CE 212
Engineering Materials

Introduction

The structure of materials can be described on dimensional scales

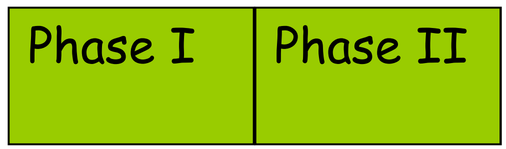
1. The molecular level
2. Materials structural level
3. The engineering level

1. The molecular level

- Smallest scale (atoms, molecules or aggregation of molecules)
- Particle sizes: 10^{-7} - 10^{-3} mm
- Examples: crystal structure of metals, cellulose molecules in timber, calcium silicate hydrates in hardened cement paste, variety of polymers

2. Materials structural level

- Up in size from the molecular level
- Material considered as a composite of different phases



Examples: Cells in timber, grains in metals, concrete, asphalt, fiber composites, masonry.

3. The engineering level

- Total material is considered
- Material is considered as continuous and homogenous
- Average properties for the whole volume of material body
- This level is recognized by construction practitioners

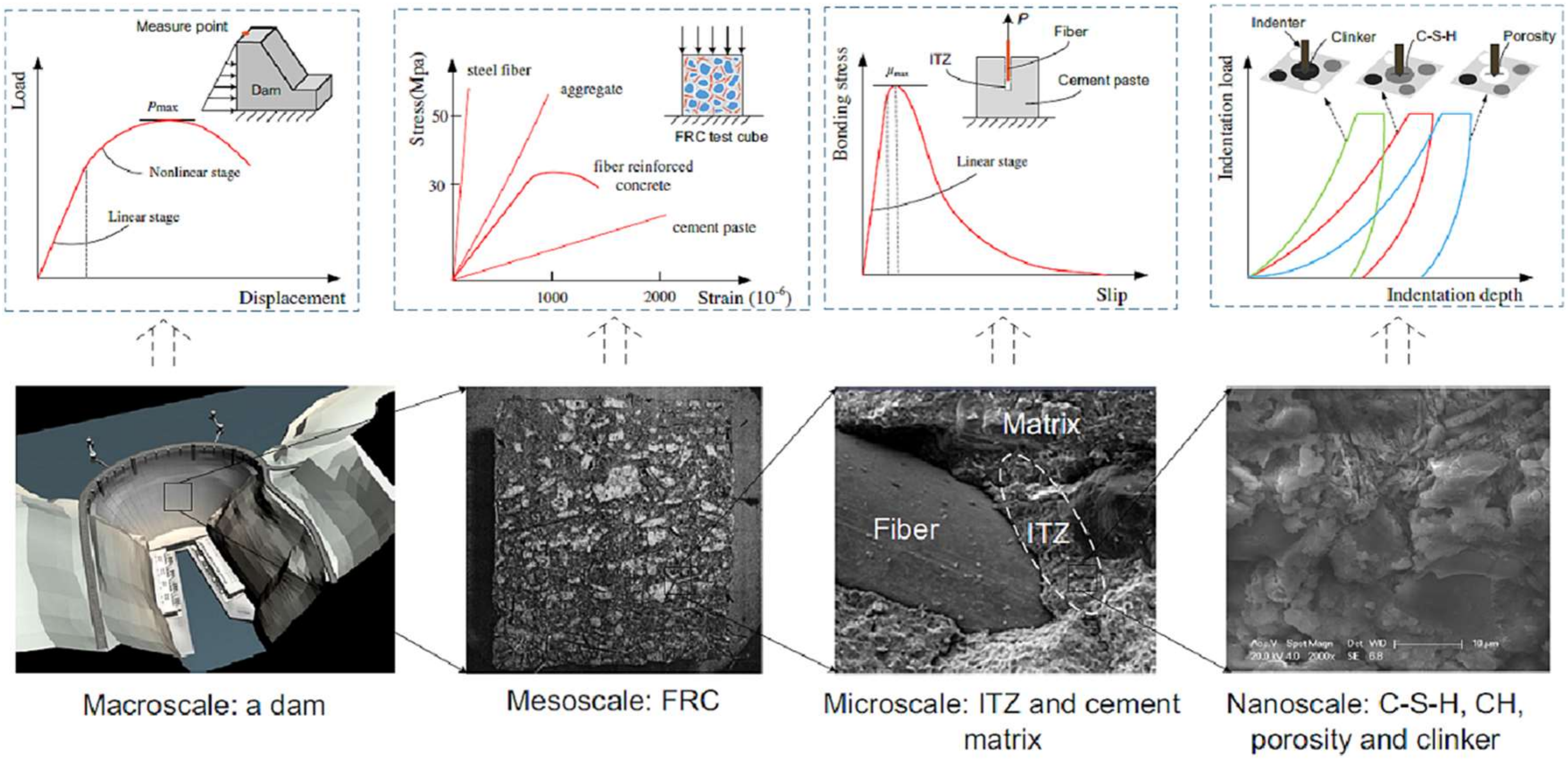


Fig. 2. Multiscale concept of FRC [19].

Figure ref: Nano-mechanical behavior of the interfacial transition zone between steel-polypropylene fiber and cement paste, Construction and Building Materials, Vol 145, August 2017, pp.619-638

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
    - Cement
    - Admixtures
    - Aggregates
  - Fresh state properties of concrete
  - Deformation of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

CONCRETE

CONCRETE

- A composite of mineral particles (aggregates) distributed in a matrix of hardened cement paste (mixture of powder cement and water at the beginning)
- Versatile, comparatively cheap and energy efficient
- Great importance for all types of construction throughout the world
- Concrete is fresh and plastic at the beginning (throughout some time after mixing of constituent materials)
- Final properties of the hardened state of concrete have been gained slowly through time
- Properties change with time
- 50-60 % of ultimate strength is developed in 7 days, 80- 85 % in 28 days
- Increases in strength have been found in 30 year old concrete

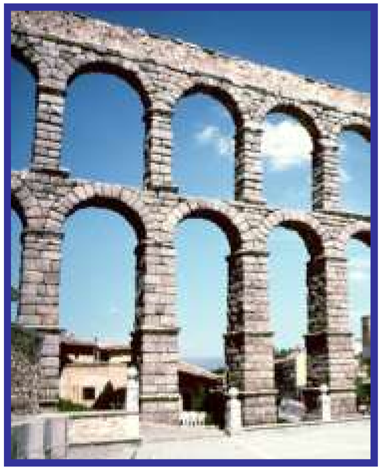
History of concrete

- History of concrete is very old
- Mixtures of lime, sand and gravels have been found in Eastern Europe, in Egypt and in Ancient Greek and Roman times
- This dates from about 5000 BC
- Romans; first concrete with a hydraulic cement (lime + volcanic ash from near Pozzuoli)
- Active silica and alumina in ash reacts chemically with lime
- Similar materials still known as pozzolona

