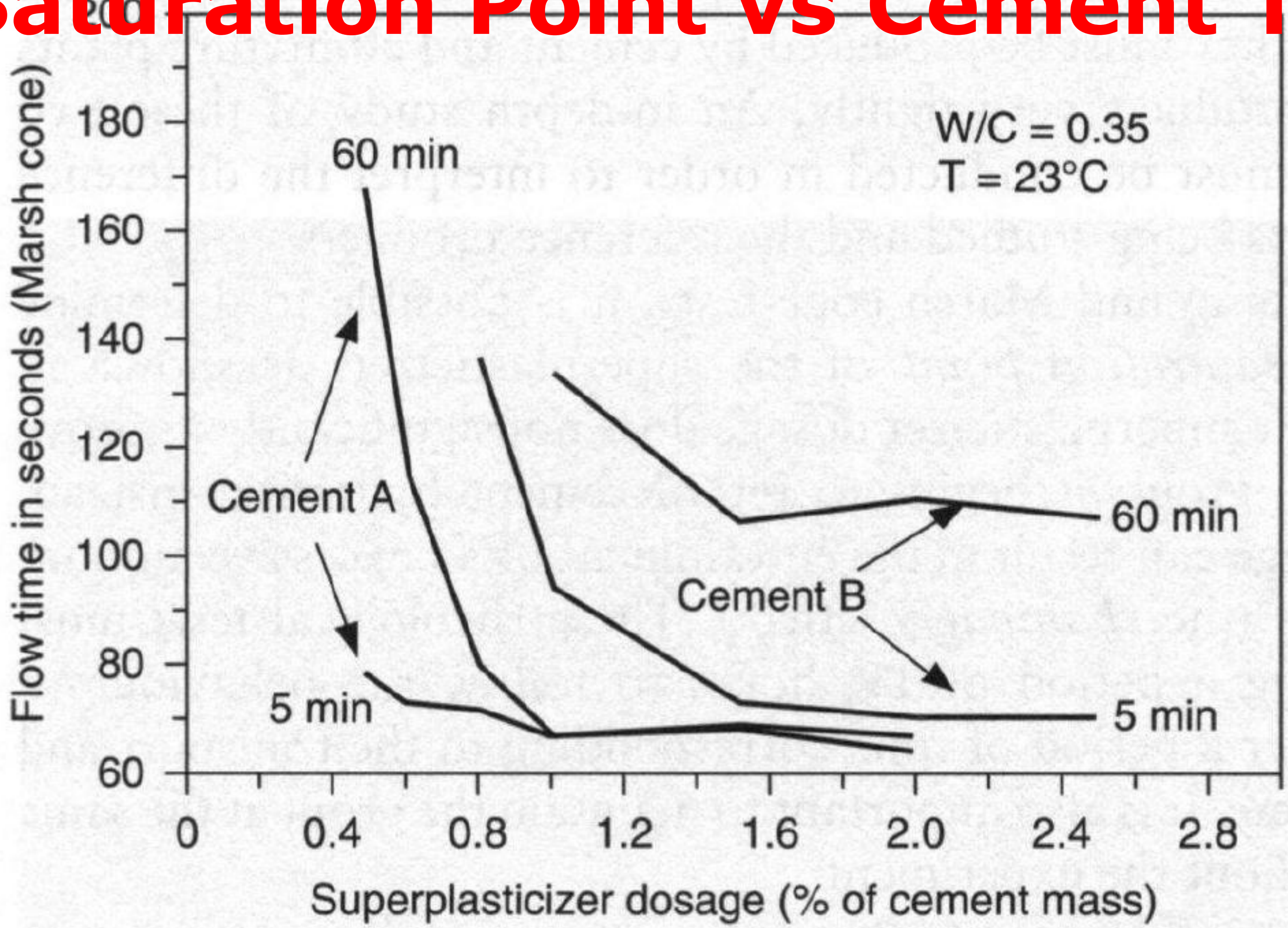


Figure 7.13 Examples of flow time at 5 and 60 minutes. Reproduced *for Durable and Sustainable Concrete*, Aïtcin 2008. Taylor & Francis).

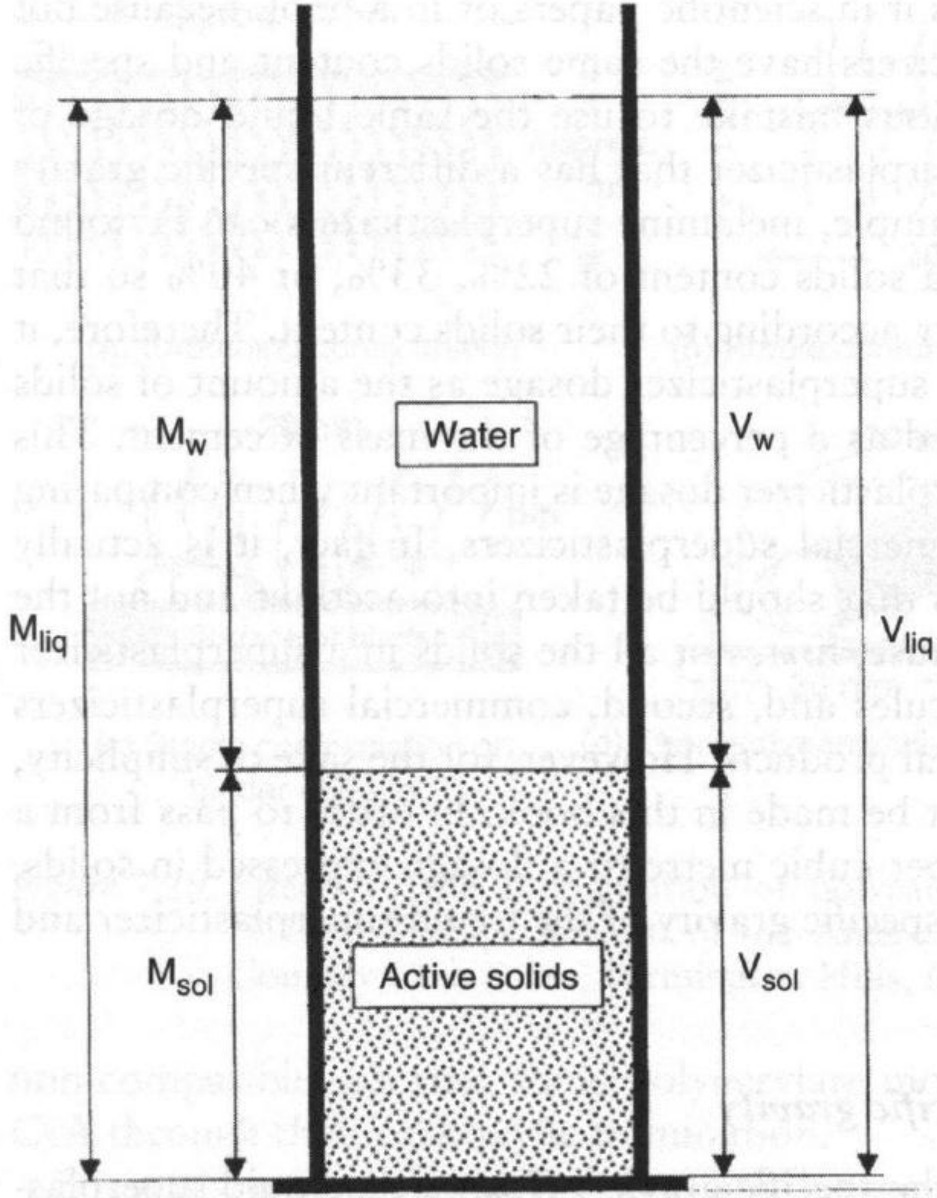


Figure 7.20 Schematic representation of a superplasticizer.
Performance Concrete, Aïtcin 1998. (Courtesy

Practical use of superplasticizers

Expressing the dosage

- Litres per cu. m. of concrete
- Solid content as a percentage of the mass of cement

  [Solid content varies with the type of superplasticizers]

Solid content, s (%) = $[M_{sol} / M_{liq}] / 100$

Mass of solid = $s \times G_{sup} \times V_{liq}$

Determine the solid content of 6 litres of the following superplasticizers:

(a) Melamine superplasticizer (Sp. gr. of 1.10 and solid content 22%)

(b) Napththalene superplasticiser (Sp. gr. of 1.21 and solid content 42%)

(a) Solid content = 0.22 x 1.1 x 6 = 1.45 kg of solids

(b) Solid content = 0.42 x 1.21 x 6 = 3.05 kg of solids

Practical use of superplasticizers

Mass of water in a given volume of superplasticizer

$M_w = M_{liq} - M_{sol}$ .... (1)

$M_{liq} = M_{sol} \times 100 / s$ .... (2)

$M_w = M_{sol}\,[(100 - s) / s]$

$M_{sol} = s \times M_{liq} / 100$

Hence, $M_w = V_{liq} \times s \times G_{sup} / 100] \times [(100 - s) / s]$

$V_w = M_w = V_{liq} \times G_{sup} \times [(100 - s) / s]$

Determine the volume of water added from 8.25 litres of superplasticizers per cu. m of concrete with the specific gravity of 1.21 and a solid content of 40% to achieve a desired slump.

$V_w = 8.25 \times 1.21 \times (100 - 40) / 100 = 6.0\ l/m^3$.

Accelerators

- These admixtures accelerate the setting, hardening or the development of early strength of concrete
- Used to
  - Reduce the amount of time before finishing operations begin
  - Reduce curing time
  - Increase rate of strength gain but lower ultimate strength
- Applications
  - Urgent repair work
  - Early formwork removal (productivity)
  - **Cold-weather concreting**
- Calcium chloride ($CaCl_2$) is most common

Accelerator: $CaCl_2$

- $CaCl_2$ causes C_3S phase of Portland cement to hydrate more rapidly. This results in an acceleration of the time of setting, a larger than usual amount of C_3S hydration products and, consequently, a higher than normal early strength.
- The basic question dealing with the mechanism through which $CaCl_2$ activates the C_3S phase of Portland cement has yet to be resolved
- $CaCl_2$ is an effective and cheap accelerator
- $CaCl_2$ has been found to increase the resistance of concrete to erosion and abrasion

Disadvantages of Using $CaCl_2$ in Reinforced Concrete

- Possibility of ***corrosion*** of reinforcing steel is increased
- Various standards and codes prohibit the use of calcium chloride in concrete containing embedded steel or aluminum

Disadvantages of Using $CaCl_2$ in Plain Concrete

- The resistance of cement to sulfate attack for lean mixes is reduced
- Risk of alkali-aggregate reaction is increased
- Drying shrinkage is increased usually by about 10 to 15%, sometimes even more
- Creep is also increased
- Resistance of air-entrained concrete to freezing and thawing at later ages is adversely affected

Non-chloride, Non-corrosive Accelerators

- Calcium nitrite and calcium nitrate, $Ca(NO_2)_2$
- Calcium formate, $Ca(CHO_2)_2$ and sodium formate

Admixture	Dosage	Increase in compressive strength %	
		3-day	28-day
$CaCl_2$	1 %	136	109
$CaCl_2$	2 %	148	102
$Ca(NO_2)_2$	1 %	128	113
$Ca(NO_2)_2$	2 %	137	112
$Ca(CHO_2)_2$	1 %	123	115
$Ca(CHO_2)_2$	2 %	133	105

Calcium Formate and Sodium Formate

- Calcium formate is effectively only when used with cements which have a ratio of C_3S to SO_3 of at least 4 and have a low SO_3 content
- Sodium formate would introduce sodium into the mix, and this alkali has a potential reaction with some aggregates

Retarders

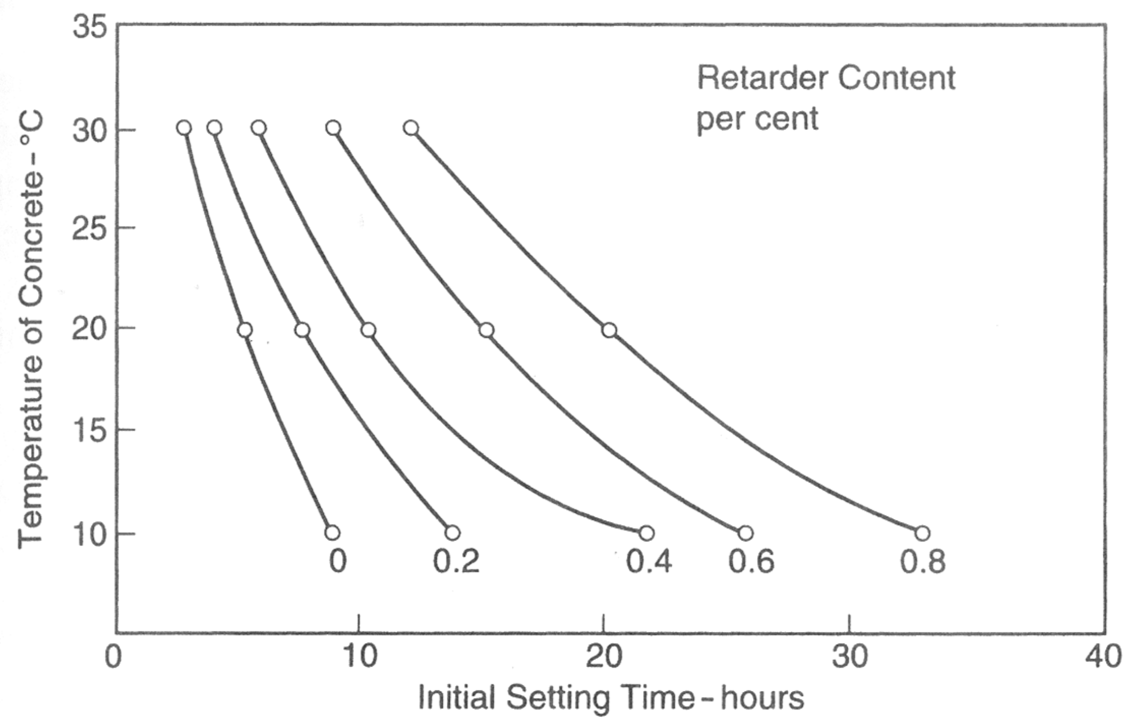
- These admixtures delay or retard initial set
  - Slowing down the early hydration reaction
  - Usually doesn't reduce final set time much
  - May reduce early strength but increase the ultimate strength
- Applications
  - **Hot weather concreting**: the normal setting time is shortened by higher temperature
  - Unusual placement
  - Long haul distance
  - Special finishes (e.g., exposed aggregate)
- Sugar is a cheap retarder

Retarder: Sugar

- It seems that, used in a carefully controlled manner, a small quantity of sugar (about 0.05% of cement by weight) acts as acceptable retarder
  - Delay in setting of concrete is about 4 hours
- A large quantity of sugar, say 0.2 to 1% of cement by weight, virtually prevents setting. Such quantities of sugar can therefore be used as an inexpensive “kill”. For instance, when a mixer or an agitator has broken down and cannot be discharged

Retarder

- Retarders are often used in hot weather. Therefore, it is important to note that the retarding effect is smaller at higher temperatures and some retarders cease to be effective at extremely high ambient temperature, about 60^{o}C



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Retarder

ASTM C 494-92

- To retard the initial set by at least 1 hour but not more than 3.5 hours, as compared with a control mix.
- The compressive strength from the age of 3 days onwards is allowed to be 10% less than the strength of the control concrete