History of concrete, cont'd

Roman structures;

- Foundations and columns of aqueducts



- In arches of the Colosseum

- In the dome of the Pantheon

Fig. 2: http://www.artchive.com/artchive/r/roman/roman_colosseum.jpg
Fig. 3: www.dolceroma.it/images/common/dove/pantheon.jpg

History of concrete, cont'd

In 1756, John Smeaton

Mixture of burnt clay bearing limestone & Italian pozzolana for producing a suitable hydraulic cement to be used in construction of Eddystone Lighthouse

Picture ref: http://www.scienceandsociety.co.uk/results.asp?image=10307921
Extra info: http://en.wikipedia.org/wiki/Eddystone_Lighthouse

History of concrete, cont'd

In 1790, James Parker

Patented "Roman cement" from calcareous clay burnt in a kiln and ground to a powder

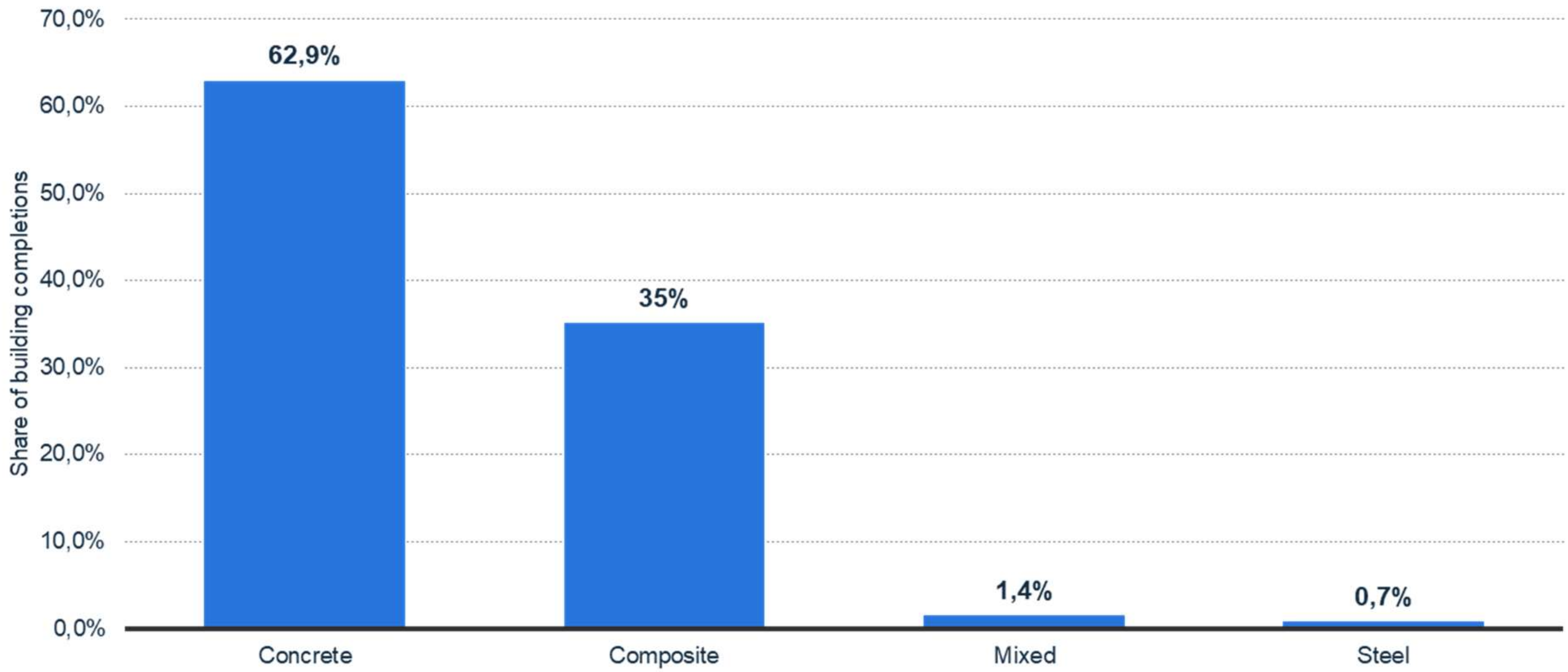
In 1824, Joseph Aspdin

Patented "portland cement" an artificial mixture of lime and clay bearing materials used in repairs of Thames Tunnel in 1828

In 1890s improvement in kiln technology reduced the cost of Portland cement production. Then widespread production and use started worldwide