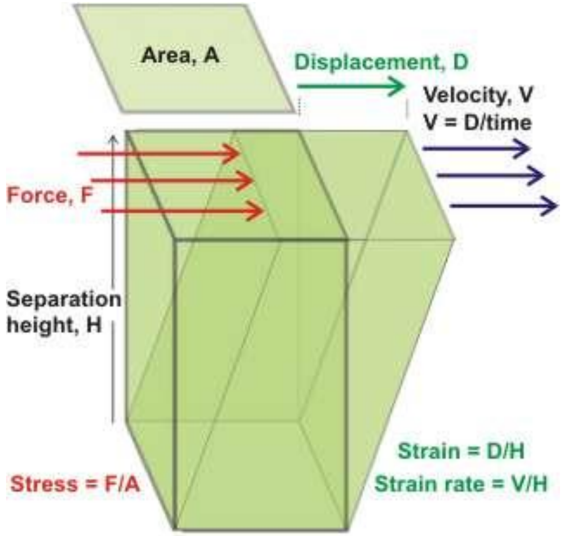
Other Chemical Admixtures – Viscosity Modifying Admixture (VMA)

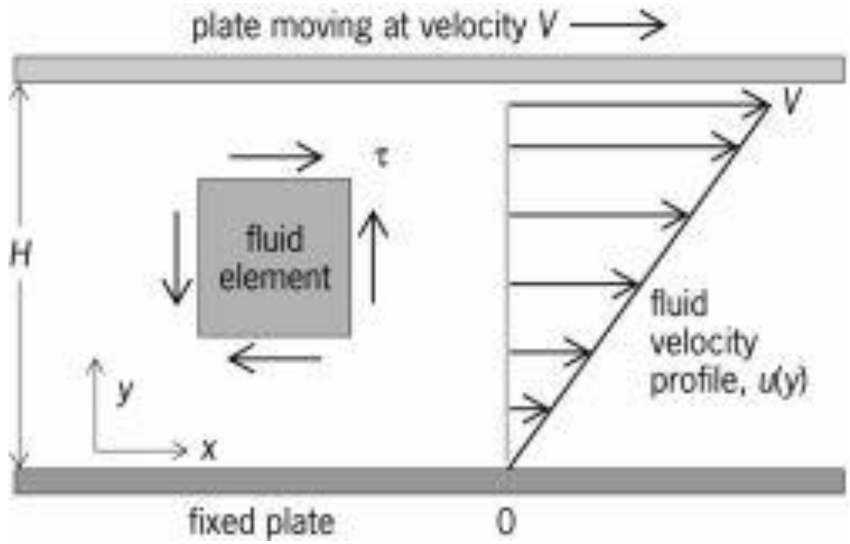
VMA used be used to produce concrete with better robustness against impact of variations in the concrete constituents and in site conditions, making it is easy to control and more friendly to the producer and the user.

Key function of VMA to modify the rheological properties of the cement paste

- Yield point (Force needed to start the concrete moving)
- Plastic viscosity
  (Resistance of a concrete to flow under external stress)

Basic Principles of Rheology



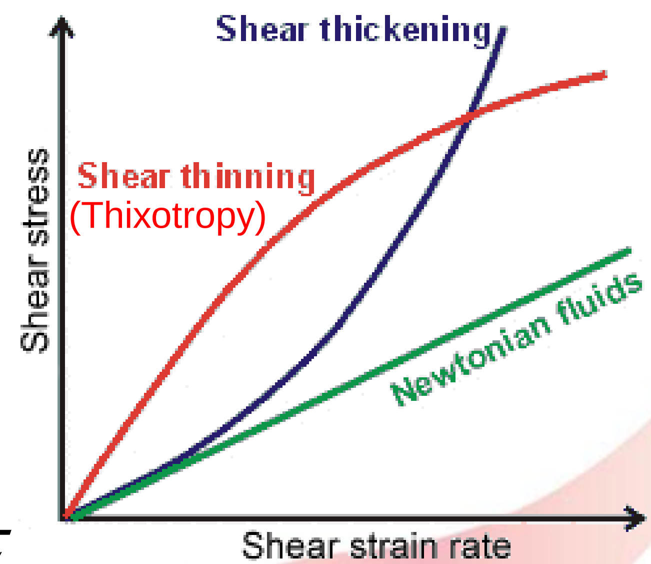


$$\tau = \eta \dot{\gamma}$$

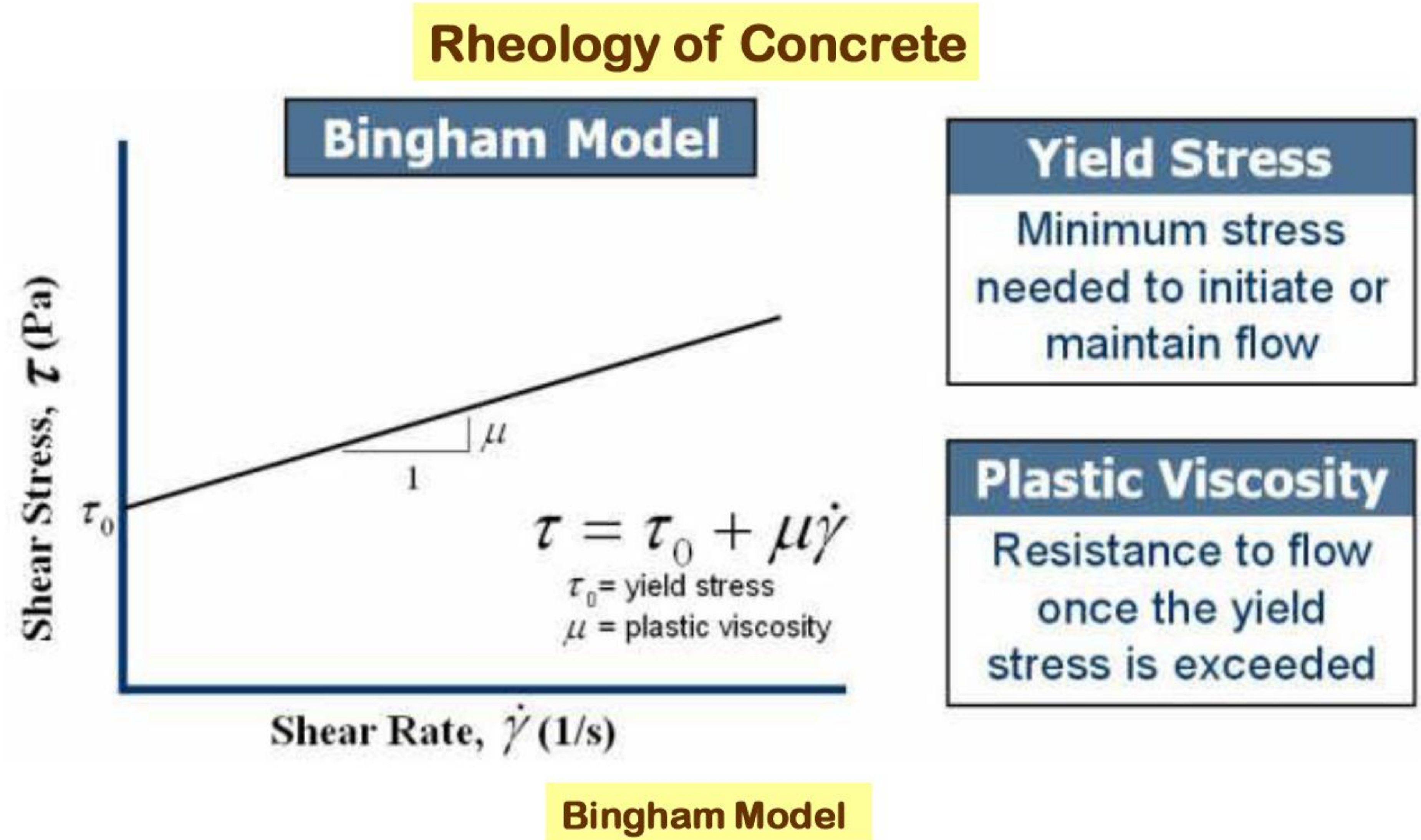
$$\text{Shear stress, } \tau = \frac{F}{A}$$

$$\text{Rate of shear, } \dot{\gamma} = \frac{dV}{dH}$$

$$\text{Coefficient of viscosity, } \eta = \frac{\tau}{\dot{\gamma}}$$



Bingham Model



Application of VMA

VMA's are a family of admixtures designed for special applications

They are used to:

1. Reduce segregation in high flowable/self compacting concrete (used together with superplasticiser)
2. Reduce washout in underwater concrete
3. Reduce friction and pressure in pumped concrete
4. Compensating for poor aggregate grading, especially a lack of fines in the sand
5. Reducing powder content in self compacting concrete
6. Improve green strength in semi-dry concrete

Most of the Viscosity Modifying Admixtures are based on high molecular weight polymers with high affinity to water

VMA supplied: Powder form or are dispersed in liquid

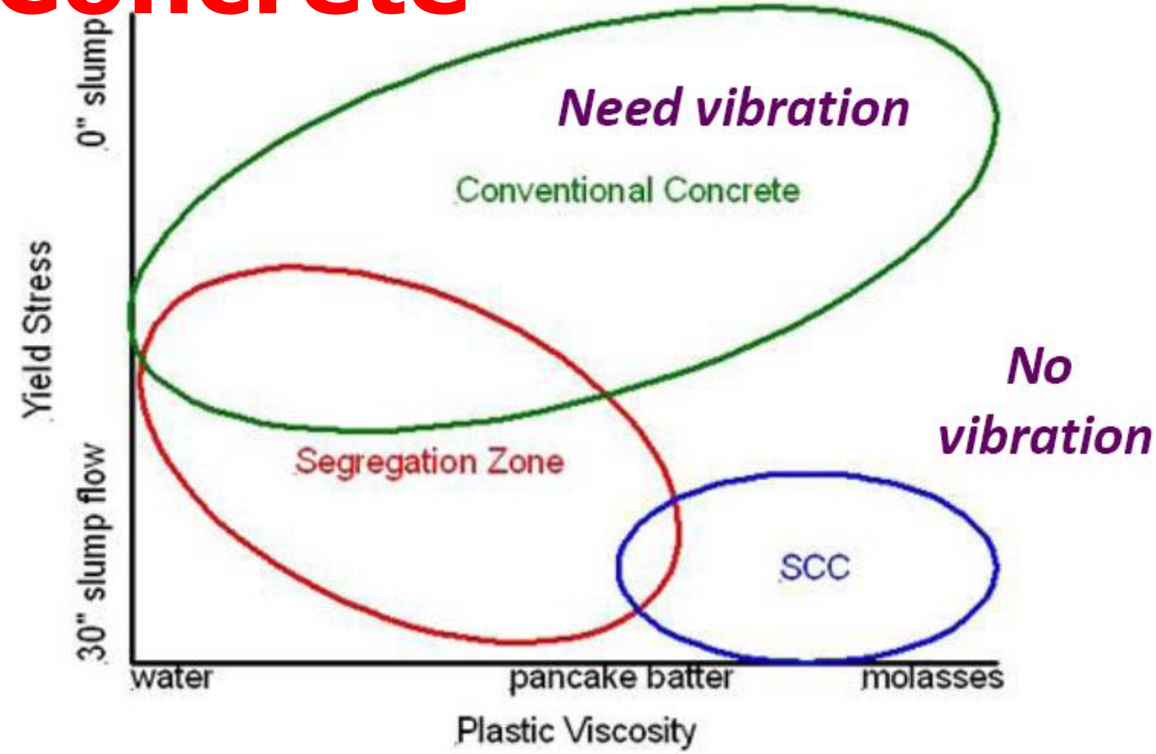
Dosage: 0.1 to 1.5% of cement weight
(Varied for specific application)

Effects: Little effect on other concrete properties; high dosage can effect setting of concrete

Mode of action:

By interaction of polymer, water and fines, VMA's *build up a three dimensional structure* in the liquid phase of the mix to increase the viscosity and/or yield point of the paste.

VMA in Producing Self-compacting Concrete



Self-compacting concrete (SCC)
Low yield stress;
High viscosity (less segregation)

Other Chemical Admixtures – Waterproofing

- Waterproofing admixtures aim at preventing water penetration into concrete by making the concrete hydrophobic. By this is meant an increase in the contact angle between the walls of the capillary pores and water, so that water is "pushed out" of the pores

Source: Hycrete Admixture

Other Chemical Admixtures – Corrosion Inhibiting

- Corrosion inhibiting admixtures reduce the tendency for reinforcing steel to undergo corrosion in concrete. Such compounds probably do no inhibit the corrosion reactions completely, but reduce the rate of corrosion to a level that major damage to concrete will be avoided or at least greatly reduced.
  - Calcium nitrite (also a nonchloride accelerator)
  - Sodium chromate
  - Sodium benzoate

Other Chemical Admixtures – Bonding, Coloring

- Bonding admixtures
  - These are organic polymer emulsions used to enhance the bonding properties of concrete, particularly for patching and remedial work
- Coloring admixtures or pigments
  - Coloring pigments, in powder form, are normally used in concrete for architectural purposes and the best effect is produced when they are interground with the cement clinker rather than added during mixing

Sustainability of Concrete and Admixture Usage

First-Order Contributions

Sustainability related to material properties

Concrete with higher strength	⇒	Use less concrete
Concrete with greater durability	⇒	Longer service life
Strength with less cement	⇒	Use less cement
Strength with less water	⇒	Use less water

For constant water to cement ratio

Reduction of cement will be:

5 to 10% with Plasticizer

15 to 40% with Superplasticiser

For constant workability

Reduction in water to cement ratio leads to decreased permeability and increased strength

Sustainability of Concrete and Admixture Usage

Second-Order Sustainability Contributions Related to SCM's

Incorporation of FA, BFS, SF, etc. improve

STRENGTH and DURABILITY (FIRST–ORDER gains)

+

- Beneficiation of industrial residues
- Reduction of cement consumption
- Less CO_2 from cement fabrication (environment)
- Energy savings (clinker, grinding)

Sustainability of Concrete and Admixture Usage

Third-Order Sustainability Contributions

Related to concrete technologies

- Fluid concrete ⇒ Reduced batching energy
- Pumpable concrete ⇒ Reduced transportation energy
- Self-consolidation ⇒ Lower placing energy (vibration)
- High workability ⇒ Reduced construction times

FRESH CONCRETE

Properties of Fresh Concrete Can…

- Affect the choice of equipment needed for handling and consolidation
- Affect the properties of the hardened concrete

Requirements of Fresh Concrete

1. **Consistency:** Sufficient consistency for proper mixing
2. **Uniformity** within & between batches
3. **Flowability:** Ability to flow into any shapes of the moulds and between reinforcements
4. **Pumpability:** Ability to place concrete by pumping method

Requirements of Fresh Concrete

5. **Compactability:** Ability to compact with ease in place

6. **Stability:** Segregation and bleeding during transporting, placing and compacting

7. **Finishability:** Possible to finish the concrete surface with ease

Compaction and Finishing of concrete

Improperly consolidated Concrete


Segregated concrete with poor compaction

- 80MPa concrete, pumped to 606m
- 100mm aluminum tube for pumping (50T)
- 12 cu. m. concrete needed to fill the tube
- 165,000 cu. m. pumped concrete in 32 months
- Pumping done in night
- Crushed ice was used to achieve 28°C