Worldwide tall building completions in 2018, by structural material*

Materials used for global tall buildings 2018

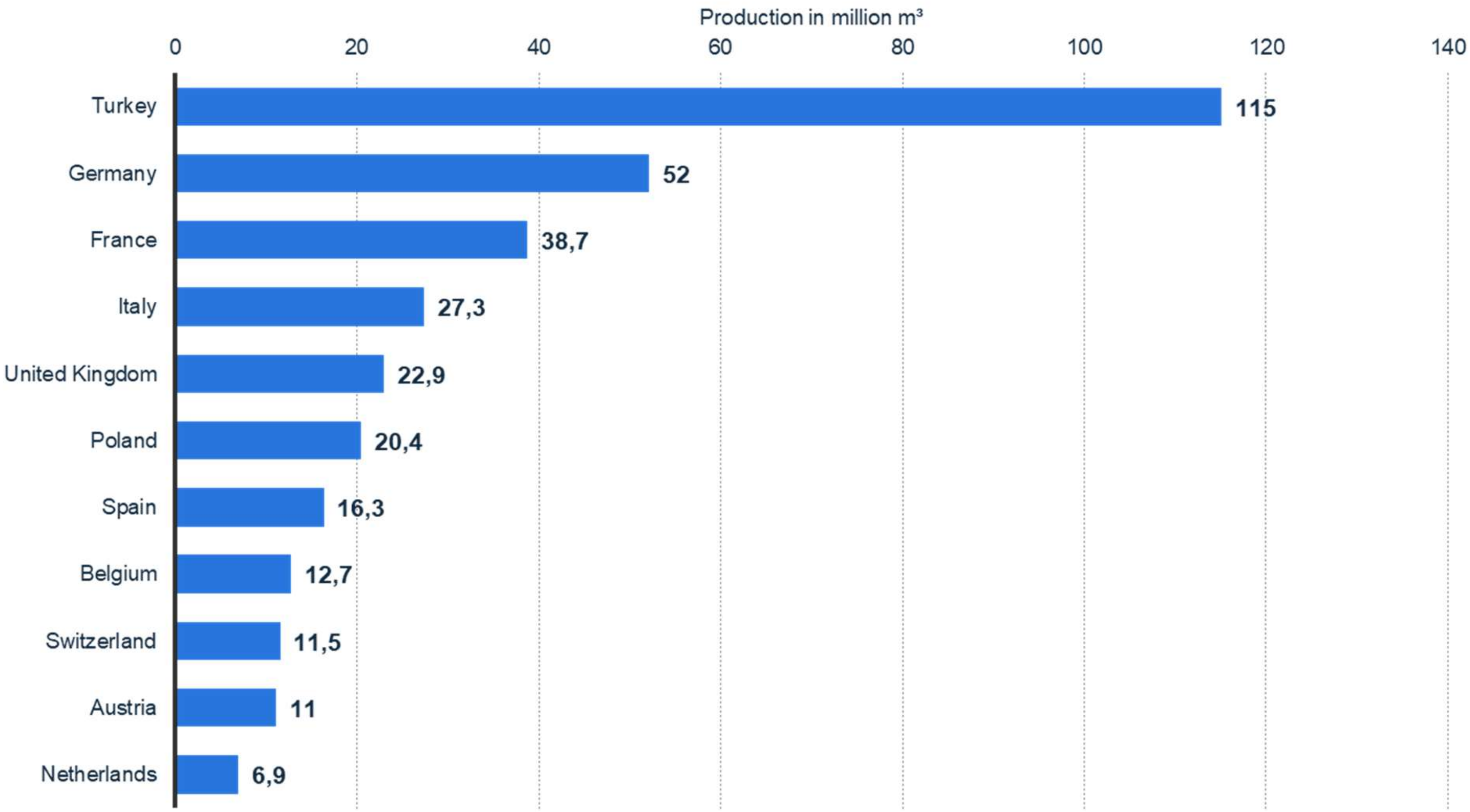


Note: Worldwide; 2018
Further information regarding this statistic can be found on page 8.
Source(s): CTBUH; ID 319931

https://www.statista.com/statistics/319931/structural-materials-of-tall-buildings-worldwide/

Production of ready-mix concrete in European countries in 2017 (in million cubic meters)

Production of ready-mix concrete in European countries 2017



Note: Europe
Further information regarding this statistic can be found on page 8.
Source(s): ERMCO; Bundesverband der Deutschen Transportbetonindustrie; ID 244083

https://www.statista.com/statistics/244083/production-of-ready-mix-concrete-in-european-countries/

Chapter Outline

CONCRETE

- History of concrete
- Constituents of concrete
  - Cement
  - Admixtures
  - Aggregates
- Fresh state properties of concrete
- Deformation of concrete
- Strength and failure of concrete
- Durability of concrete
- Statistical quality control in the production of concrete
- Property composition relations for concrete and concrete mix design

Subchapter Outline

- Cement
  - a. Cement manufacturing process
  - b. Composition of cement
  - c. Different types of cements
  - d. Related standards
  - e. Hydration
  - f. Structure of hardened cement paste

CEMENT

Portland Cements

Raw materials; Clay and calcareous stones

Silica from clay (SiO_2) + lime from calcareous stone (CaO)

Al_2O_3, Fe_2O_3, MgO, K_2O also exist in clay

a. Cement manufacturing process

- Clay + calcareous stones reduced to 75μm or less and mixed
- Blend fed into upper end of inclined long (up to 250m), 6m diameter rotating kiln which is heated to 1500°C at lower end

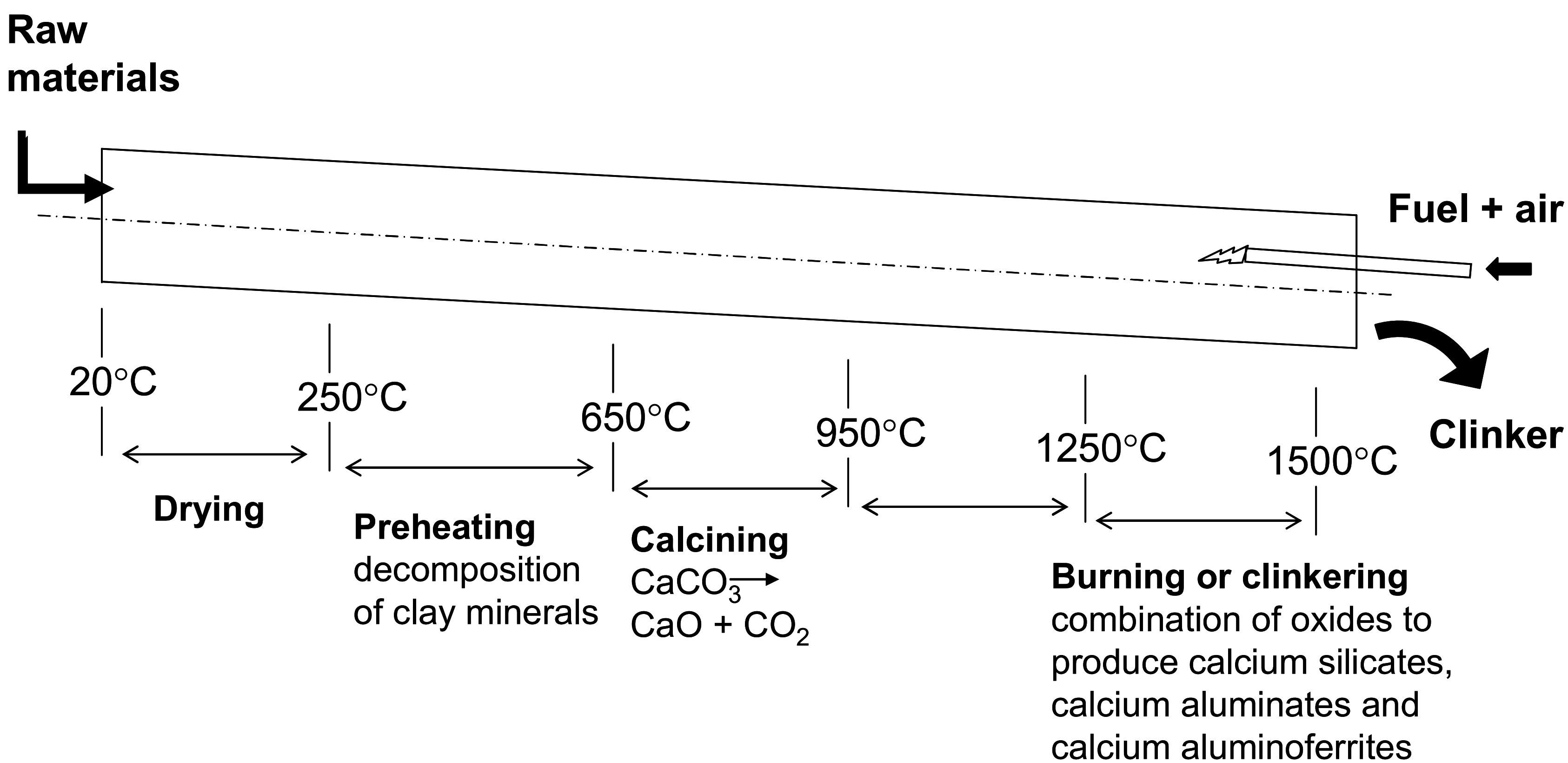


Fig. The processes taking place in a Portland cement kiln in the wet process

a. Cement manufacturing process, cont'd

- At 600°C, $CaCO_3$ in calcareous stones decomposes to give quicklime (CaO) and gaseous CO_2