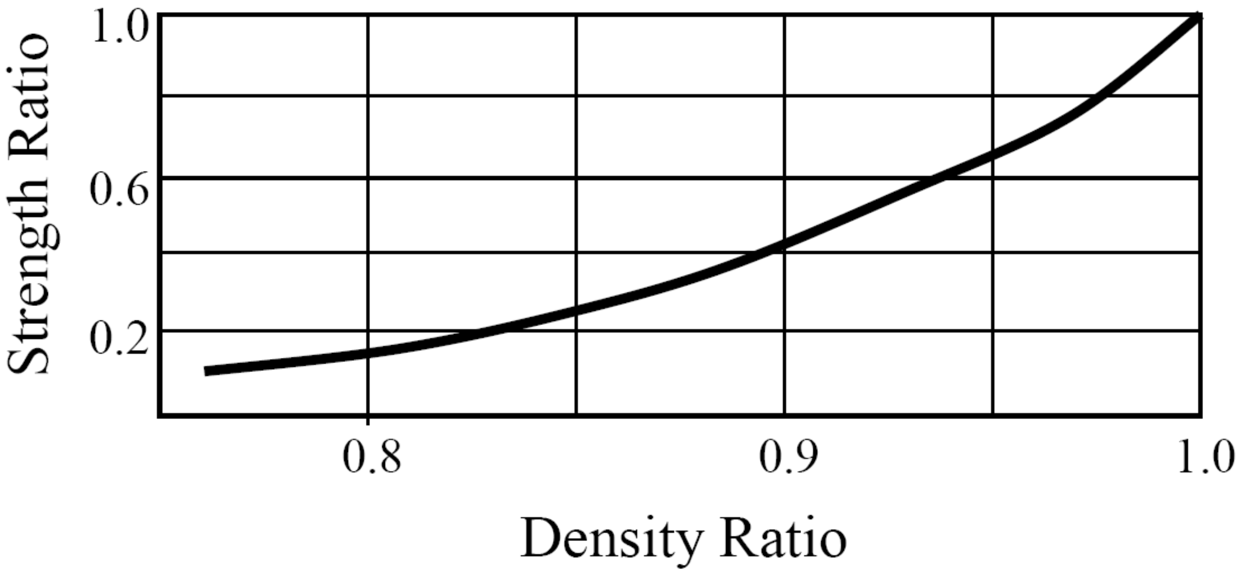
World Tallest Building 828m Burj Khalifa (Dubai) 2010

Workability of Concrete

- Definition
  - The amount of mechanical work, or energy, required to produce full compaction of the concrete w/o segregation
  - **ASTM C 125-93**. Property determining the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity
  - **ACI 116R-90**. Property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished

Workability of Concrete

- Concrete must have a workability such that compaction to maximum density is possible with a reasonable amount of work



Density ratio. Ratio of actual density of given concrete to density of the same mix when fully compacted
Strength ratio. Ratio of actual strength of give concrete to strength of the same mix when fully compacted

Two Main Components of Workability

- **Consistency** describes the ease of flow.
  - **ACI**. The relative mobility or ability of freshly mixed concrete or mortar to flow
- **Cohesiveness or stability** describes the tendency to bleed or segregate.

Required Consistency for Fresh Concrete Depends On …

- Transportation method
- Reinforcement details
- Type of compaction
- Member size
- Member shape

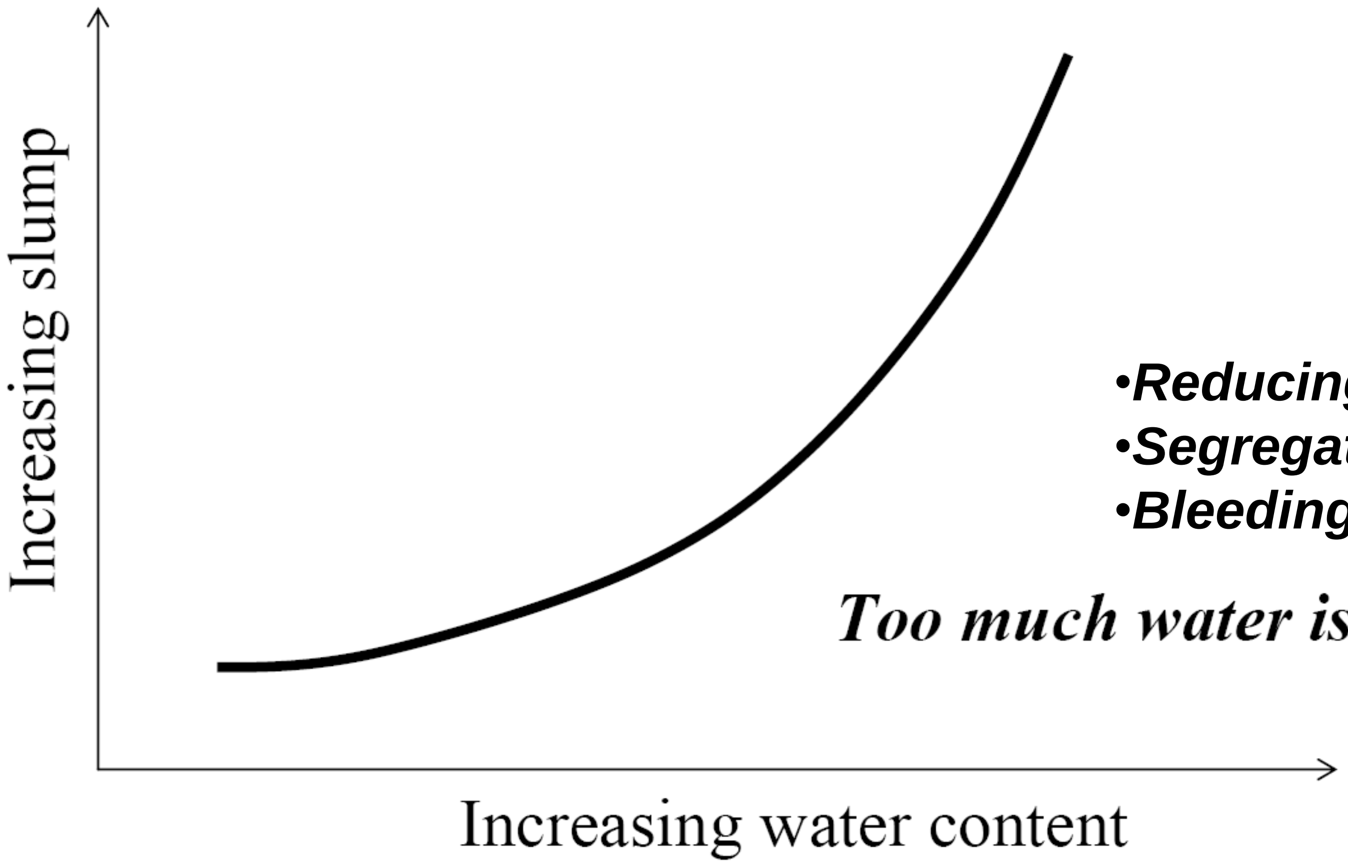
Consistency Requirement for Fresh Concrete

Factors Affecting Workability

1. Free Water Content (Primary Factor)

- Water absorbed by concrete materials
- Free Water (Responsible for workability)
  [Increase in free water content increases the consistency of concrete]
  - Cement + Free Water = Cement Paste
  - Cement Paste
    - Coats the aggregate particles
    - Lubricates the concrete (Workability)

Effect of Water Content on Slump



- *Reducing strength*
- *Segregation*
- *Bleeding*

Too much water is not good !

2. Cement Content (Primary)

Increase in cement content increases the workability of concrete

- **Increases the cement paste content**
- **Decreases the aggregate content**

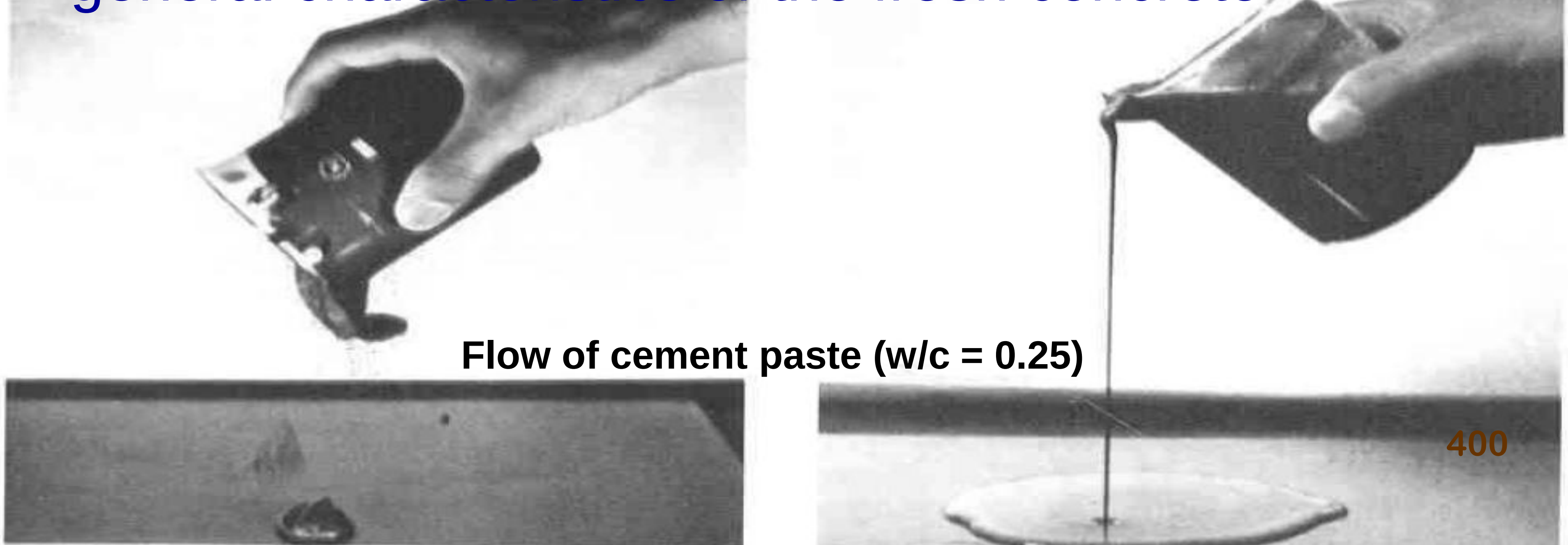
Concrete will become more cohesive and sticky

3. Water-Reducing Admixtures (Primary)

- **Addition of (Plasticizer and Superplasticizer) increases the workability**
- **Addition of air-entraining admixture increases the workability**

Effect of Admixtures on Workability

- The principal admixtures affecting improvement in workability of concrete are **water-reducing** and **air-entraining** agents as well as fly ash.
- The extent of increase in workability is dependent on the type and amount of admixture used and the general characteristics of the fresh concrete



Flow of cement paste (w/c = 0.25)

4. Aggregate Grading (Primary)

- Continuous aggregate grading reduces the void content and improves workability of concrete
- Under-sanded (Harsh) and over-sanded (Fat) mixes difficult to compact
- Amount of water necessary to wet the aggregate particles depends on the total surface area of the aggregates particles
- Increase in the fine aggregate proportion reduces the workability
- Increase in the fineness of sand decreases the workability

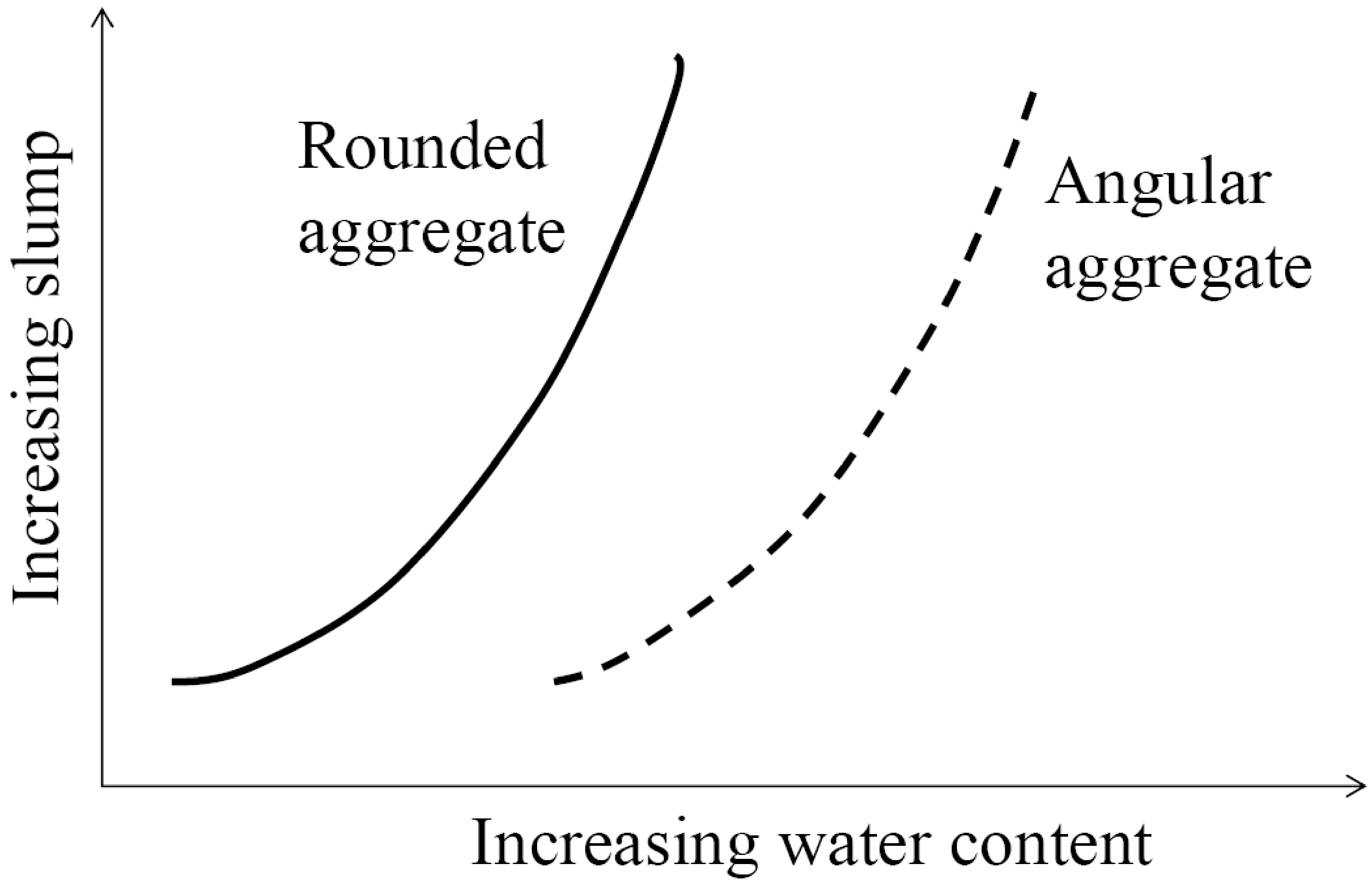
5. Aggregate Shape and Size (Primary)

- For a given mix, low Angularity No. (rounded and smooth aggregates) produce more workable concrete
- Decrease in the maximum aggregate size of coarse aggregate reduces the workability

6. Temperature and Time (Primary)

- Increase in concrete temperatures reduces the workability of concrete
- Increase in the time after mixing reduces the workability due to: Cement hydration (stiffening); and Evaporation.