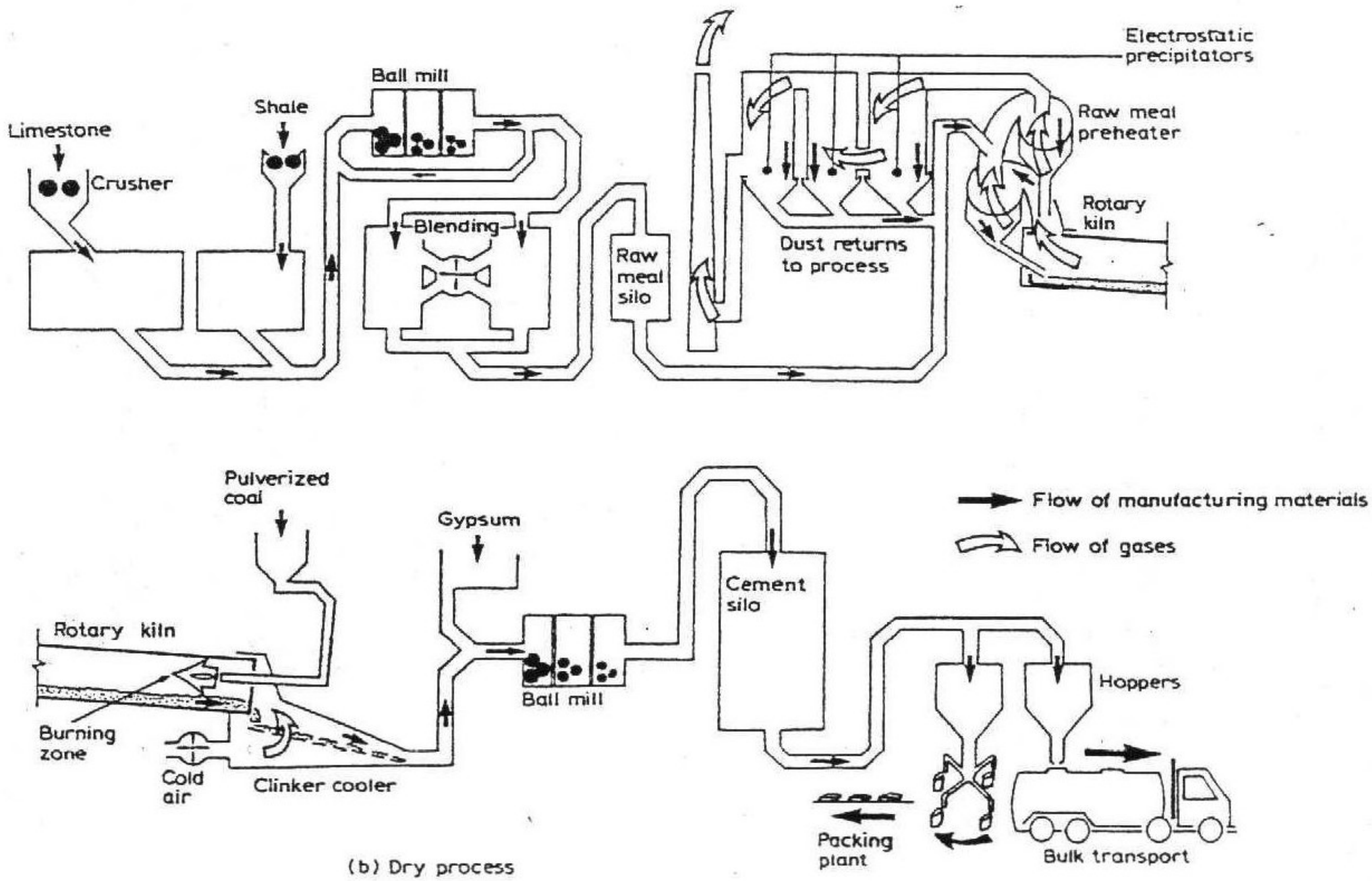
- Fusion reactions start at 1200°C
  - Calcium silicates, $2CaOSiO_2$ or $3CaOSiO_2$
  - Calcium aluminates, $3CaOAl_2O_3$
  - Other oxides act as a flux

  (Calcium silicates and calcium aluminates: Form as a result of these reactions)

- Clinker particles (a few mm) emerge from kiln
- After cooling, 3-4% gypsum ($CaSO_4 2H_2O$) is added to clinker
- Mixture is ground to powder (2-80μm size), (300m^2/kg specific surface)

www.cement.org/tech/cct_port_cem_prod_tech.asp

a. Cement manufacturing process, cont'd



Diagrammatic representation of the dry process of manufacture of cement

b. Composition of cement

Principle oxides in cement

CaO (lime): C

SiO_2 (silica): S

Al_2O_3 (alumina): A

Fe_2O_3 (iron oxide): F

Four main compounds (phases) formed in fusion process:

Tricalcium silicate: $3CaO.SiO_2$ (C_3S)

Dicalcium silicate: $2CaO.SiO_2$ (C_2S)

Tricalcium aluminate: $3CaOAl_2O_3$ (C_3A)

Tetracalcium aluminoferrite: $4CaOAl_2O_3Fe_2O_3$ (C_4AF)

b. Composition of cement, cont'd

Each cement grain consists of an intimate mixture of these compounds. Direct chemical analysis is not possible to determine the amounts. Instead BOGUE formulas are used that were calculated from the results of oxide analysis.

If A/F > 0.64

$$\% \ C_3S = 4.07C - 7.60S - 6.72A - 1.43F - 2.85\bar{S} \qquad \bar{S} = SO_3$$

$$\% \ C_2S = 2.87S - 0.754C_3S$$

$$\% \ C_3A = 2.65A - 1.69F$$

$$\% \ C_4AF = 3.04F$$

If A/F ≤ 0.64

$$C_3S = 4.07C - 7.60S - 4.48A - 2.86F - 2.85\bar{S}$$

$$C_2S = 2.87S - 0.754C_3S$$

$$C_2F + C_4AF = 2.1A + 1.70F$$

b. Composition of cement, cont'd

The approximate range of oxide composition that can be expected for Portland Cements

Compositions of Portland Cements	
Oxides (% by wt)	Range
CaO	60-67
SiO_2	17-25
Al_2O_3	3-8
Fe_2O_3	0.5 – 6.0
$Na_2O + K_2O$	0.2 – 1.3
MgO	0.1 – 4.0
Free CaO	0 – 2
SO_3	1 – 3

Principle oxides: CaO & SiO_2 ~ 3 to 1by wt.

Main compounds: C_3S & C_2S ~ 75 – 80 % by wt.

b. Composition of cement, cont'd

Composition of cement depends on quality and proportions of raw materials (limestone and clay)

Relatively small variations in oxide composition result in considerable changes in compound composition

Properties of compound cement constituents

	Rate of reaction	Cementing value		Heat of hydration	Sulfate resistance
		Early	Final		
C_3S	Medium	High	High	Medium	Medium
C_2S	Slow	Medium	High	Low	High
C_3A	Flash	Low	Low	Very high	Very low
C_4AF	High	Low	Low	High	Medium

b. Composition of cement, cont'd

Typical Portland Cements				
Oxides (% by wt)	**A**	**B**	**C**	**D**
CaO	66	67	64	64
SiO_2	21	21	22	23
Al_2O_3	7	5	7	4
Fe_2O_3	3	3	4	5
Free CaO	1	1	1	1
SO_3	2	2	2	2
Potential compound composition (% by wt)				
C_3S	48	65	31	42
C_2S	24	11	40	34
C_3A	13	8	12	2
C_4AF	9	9	12	15
	Typical or average P.C	High-Early Strength P.C	Low Heat P.C	Sulphate Resisting P.C

c. Different types of cements

(only some of them given here)

- High-early strength or rapid-hardening PC: develops strength more rapidly (do not confuse rate of hardening with the rate of setting: ordinary and rapid-hardening cements have similar setting times), used where a rapid strength development is desired, e.g. when formwork is to be removed early for re-use, or where sufficient strength for further construction is wanted as quickly as possible.
- Low-heat portland cement: used where a limitation of rate of heat evolution is needed, especially when large concrete masses were cast since the heat development by the hydration of cement coupled with a low thermal conductivity of concrete, can lead to serious cracking.
- Sulphate resisting PC: sulphate from the outside environment can be harmful for concrete. Therefore, especially for concretes that are intended to be used in sulphate environments should have low C_3A content.

d. Related standards

1. EN 197-1 or TS EN 197-1 (European standard)
2. ASTM C 150 (American standard)

TS EN 197-1 is used in Turkey!!!

d. Related standards, cont'd

1. EN 197 or TS EN 197-1:2012

<u>5 main cement types and 27 products (next slide)</u>

CEM I – Portland cement
CEM II – Portland composite cement
CEM III – Blast furnace slag cement
CEM IV – Pozzolanic cement
CEM V – Composite cement

EN 197 or TS EN 197-1:2012 Types of cement and compositions

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass[a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D[b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement[c]	CEM II/A-M	80-88	← 12-20 →									0-5
		CEM II/B-M	65-79	← 21-35 →									
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement[c]	CEM IV/A	65-89	–	<— 11-35 —>					–	–	–	0-5
		CEM IV/B	45-64	–	<— 36-55 —>					–	–	–	0-5
CEM V	Composite cement[c]	CEM V/A	40-64	18-30	–	<— 18-30 —>			–	–	–	–	0-5
		CEM V/B	20-38	31-49	–	<— 31-49 —>			–	–	–	–	0-5

a The values in the table refer to the sum of the main and minor additional constituents.

b The proportion of silica fume is limited to 10 %.

c In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for examples, see Clause 8).

d. Related standards, cont'd

EN 197 or TS EN 197-1:2012

- Sulfate resisting cements as listed in the standard
  - Sulfate resisting PC
    - CEM I – SR 0 (C_3A content of the clinker = % 0)
    - CEM I – SR 3 (C_3A content of the clinker ≤ % 3)
    - CEM I – SR 5 (C_3A content of the clinker ≤ % 5)
  - Sulfate resisting blast furnace cement
    - CEM III – B /SR (No requirement on C_3A content of the clinker)
    - CEM III – C/SR (No requirement on C_3A content of the clinker)
  - Sulfate resisting pozzolanic cement
    - CEM IV – A/SR (C_3A content of the clinker ≤ % 9)
    - CEM IV – B/SR (C_3A content of the clinker ≤ % 9)

- Low early strength cements
  - CEM III blast furnace slag cements

d. Related standards, cont'd

EN 197 or TS EN 197-1:2012

Mechanical requirements given as characteristics values

Strength class	Compressive strength MPa				Initial setting time	Soundness (expansion)
	Early strength		Standard strength			
	2 days	7 days	28 days		min	mm
32,5 L[a]	-	≥ 12,0	≥ 32,5	≤ 52,5	≥ 75	≤ 10
32,5 N	-	≥ 16,0				
32,5 R	≥ 10,0	-				
42,5 L[a]	-	≥16,0	≥ 42,5	≤ 62,5	≥ 60	
42,5 N	≥ 10,0	-				
42,5 R	≥ 20,0	-				
52,5 L[a]	≥ 10,0	-	≥ 52,5	-	≥ 45	
52,5 N	≥ 20,0	-				
52,5 R	≥ 30,0	-				

a Strength class only defined for CEM III cements.

d. Related standards, cont'd

2. ASTM C 150 (American standard)

5 main cement types, 10 products

- Type I – when no special properties are required
- Type II – when moderate sulfate resistance is required
- Type III – when high early strength is required
- Type IV – when a low heat of hydration is desired
- Type V – for use when high sulfate resistance is required

e. Hydration

Hydration; reaction takes place between cement and water and results in a hard solid structure (cement paste). Described in 5 stages by using rate of heat output vs. time graph.

Cement + Water → Cement paste

e. Setting of cement

- Setting; stiffening of the cement paste. (Note that stiffening and hardening are different)

- **Initial set;** mix starts to stiffen at a much faster rate, mix can no longer be mixed, placed and compacted (between 2-4 hours of mixing).
- **Final set;** the time after which strength begins to develop at a significant rate. (Max. 10 hours after mixing)
- **Flash set;** very rapid reaction of C_3A with water results in a flash set in a few minutes (results in very high heat evolution). Gypsum is added to clinker during cement manufacturing process to prevent the flash set. Dormant period is made possible owing to addition of gypsum.