Effect of Agg. Shape on Slump

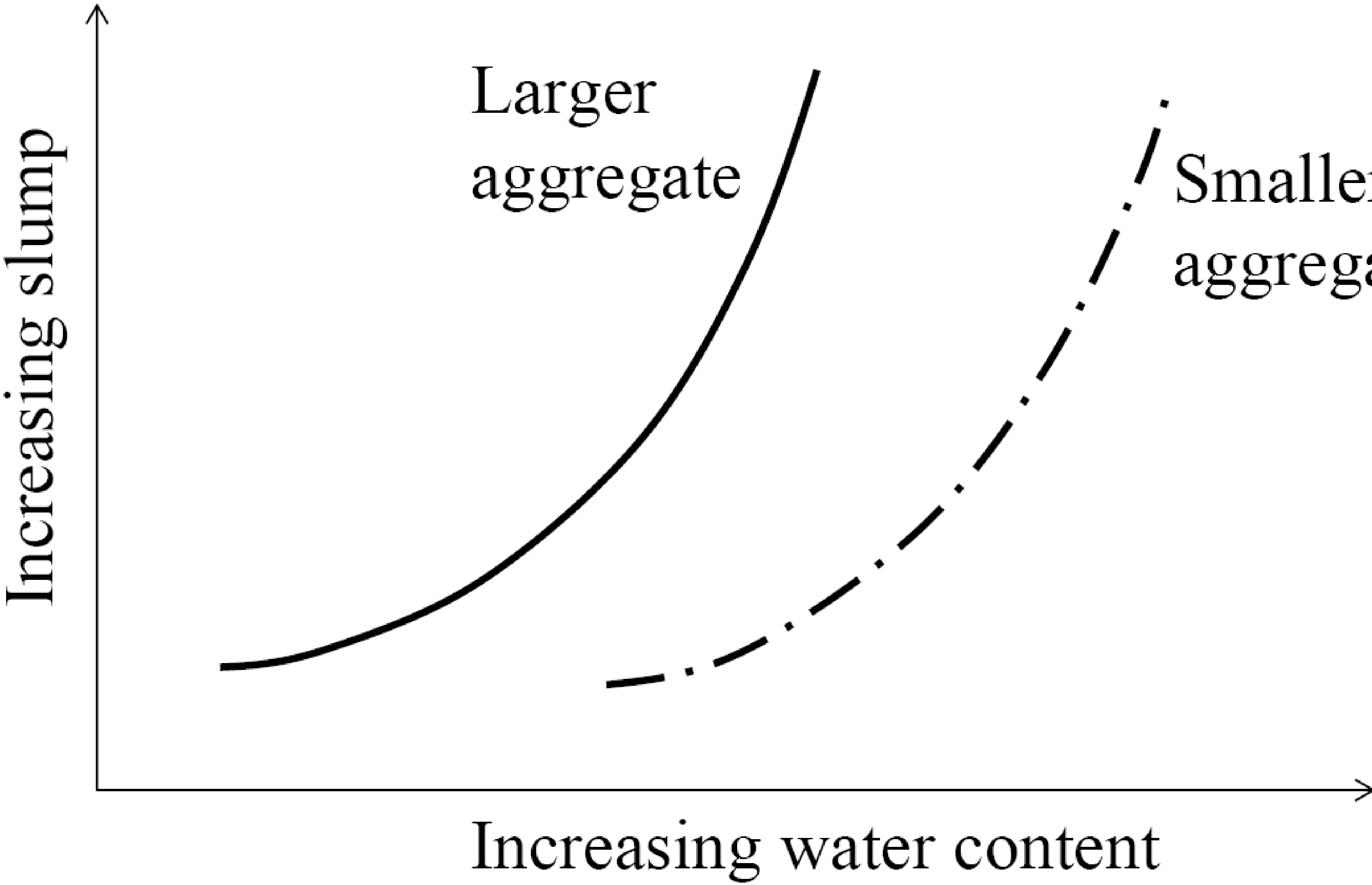


Roundness and smoothness of aggregates increases slump.

Experimental Date

- Mix proportion
  - w/c: 0.5
  - Cement: 462 kg/m^3
  - Coarse aggregate: 924 kg/m^3
  - Fine aggregate: 693 kg/m^3
  - Water: 231 kg/m^3
  - Gradation: continuous
- Slump
  - Rounded: 175 mm
  - Angular: 140 mm

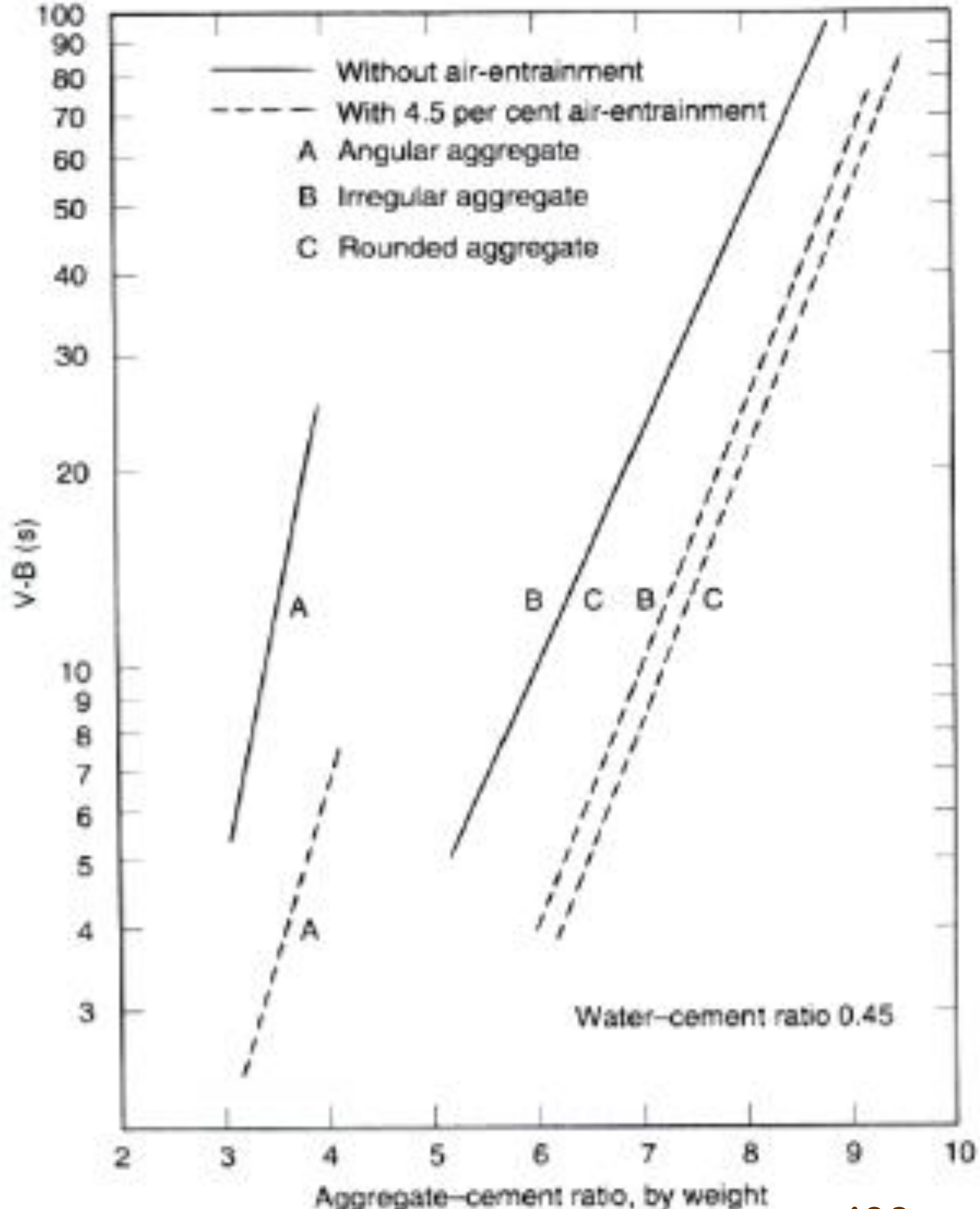
Effect of Agg. Size on Slump



Slump decreases as specific surface are of aggregate increases (smaller size), since this requires a greater proportion of water to wet aggregate particles, thus leaving a smaller amount of water for lubrication.

Influence of Aggregate to Cement Ratio on Workability

- For a constant w/c ratio, an increase in the agg/c ratio will decrease the workability
- Higher Vebe time (V-B) corresponds to lower workability



Source: Jackson & Dhir

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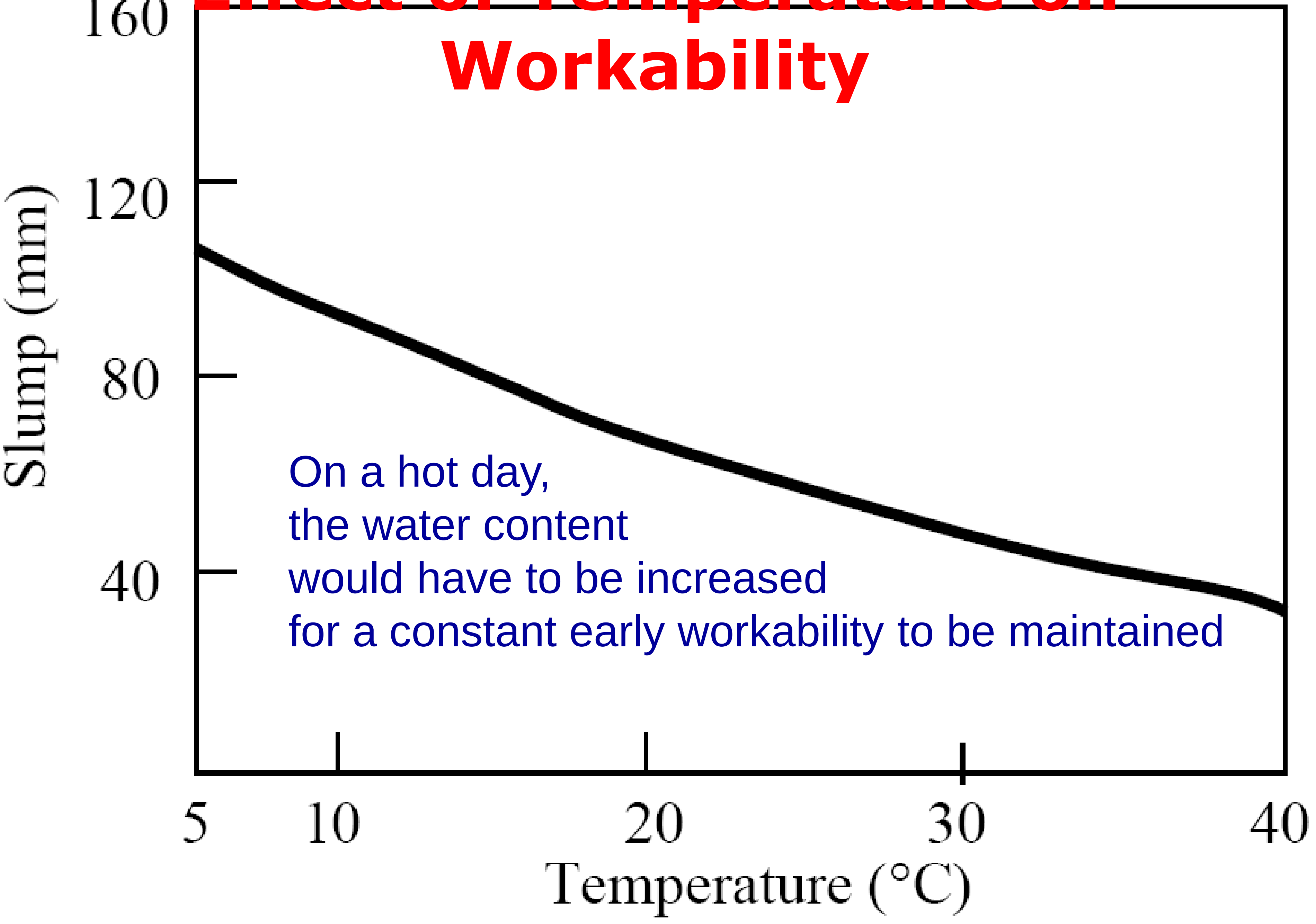
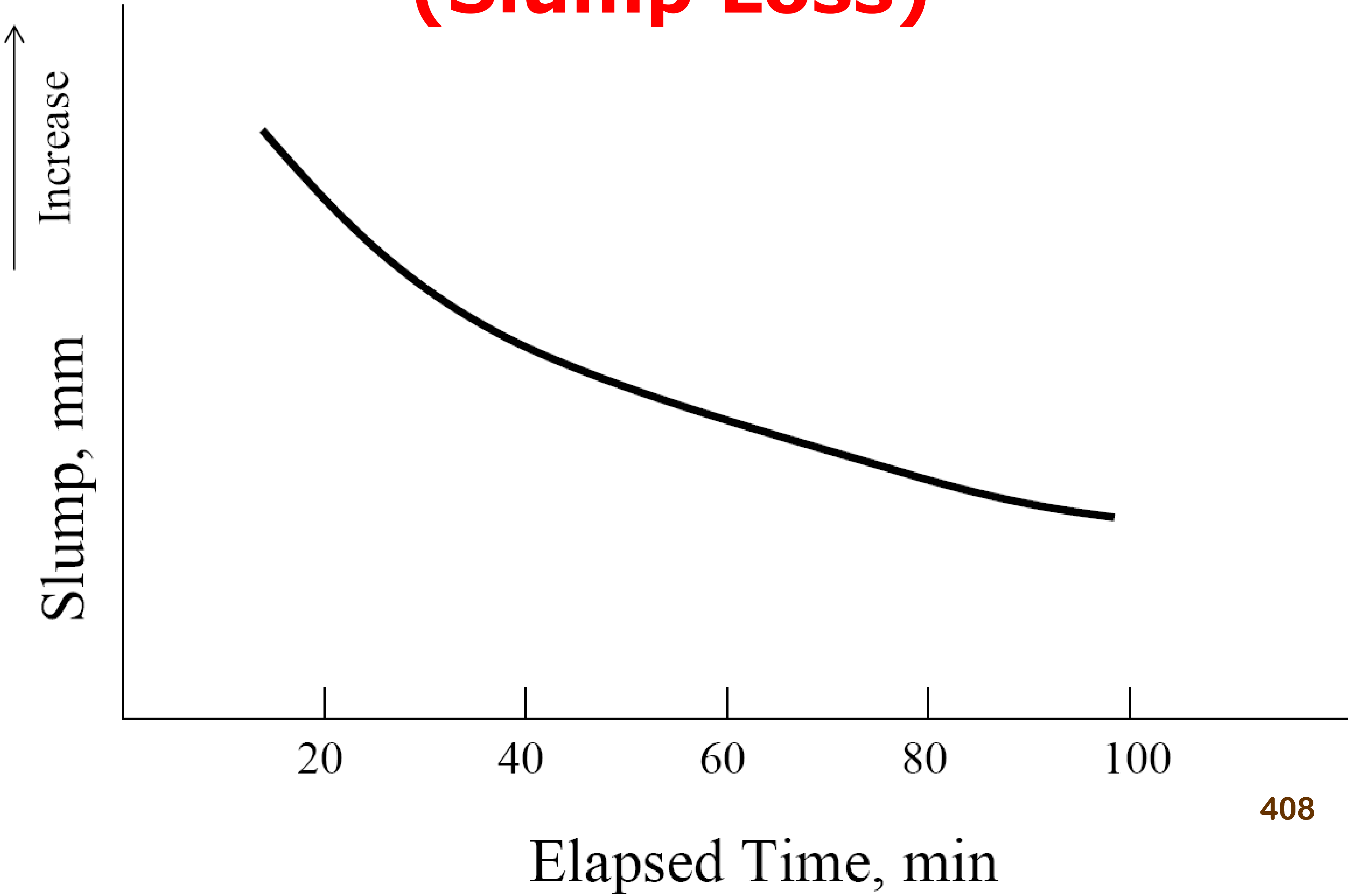
Effect of Temperature on Workability



Effect of Time on Workability (Slump Loss)



Cause of Slump Loss

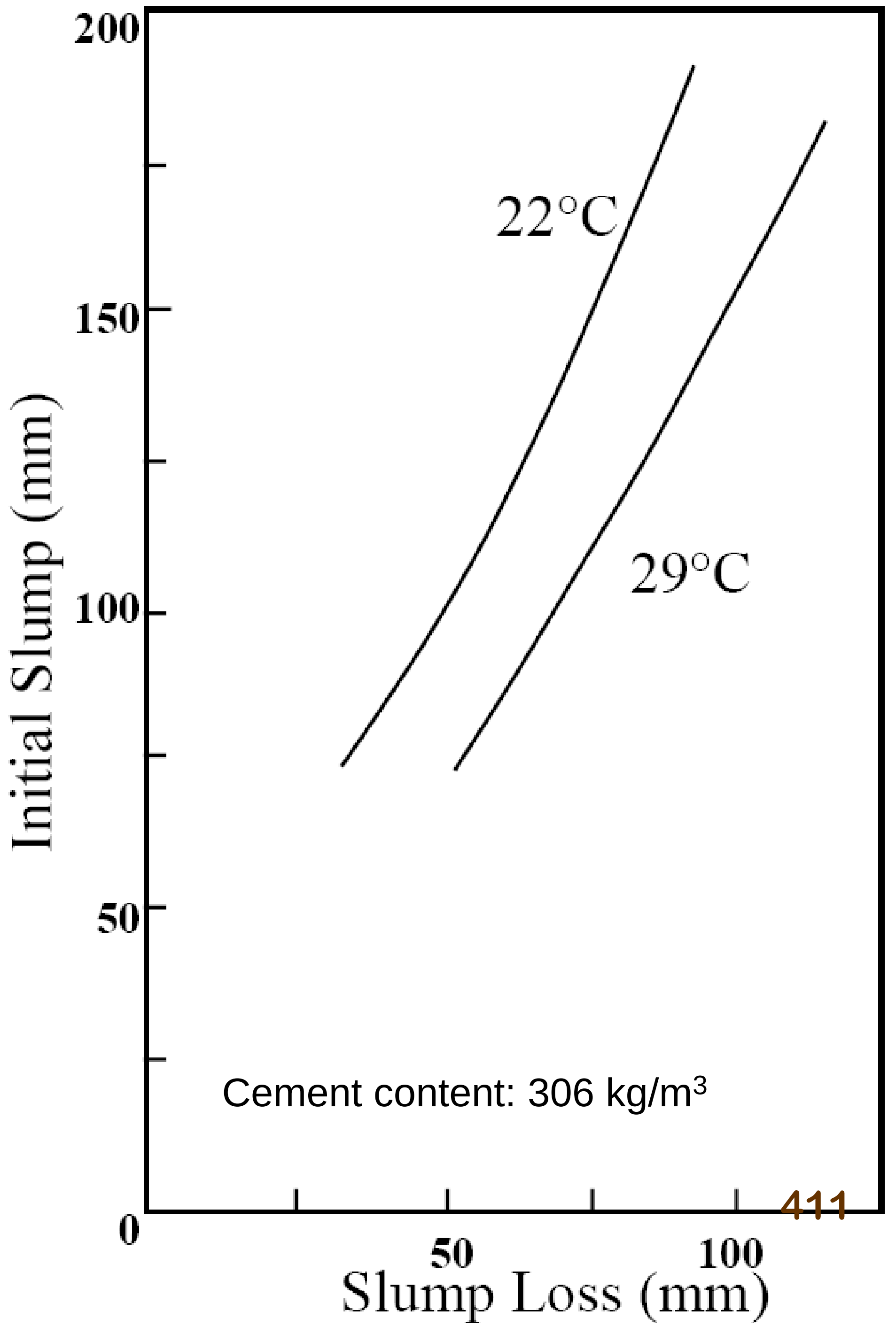
- Hydration of C_3S and C_3A
- Particle interactions change because of the presence of hydration products on their surface
- Some water from mix is absorbed by aggregate, some is lost by evaporation, and some is removed by initial chemical reactions. The reduction of water content will cause ***Slump Loss***

Rate of Slump Loss

- Higher the initial workability, greater the slump loss
- Rate of slump loss is higher in rich mixes
- Slump loss is greater with dry aggregate
- water reducer often lead to a somewhat increased rate of slump loss with time
- Rate of slump loss is higher when the alkali content (Na, K) in cement is high and when the sulfate content is too low

Rate of Slump Loss

- Rate of slump loss increases with increase of concrete temperature



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Cohesion and Segregation

- Concrete with good workability ought to be **cohesive**, should not segregate
- **Segregation** can be defined as separation of constituents of a heterogeneous mixture so that their distribution is no longer uniform. Tendency for
  - Sand-cement mortar to separate from coarse aggregate
  - Cement paste to separate from fine aggregate

http://youtu.be/aHNxq-Eda0c

Cause of Segregation

- In concrete, primary causes of segregation are
  - Larger max. agg. size and proportion of the large agg., e.g. gap grading
  - High specific gravity of coarse agg.
  - Decreased amount of fines (sand or cement)
  - Odd shaped, rough particles
  - Too wet or too dry mixes
  - Excessive vibration
  - Dropping fresh concrete from a height

Effects of Segregation

- Non-uniformity
- Poor consolidation
- Honeycombed
- Poor strength
- Poor steel-concrete bond
- Increased permeability
- Poor durability


Control of Segregation

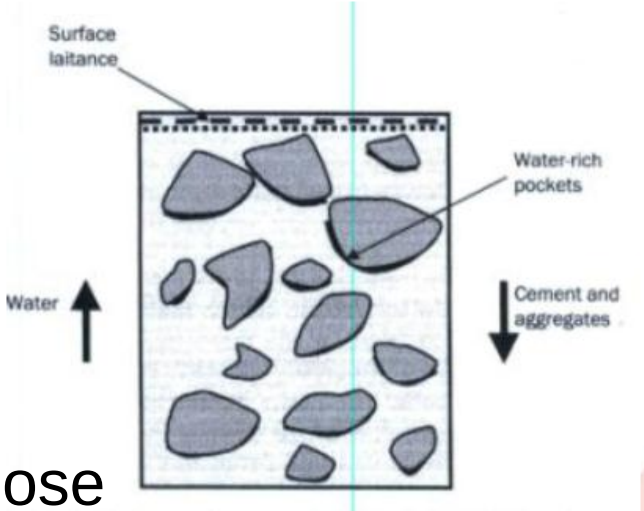
- Extent of segregation can be controlled by choice of suitable grading and by care in handling (Primary)
- The use of finely divided mineral admixtures or air-entraining agents reduces the tendency toward segregation (Secondary)

Proper placement

Proper vibration

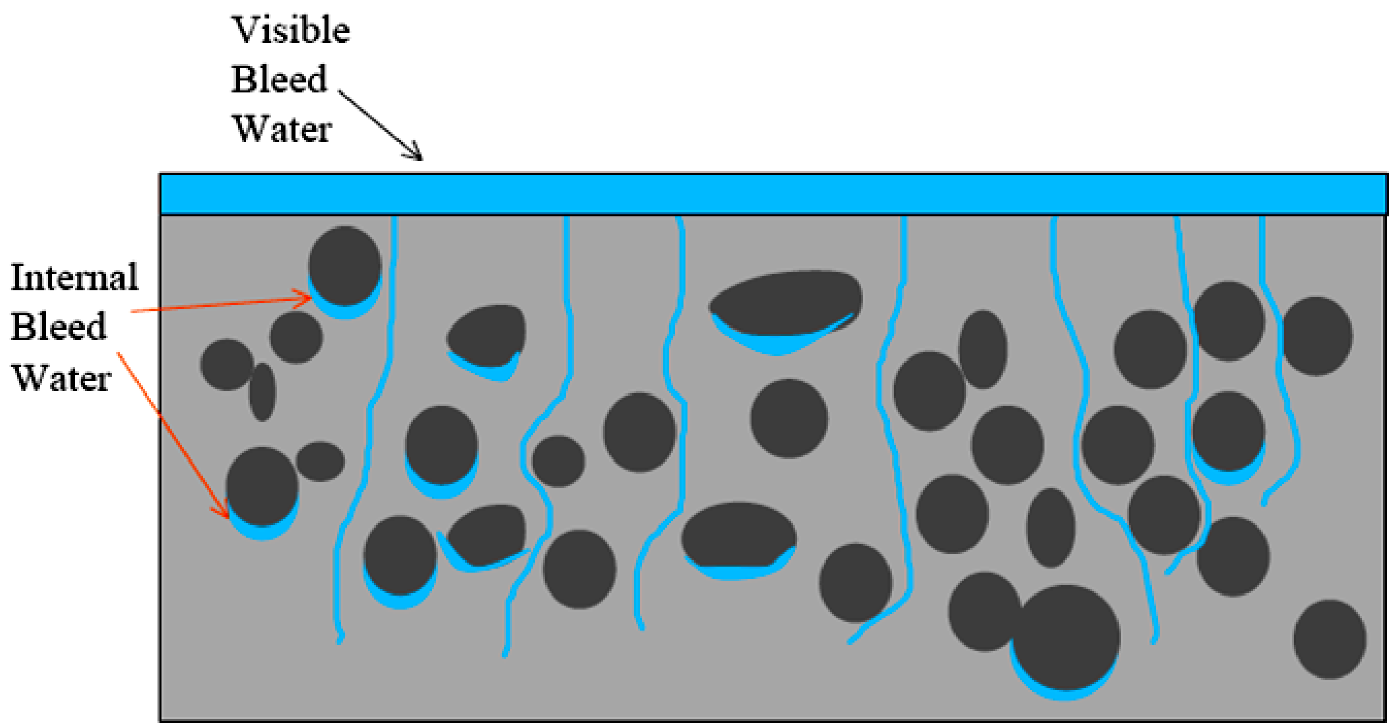
Bleeding (Water Gain)

- A special form of segregation in which some of the water in mix tends to rise to the surface of freshly placed concrete
- Due to the inability of agg. holding free water while settling
- Causes of bleeding
  - Lack of fines (300 μm and below)
  - High free water content
  - Water reducing admixture overdose

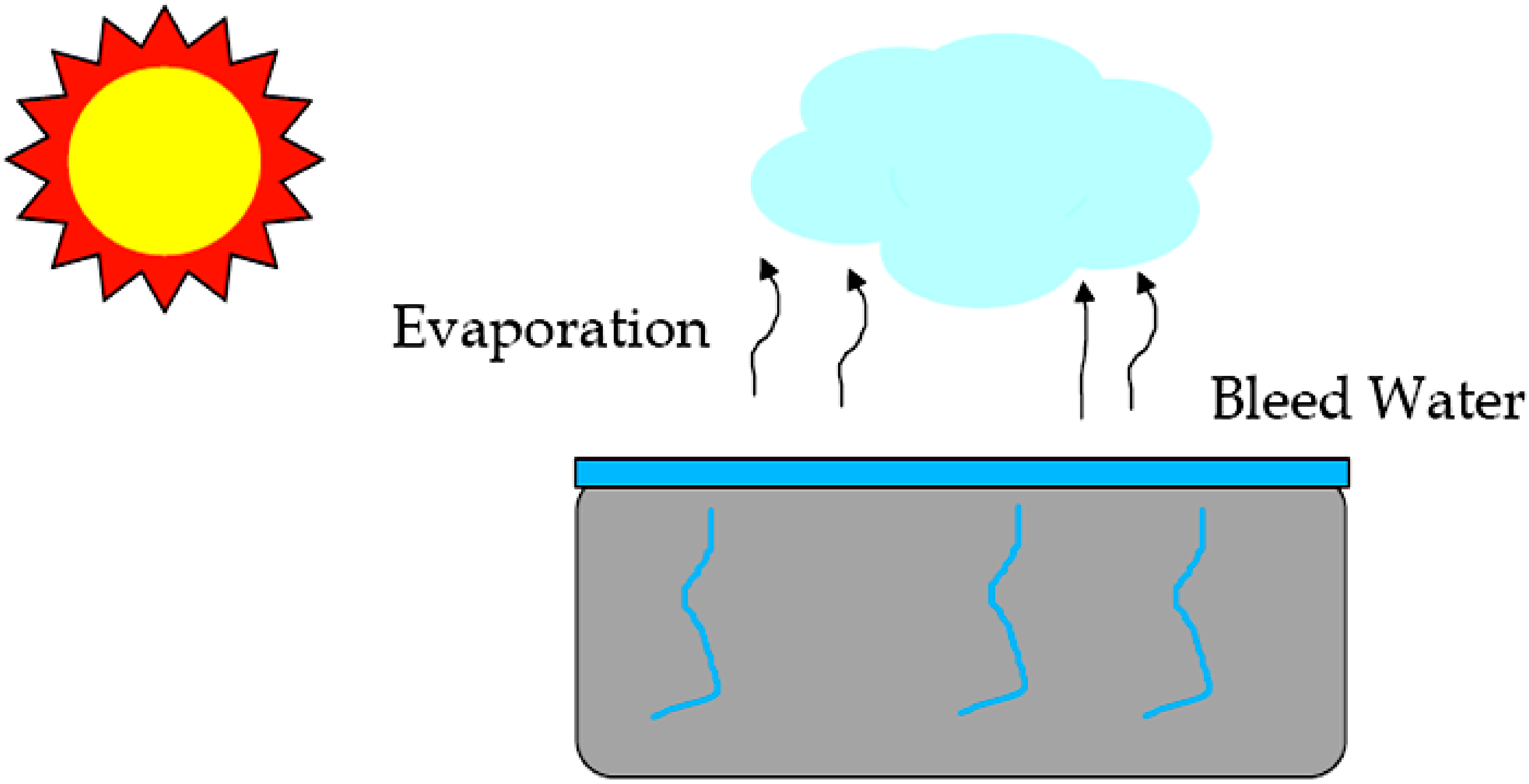


Effects of Bleeding

- Create a porous and weak layer of non-durable concrete and zones of poor bond between cement paste and large aggregate particles or reinforcement



Interaction Between Bleeding and Evaporation



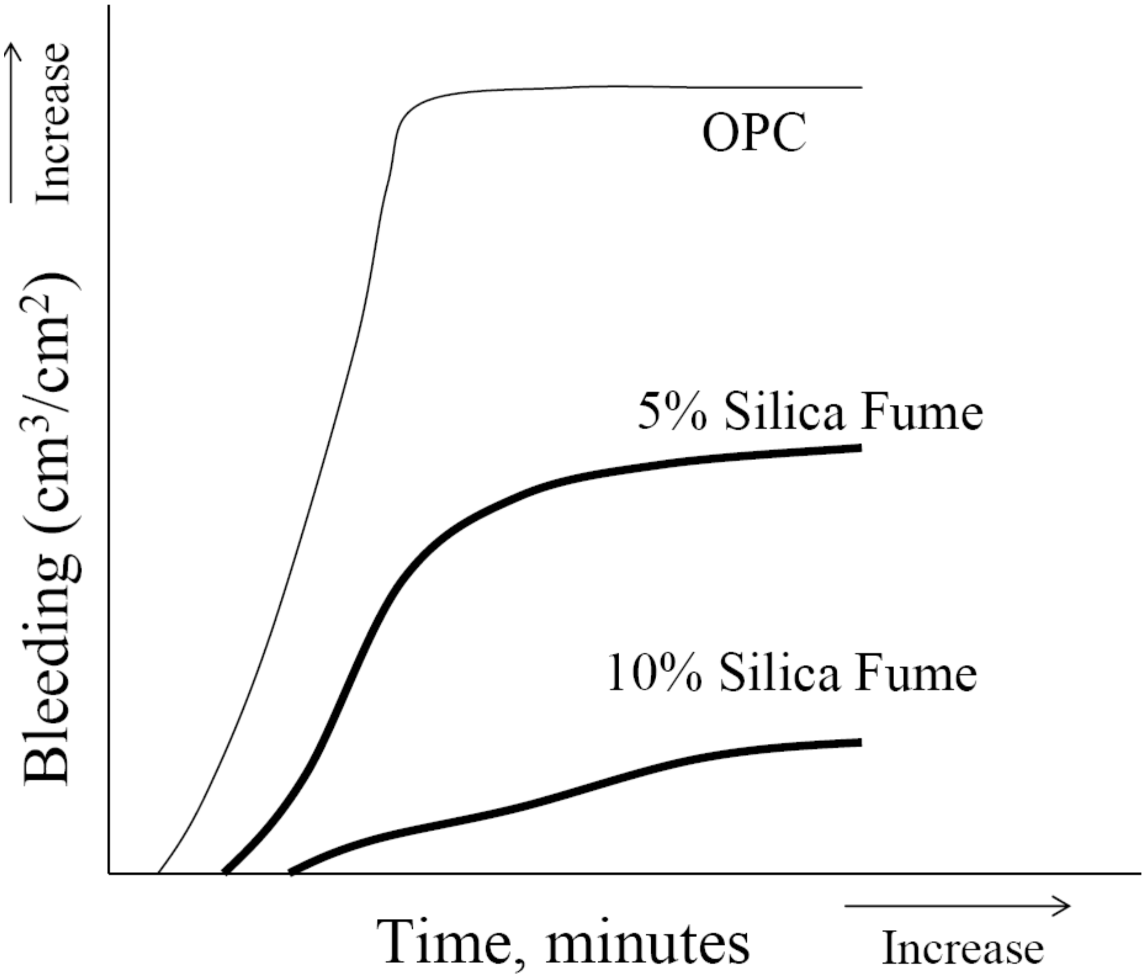
bleeding rate = evaporation rate → NOT BAD