Ref: Neville, A., Properties of concrete and Mehta and Monteiro, Concrete

e. Measurement of setting of cement (EN 196-3)

- For the setting time test, the cement paste should have normal consistency.

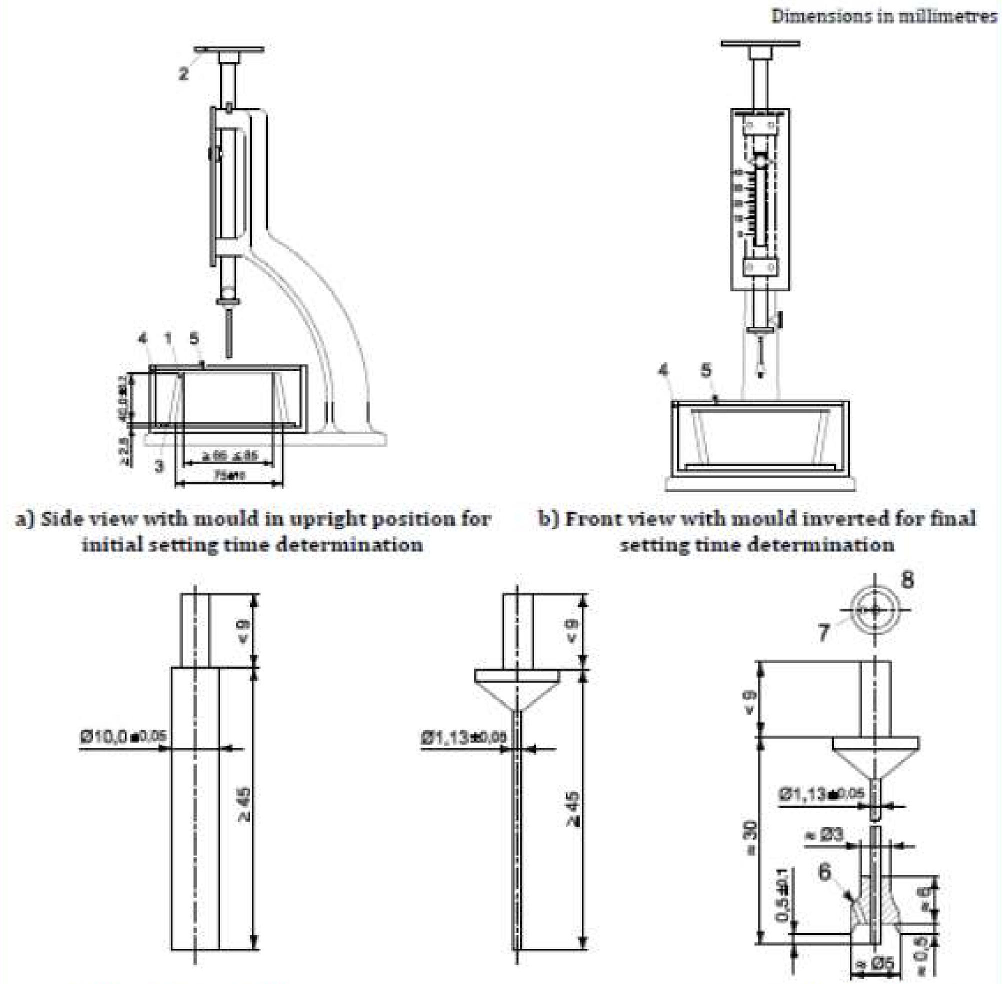
- **Normal consistency:** A standard measure of plasticity of a cement paste. (500grams of cement and some water (i.e. 125gr.) A paste has normal consistency when a Vicat plunger penetrates 34 ± 2 mm in 30 sec. Repeat the test until required penetration is reached.

e. Measurement of setting of cement (EN 196-3)

- **Time of initial set:** The time at which the cement paste can no longer be properly mixed, finished or compacted. Represented by a Vicat needle penetration when distance between the needle and the base-plate is 6 ± 3 mm, measured to the nearest 5 minutes.

- **Time of final set:** The time required for the cement to harden to a point where it can sustain some load. Represented by 0,5 mm penetration of Vicat needle.

Vicat apparatus dimensions (based on EN 196-3)



a) Side view with mould in upright position for initial setting time determination