To prevent plastic shrinkage

Control of Bleeding

- Use a finer cement
- Use cement with high alkali content, C_3A content
- Add calcium chloride
- Use richer mix
- Add pozzolanas (fly ash and silica fume)
- Add air entrainment
- Increase proportion of very fine aggregate particles (< 150 μm)
- Reducing water content

Bleeding Rate of OPC and Silica Fume Concrete



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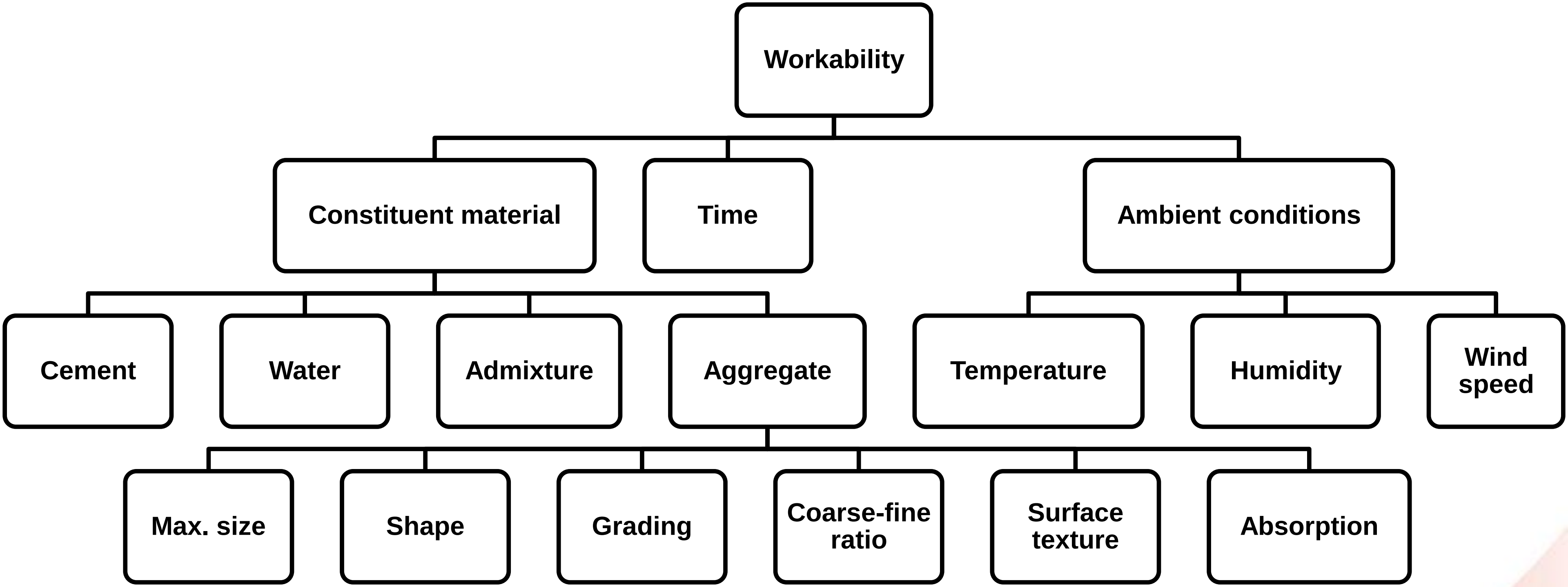
Factors Affecting Workability of Fresh Concrete



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Source: Jackson & Dhir

Workability Tests

- Slump test
- Compacting factor test
- Vebe test
- Flow test
- Ball penetration test

Purpose of Testing of Fresh Concrete

- To evaluate the trial mixes during the process of designing a concrete mix
- The control the fresh concrete quality and to make necessary mix adjustments, if necessary
- For compliance testing of fresh concrete supply with the specification requirement of acceptance of concrete

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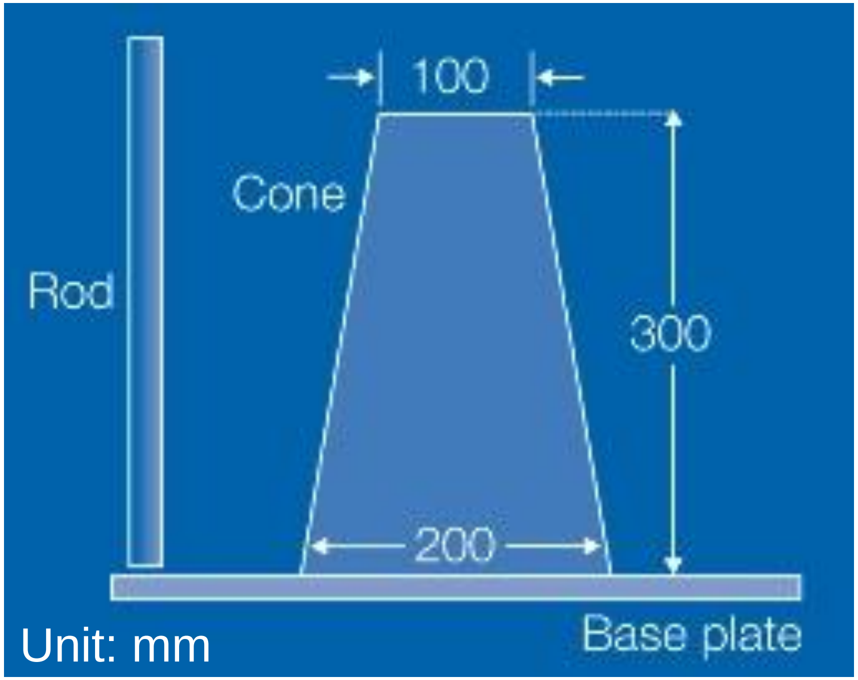
Slump Test (ASTM C 143): Principle

- The slump test is a measure of the behaviour of a compacted inverted cone of concrete under the action of **gravity**. It measures the consistency or the wetness of concrete.

Slump Test: Apparatus and Procedure

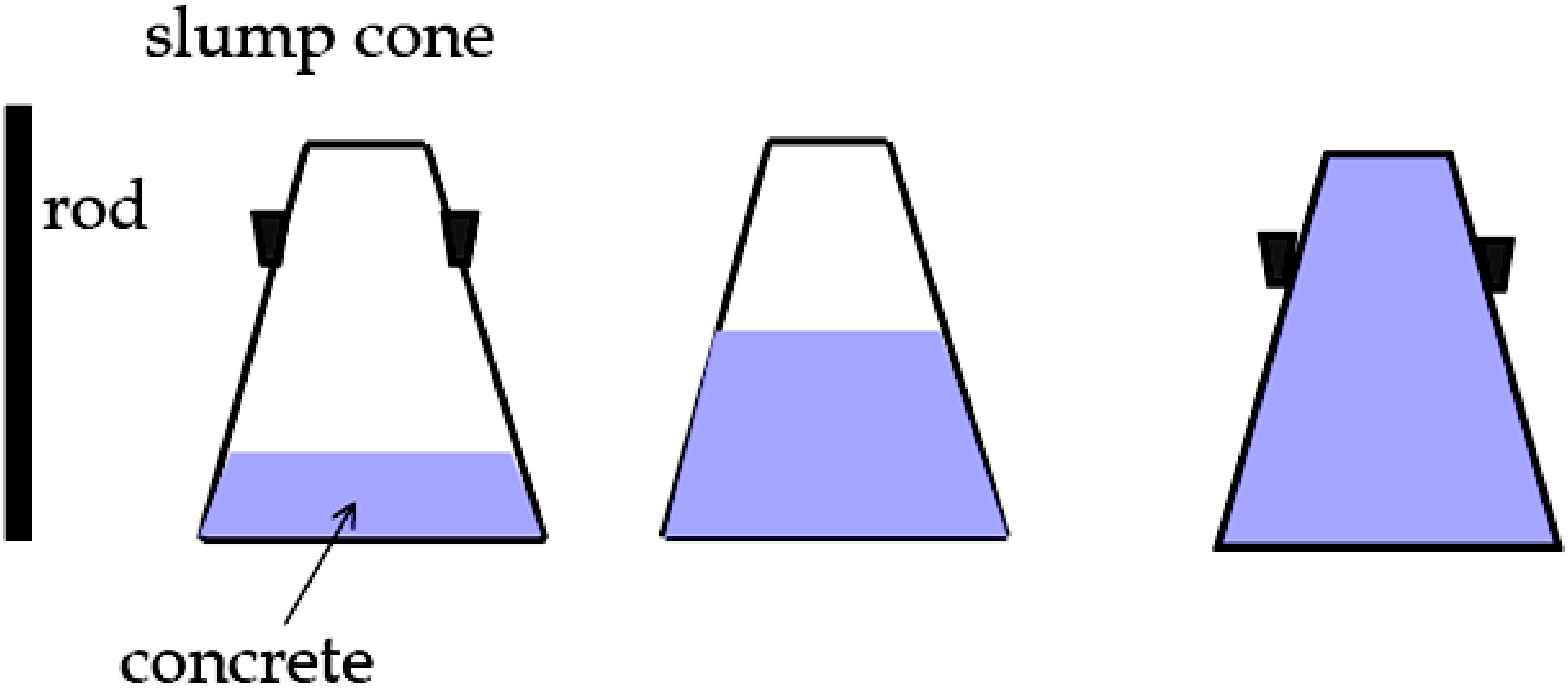
- Use inverted cone
- Fill it up with three layers of equal volume
- Rod each layer 25 times
- Scrape off surface
- Cone lift away vertically
- Slump measurement: Downward movement of the concrete

http://youtu.be/Hmo7tMsRD1g

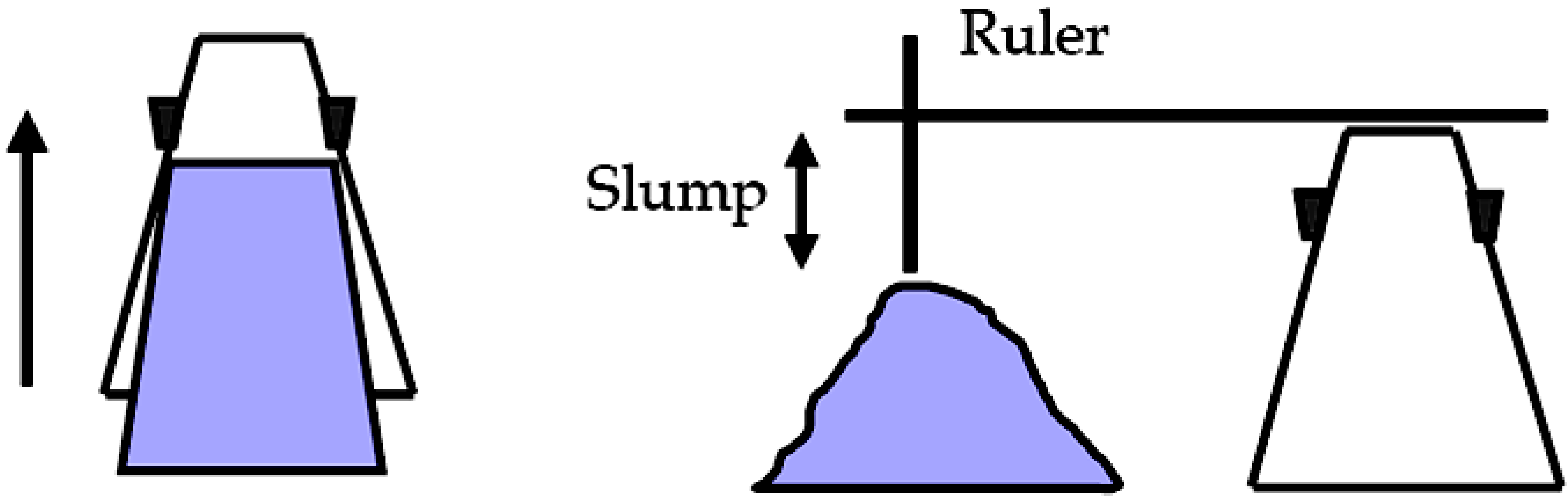


Developed in US by Chapman, 1913

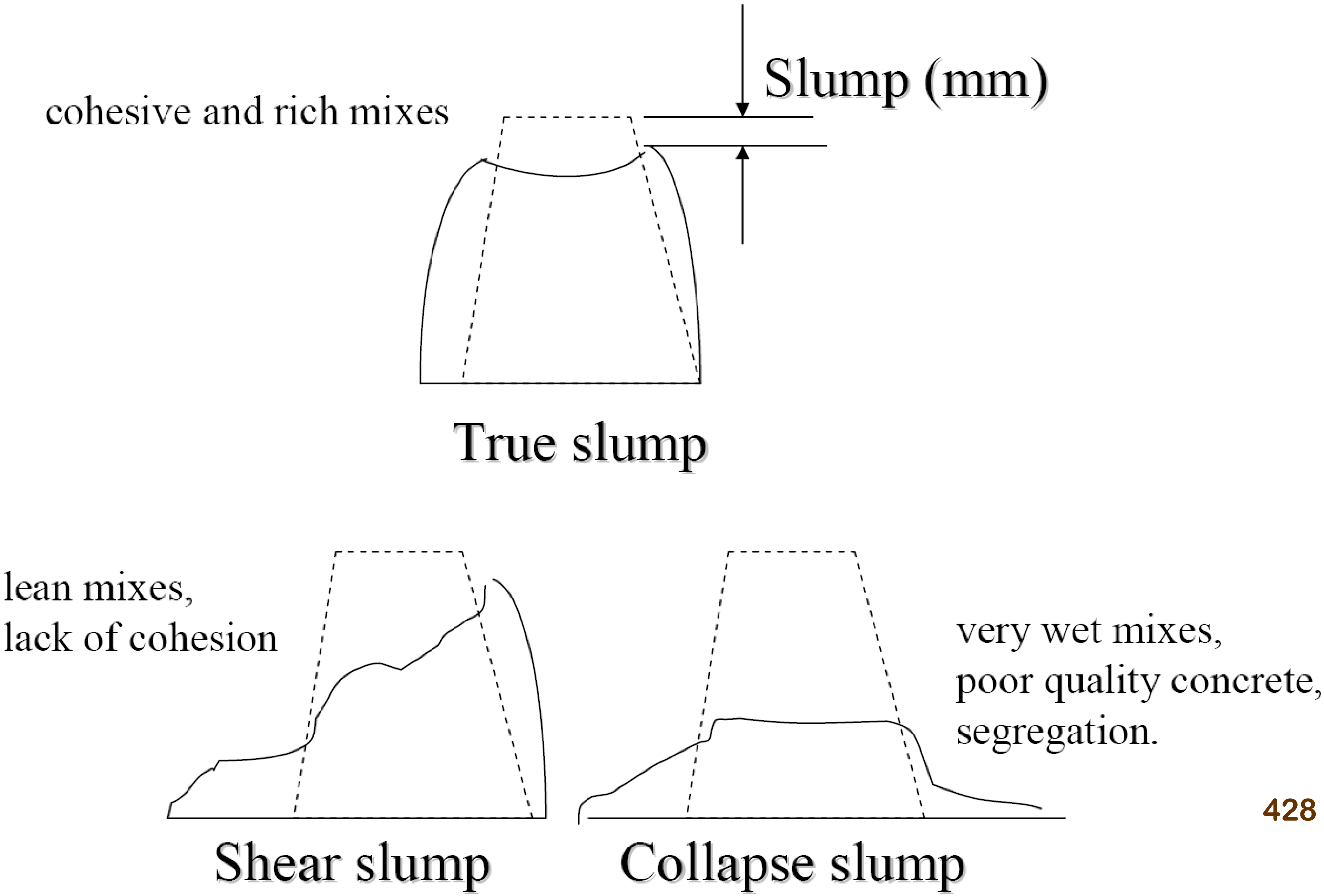
Slump Test : Procedure



Slump Test : Procedure



Types of Slump



Types of Slump

- Zero Slump
  - Very low workability
- True Slump
  - Low to medium workability
- Shear Slump
  - Poorly designed mix
  - Less cohesiveness
- Collapse Slump
  - Very high workability
  - Flowing concrete