b) Front view with mould inverted for final setting time determination

c) Plunger for standard consistence

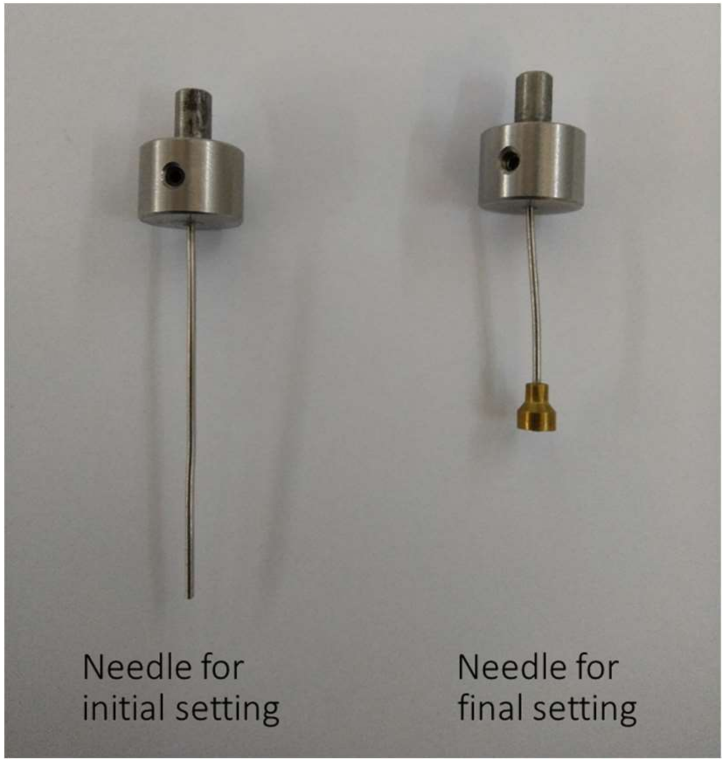
d) Needle for initial set

e) Needle with attachment for final set

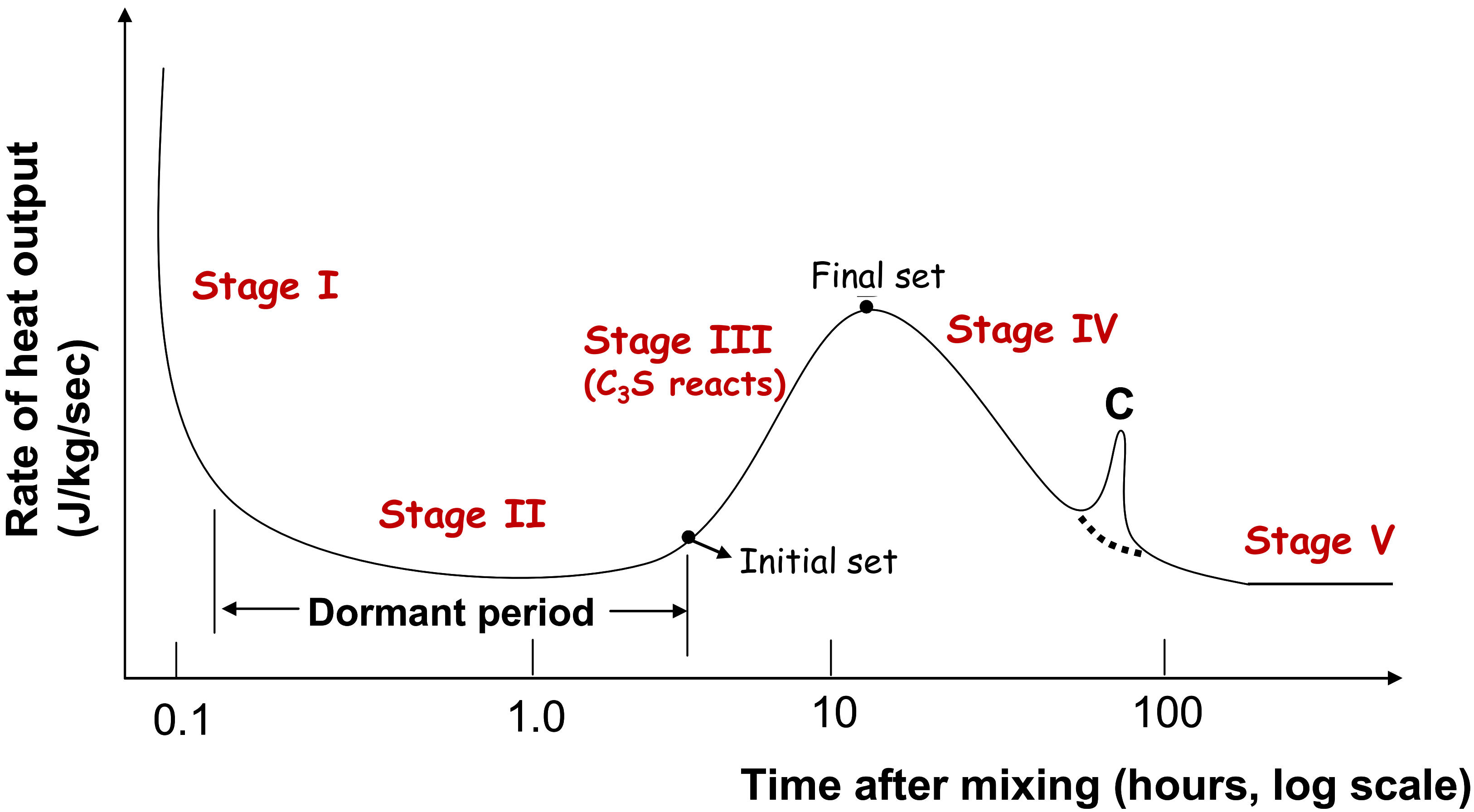
Key

1 mould
2 correcting weights
3 base plate
4 container
5 water
6 air vent (Ø approximately 1,5)
7 air vent
8 view from below needle with attachment for determining final setting time

e. Measurement of setting of cement (EN 196-3)



e. Hydration, cont'd – Stages of hydration



e. Hydration, cont'd

- **Dissolution (sometimes called hydrolysis) - (Cement + Water) →paste - initially fluid mixture (stage I)**
  - Ions from the cement particles are released into the mix water
  - Fast reaction, high heat output. An amorphous layer of hydration products form around the cement particles delaying further rapid dissolution from cement particles
- **Induction - Fluidity or consistency remains constant for an initial period after mixing (stage II) – also called dormant period**
  - Reactions are very slow – concrete is transported and placed during this stage
- **Rapid reaction period – begins with initial set (2-4 hours after mixing): Mix starts to stiffer, fluidity is lost at a faster rate (stage III) –**
  - Hydration products grow
  - Reactions are very fast
- **Slow reaction period – begins with final set (max 10 hours after mixing): Mix is completely stiff, hardening and strength gain starts (stage IV)**
- **Steady state - (Stage V)**
  - Reactions continue at a very slow manner

Initial set; fresh concrete can no longer be properly mixed, placed and compacted.
Final set; the time after which strength begins to develop at a significant rate. (Concrete, Mehta, Monteiro)

e. Hydration, cont'd - Hydration reactions

- Reactions of C_3S and C_2S – Products : CSH and CH
  - $2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$
  - $2C_2S + 4H \rightarrow C_3S_2H_3 + CH$
- Reactions of C_4AF - similar to that of C_3A

e. Hydration, cont'd - Hydration reactions

- Reactions of C_3A – Products : Ettringite
  - $C_3A + 6H \rightarrow C_3AH_6$

    very rapid reaction of C_3A with water results in a flash set in a few minutes. Gypsum is added to clinker during cement manufacturing process to prevent the flash set. Dormant period is made possible owing to addition of gypsum.

  - C_3A reacts with gypsum and ettringite (calcium sulphoaluminate) forms

$$C_3A + 3C\overline{S}H_2 + 26H \rightarrow C_6A\overline{S}_3H_{32}$$

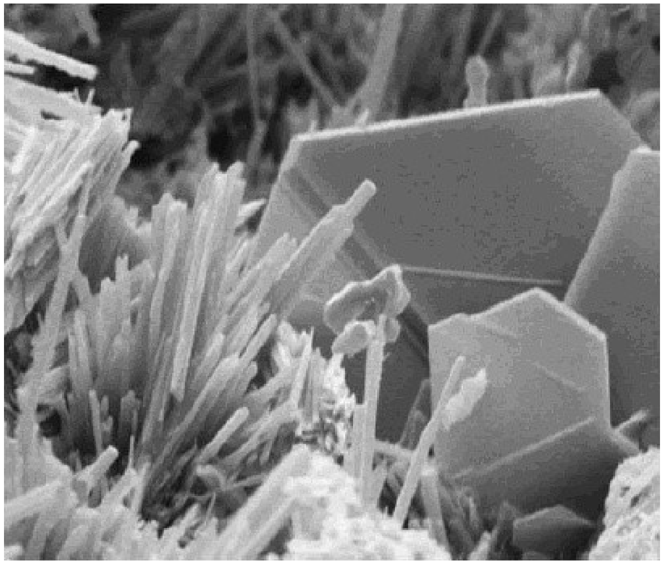
  - If all sulphate ions are consumed before C_3A has completely reacted, ettringite transforms to monosulfoaluminate. This occurs as **peak "C"** in cements with C_3A>12%