Slump Test: Interpretation of Results

- Only a true slump is of any use in the test
- If a shear or collapse slump is achieved, a fresh sample should be taken and the test repeated
- A collapse slump will generally mean that the mix is too wet or that it is a high workability mix, for which slump test is not appropriate

Description of Workability Based on Slump

Description of workability	Slump (mm)
No slump	0
Very low	5-10
Low	15-30
Medium	35-75
High	80-155
Very high	160 to collapse

- **Very dry mixes; having slump 0 – 25 mm are used in road making**
- **Low workability mixes; having slump 10 – 40 mm are used for foundations with light reinforcement**
- **Medium workability mixes; 50 - 90 for normal reinforced concrete placed with vibration**
- **High workability concrete; > 100 mm**

Classification of Workability Based on Slump (EN 206-1:2000)

Classification of workability	Slump (mm)
S1	10-40
S2	50-90
S3	100-150
S4	160-210
S5	> 220

Slump Test: Advantages

- Widely used test around the world
- Simple, rugged, and inexpensive to perform
- Results are obtained immediately
- Workability and slump are used interchangeably, even though they have different meanings
- Specifications for concrete in terms of slump

Slump Test: Limitations

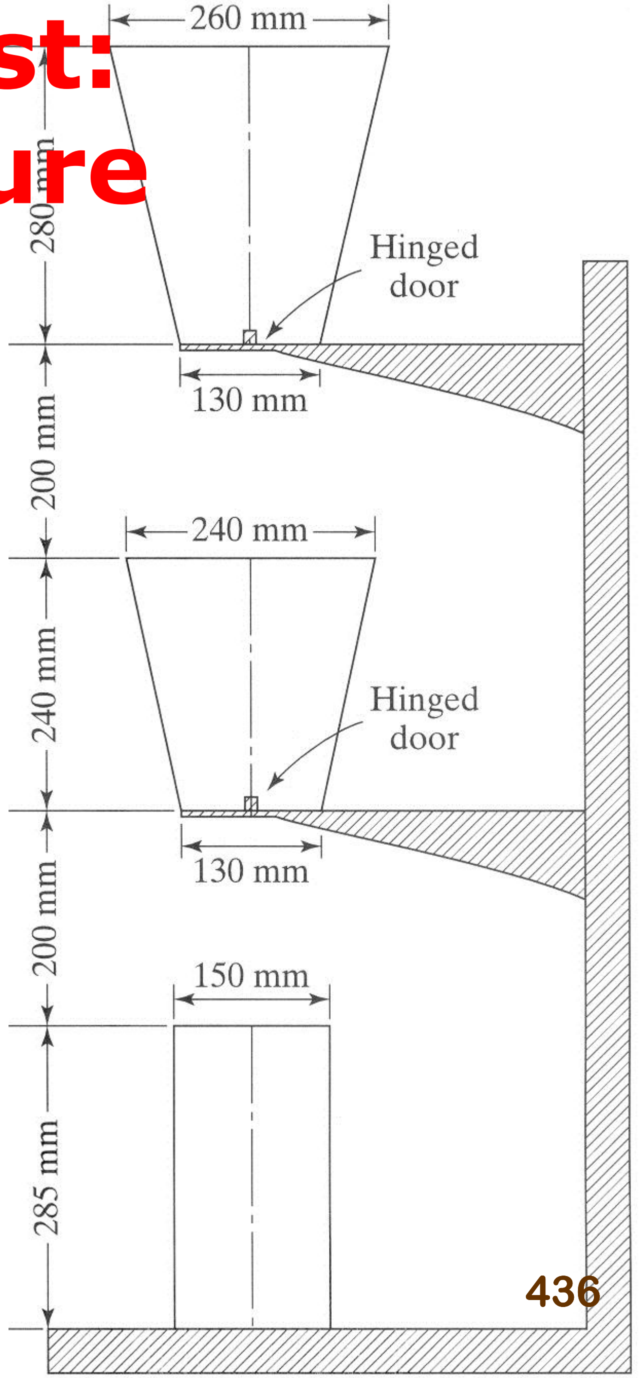
- Static test
- Does not provide any indication compatability
- Suitable for slumps of **medium to high** workability, slump in the range of 25 – 125 mm.
- Less relevant for either low or very high workability concretes

Compacting Factor Test: Principle

- The compacting factor test measures the **degree of compaction** resulting from the application of a **standard amount of work**

Compacting Factor Test: Apparatus and Procedure

- Upper hopper is filled with concrete
- Bottom door of upper hopper is then released and concrete falls into lower hopper
- Bottom door of lower hopper is released and concrete falls into cylinder
- Excess concrete is cut and net weight of concrete in known volume of cylinder is determined
- The density of concrete in cylinder is now calculated, and this density divided by density of fully compacted concrete is defined as ***Compacting Factor***



http://youtu.be/SRo2vYw_QPI

Description of Workability Based on Compacting Factor

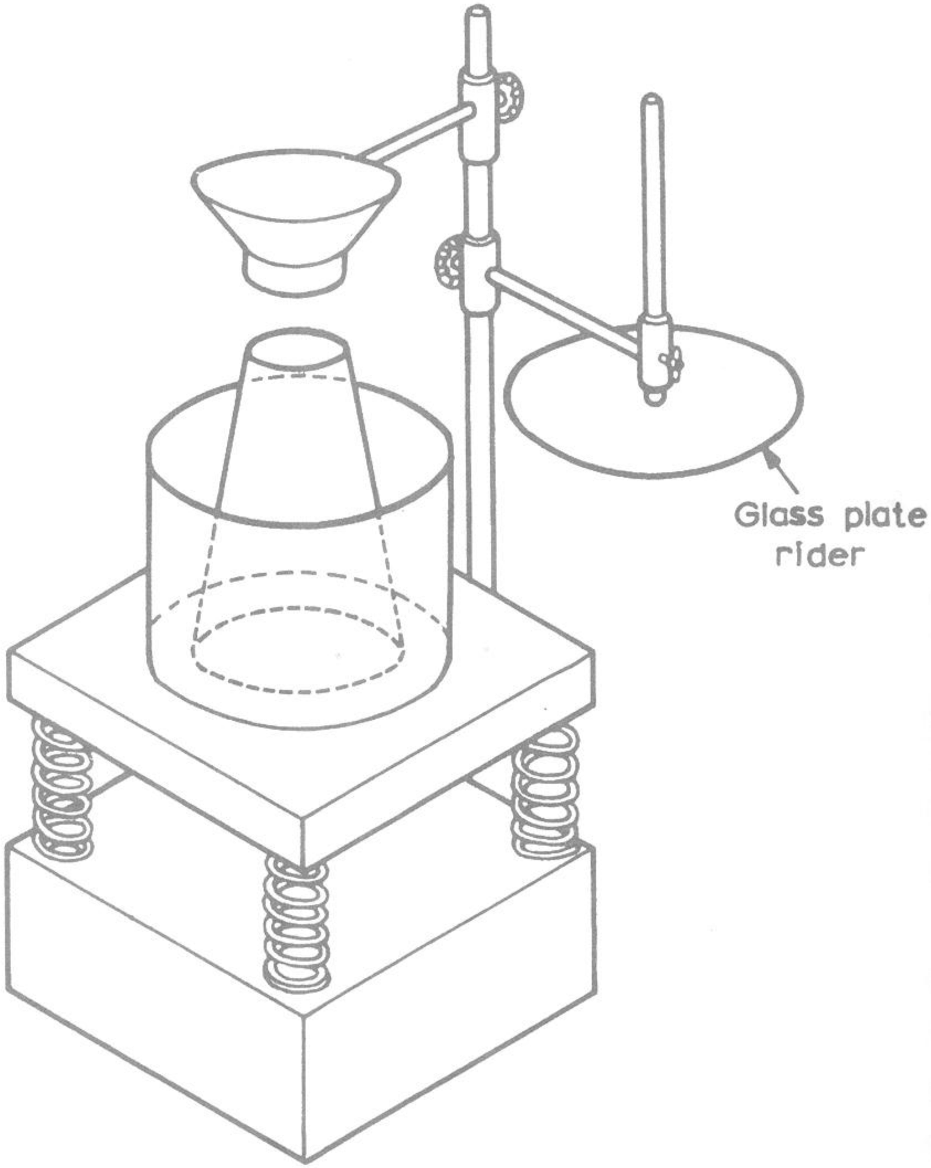
Description of workability	Compacting factor	Corresponding slump (mm)	Applications
Very low	0.78	0-25	Vibrated concrete in roads or other large sections
Low	0.85	25-50	Mass concrete foundations w/o vibration. Simple reinforced sections with vibration
Medium	0.92	50-100	Normal reinforced work w/o vibration and heavily reinforced sections w/ vibration
High	0.95	100-180	Sections w/ congested reinforcement. Not normally suitable for vibration

Compacting Factor Test: Pros & Cons

- Advantages:
  - A dynamic test indicating the compactability of concrete
  - More sensitive and accurate than slump test, especially for concrete mixes of ***medium*** to ***low*** workability, i.e. compacting factor of 0.9 to 0.8
  - Simple and inexpensive
- Disadvantages:
  - Mixes with the same compacting factor do not necessarily require the same amount of work for compaction
  - Not suitable for concrete with ***very low*** workability, 0.7 or below

Vebe Test (ASTM C 1170): Principle

- The Vebe test measures the remolding ability of concrete under vibration
- It is assumed energy required for compaction is a measure of workability, and this is expressed in Vebe seconds, i.e. time required for remolding to be complete



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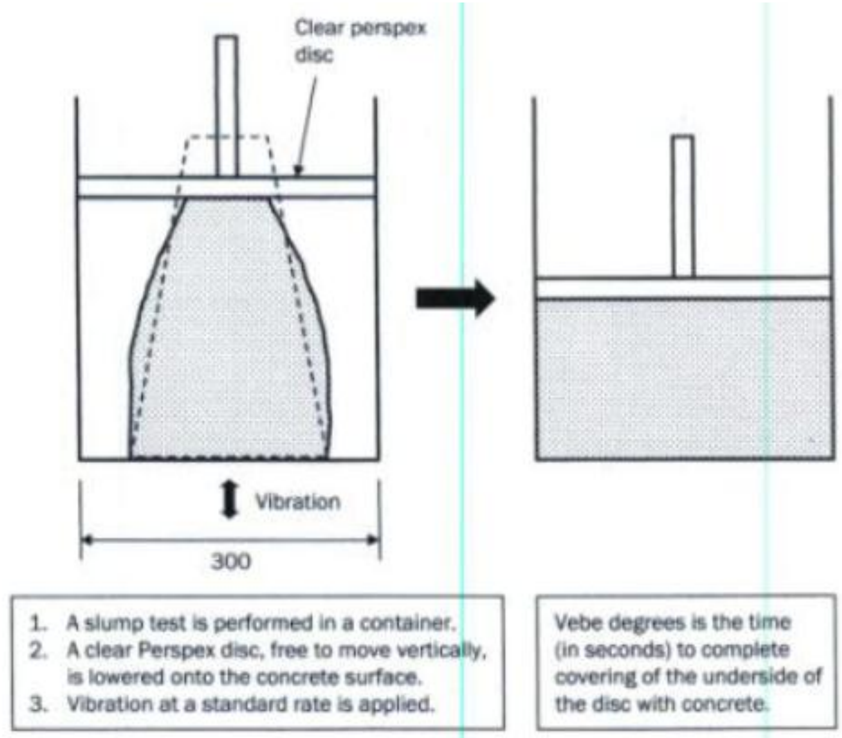
Vebe Test: Apparatus and Procedure

- A slump cone is placed and filled in the center of the cylinder
- After removing the slump cone, a glass plate is set atop the fresh concrete
- **Time** for the concrete to remold is recorded

http://youtu.be/8n2wpCwYtq4

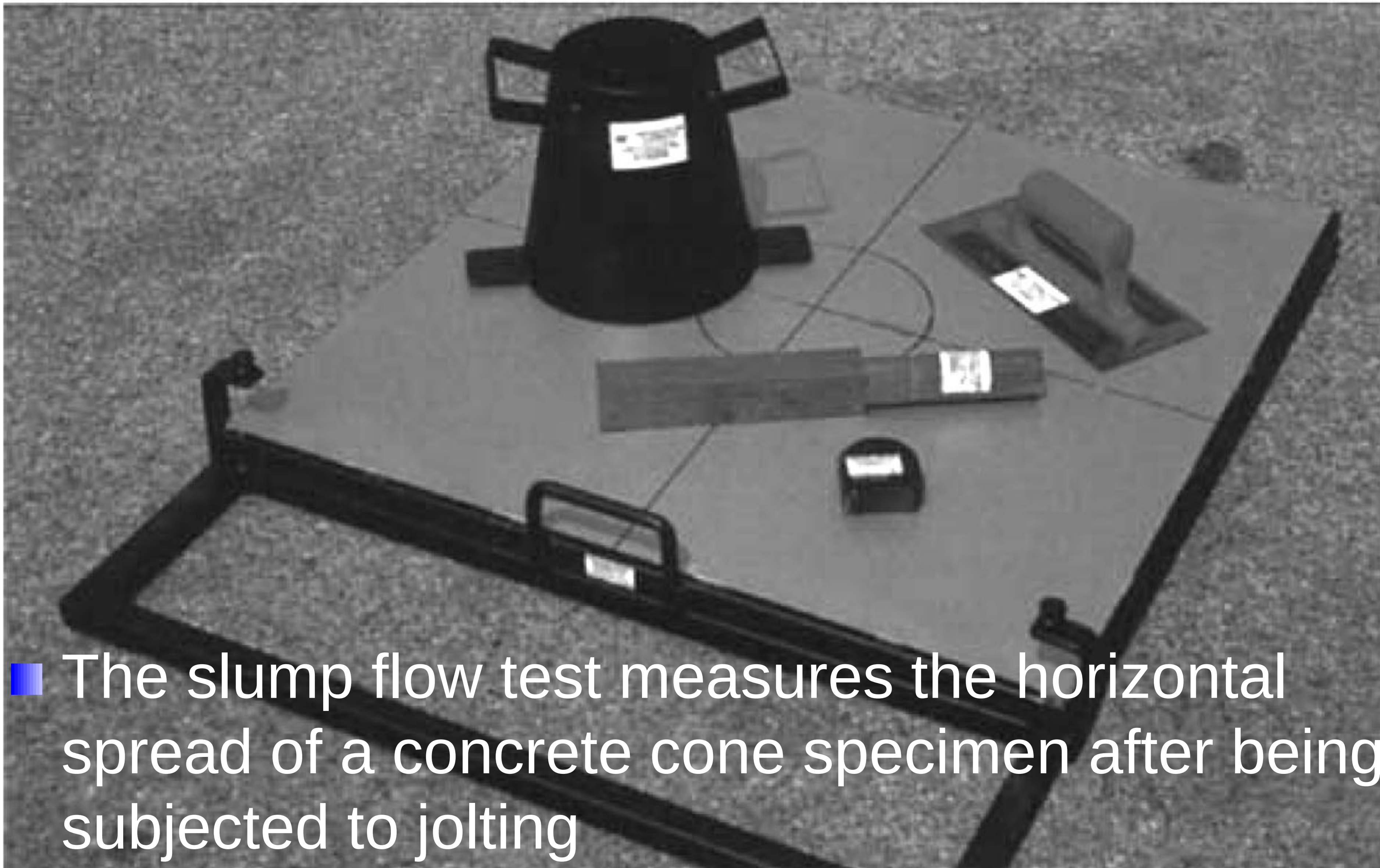


The Vebe test.

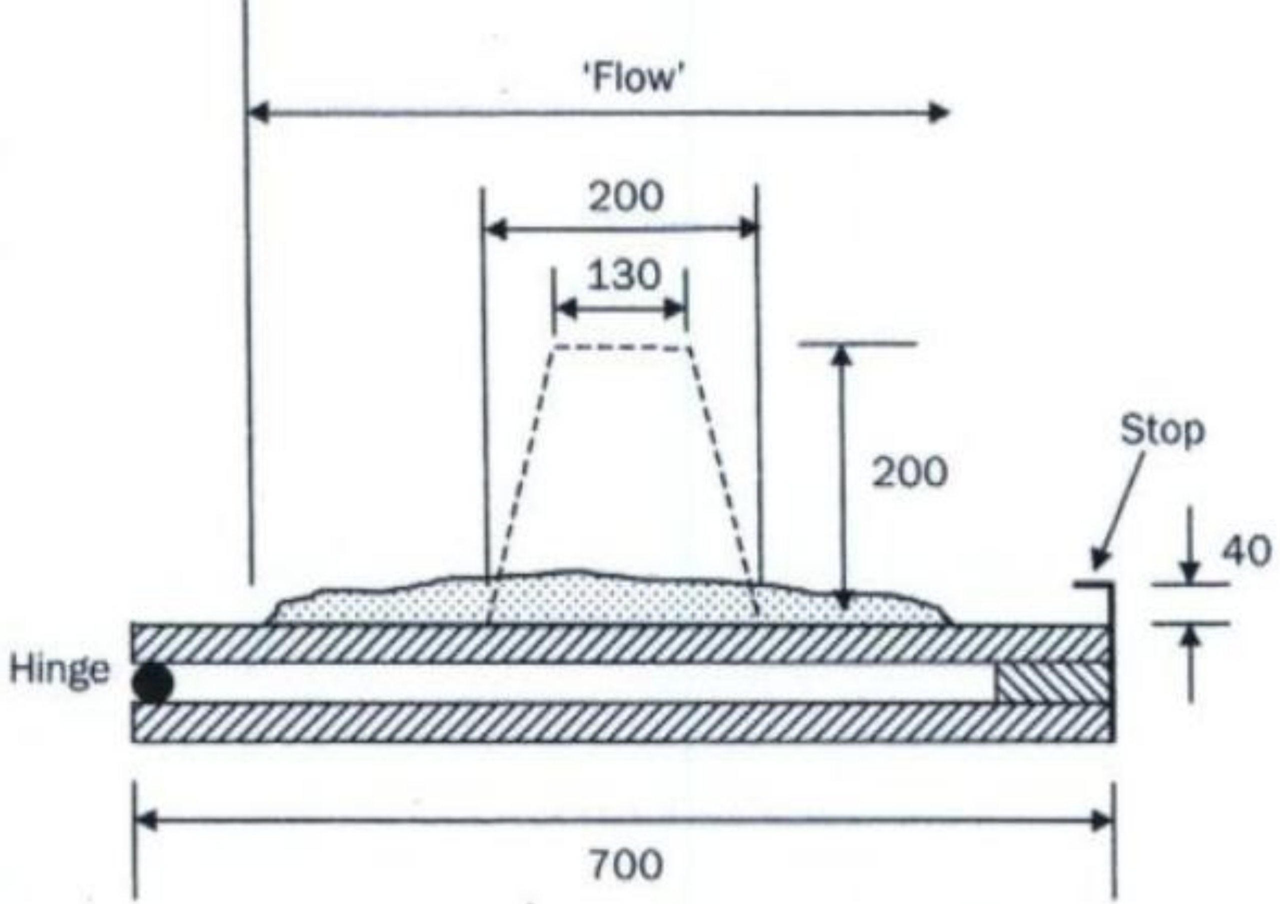
Vebe Test: Pros and Cons

- Advantages:
  - Good laboratory test, particularly for ***very dry*** mixes
  - A dynamic test; treatment of concrete during test is comparatively closely related to method of placing in practice
- Disadvantages:
  - Only work for low slump concrete with slumps less than 50 mm
  - Inappropriate for field use
  - Difficult to determine the end point
  - Type of motor (single of three phase)

Flow Test (ASTM C 124): Principle



- The slump flow test measures the horizontal spread of a concrete cone specimen after being subjected to jolting



- A conical mould (smaller than that of the standard slump test) is used to produce a sample of concrete in the center of a 700 mm square board, hinged along one edge
- The free edge of the board is lifted against the stop and dropped 15 times
- Flow = diameter of the concrete (mean of two measurements at right angles)
- Appropriate for concrete with ***high*** and ***very high*** workability, i.e. spread of 400 to 650 mm

Classification of Workability Based on Flow (EN 206-1)

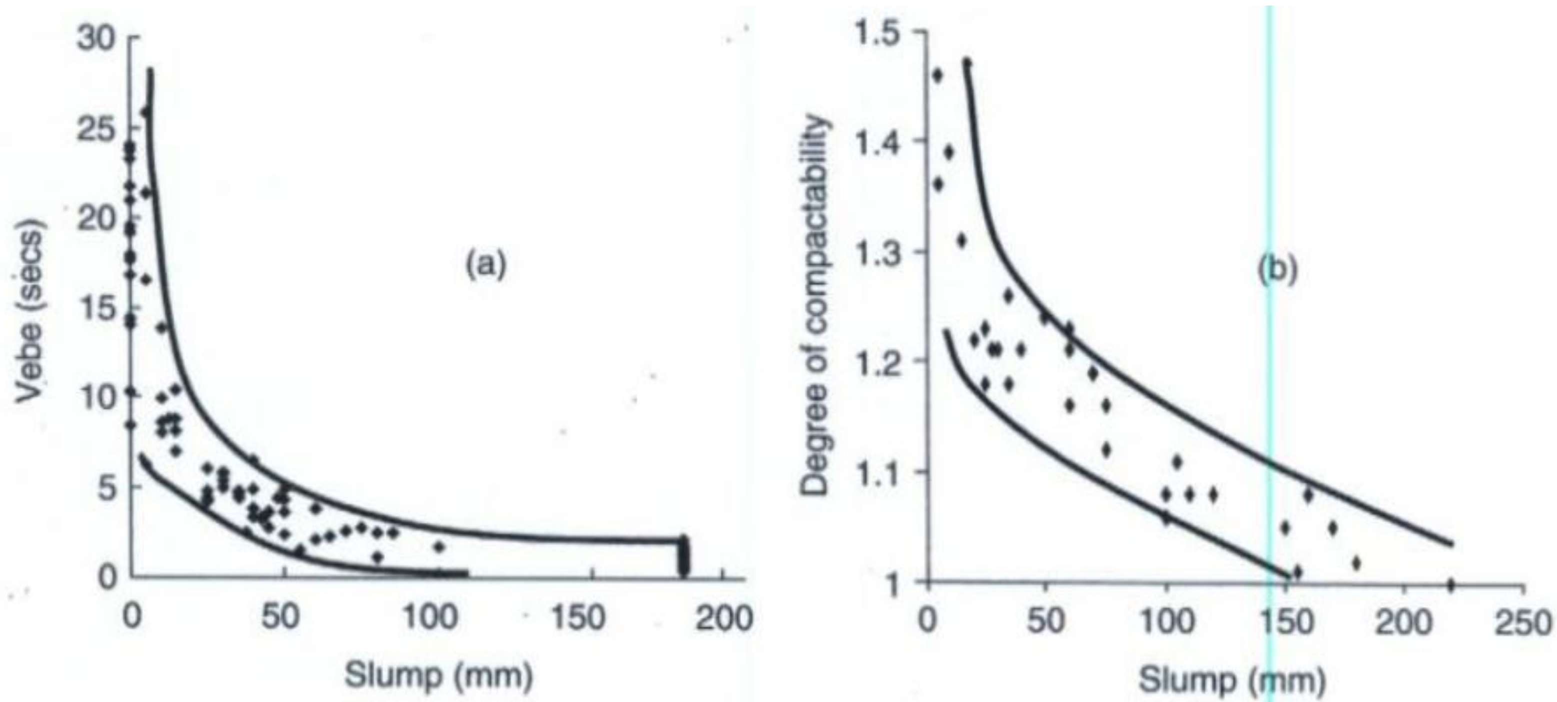
Consistence Class	Class Range (mm)
F1	$\leq$ 340
F2	350 to 410
F3	420 to 480
F4	490 to 550
F5	560 to 620
F6	$\geq$ 630

Tolerance $\pm$ 30 mm

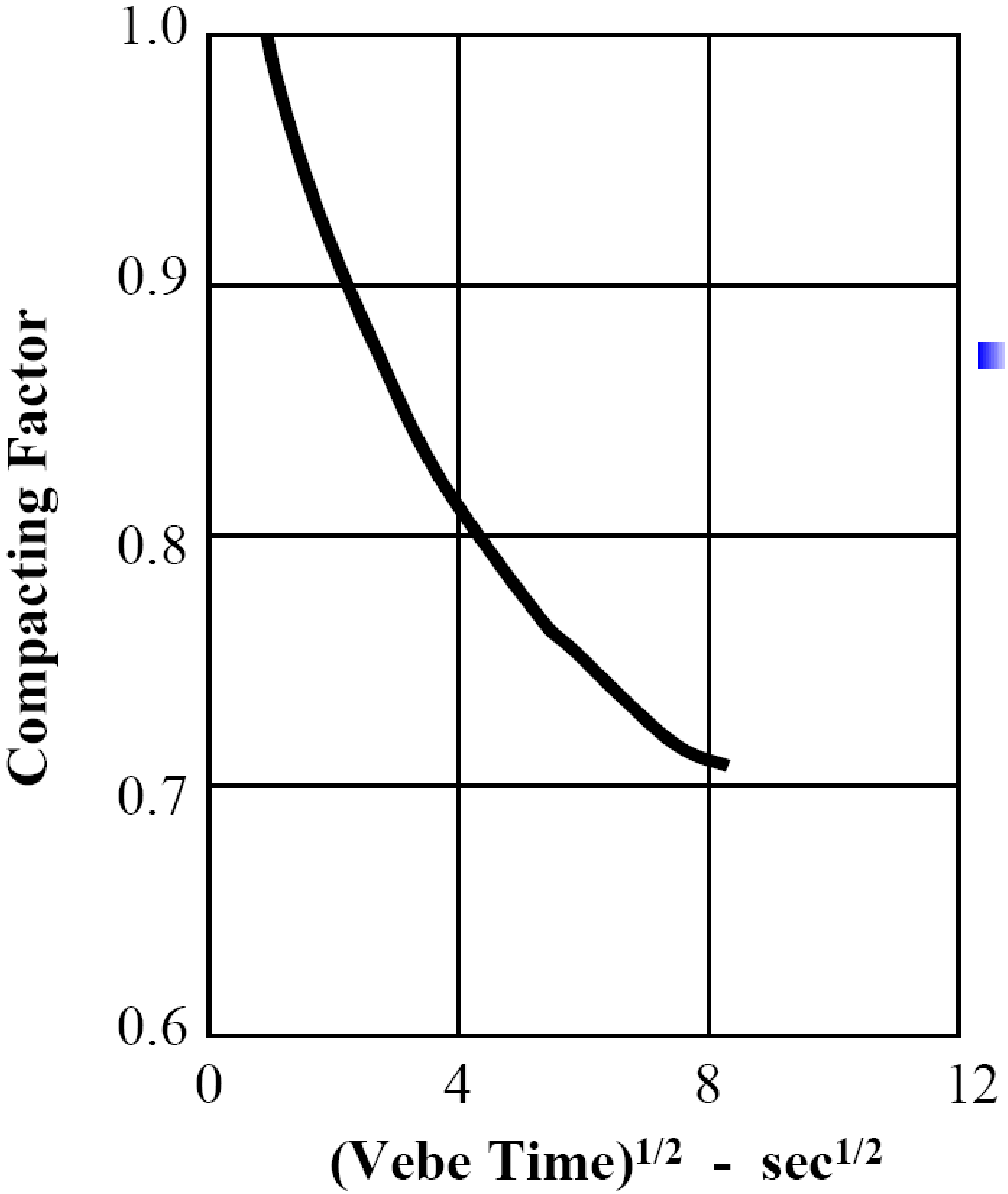
- Suitable for Very High consistency concretes
- 400mm Flow for medium consistency
- > 500 mm flow for high consistency

Test Methods Appropriate to Mixes of Different Workability (BS 1881:1983)

Workability	Method
Very low	Vebe time
Low	Vebe time, Compacting factor
Medium	Compacting factor, Slump
High	Compacting factor, Slump, Flow
Very high	Flow



Comparison of Tests



- The relation must not be assumed to be generally applicable because it depends on factors such as shape and texture of aggregate or presence of entrained air, as well as on mix proportions

Suggested Valued of Workability of Fresh Concrete for Different Placing Conditions

Placing condition	Degree of workability	Values of workability			
		Compacting factor, max. size of agg.			Vebe time, slump for 20 mm agg.
		10 mm	20 mm	40mm	
Hand compaction of heavily reinforced sections	High (flowing)	0.95	0.95	0.95	Vebe (N/A) 125-150 mm slump
Concreting of lightly reinforced section by hand or vibration of heavily reinforced sections	Medium (plastic)	0.88	0.90	0.92	5-2 s Vebe time, 25-75 mm slump
Concreting of lightly reinforced sections with vibration; road pavements and slabs with hand-operated vibrators and vibration of mass concrete	Low (stiff plastic)	0.82	0.84	0.85	10-5 s Vebe time, 5-50 mm slump
Concreting of shallow sections with vibrations	Very low (stiff)	0.75	0.78	0.80	20-10 s Vebe time, 0-25 mm slump
Concreting by intensive vibrations with vibropressing, centrifugation etc.	Extremely low (very stiff)	0.65	0.68	N/A	30-20 Vebe time Slump (N/A)