$$2C_3A + C_6A\overline{S}_3H_{32} + 4H \rightarrow 3C_4A\overline{S}H_{12}$$

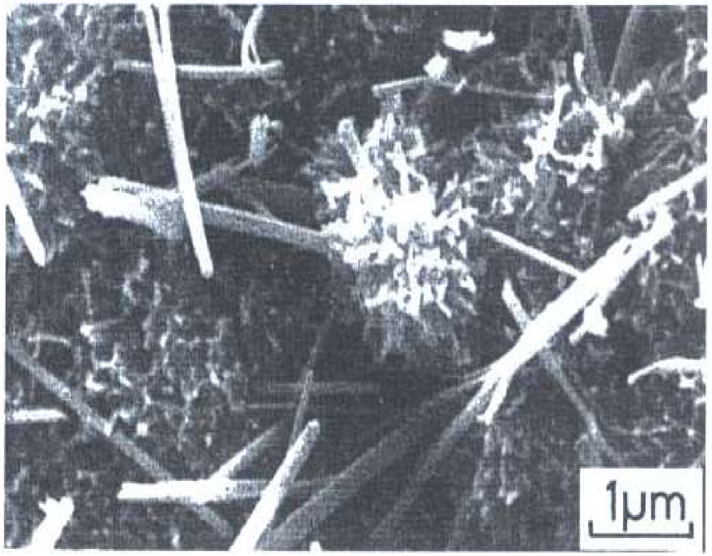
Flash set; immediate stiffening of the paste due to violent reaction of C_3A with water

e. Hydration, cont'd - Hydration products

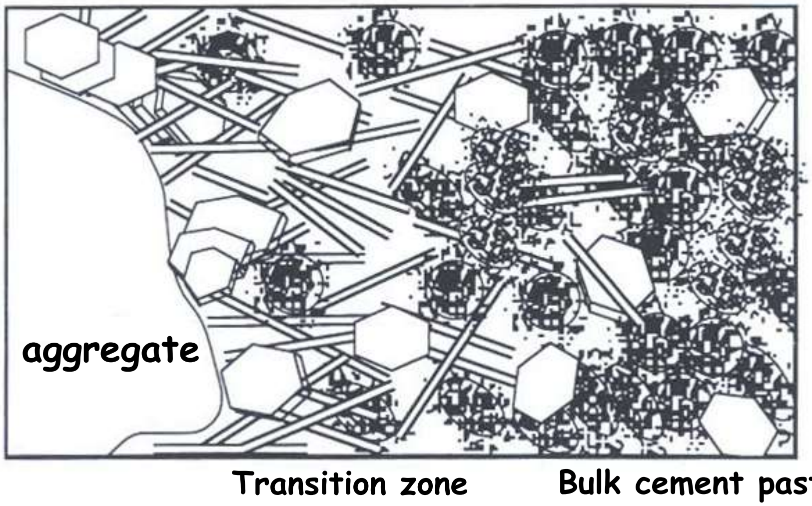
CSH – $CaO.SiO_2.H_2O$
CH - $Ca(OH)_2$
Ettringite



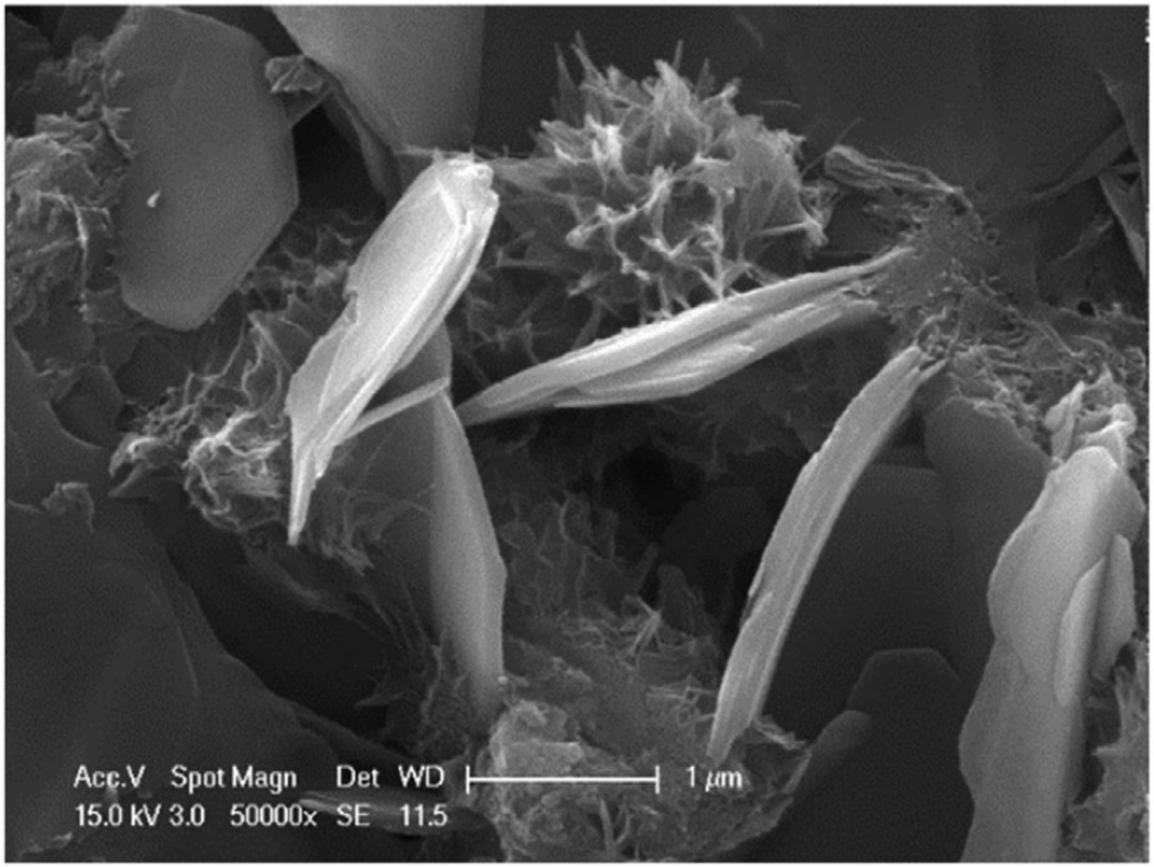
Fracture surface of 24 hour old cement paste, showing $Ca(OH)_2$ and ettringite



Fracture surface of 24 hour old cement paste, showing C-S-H and ettringite

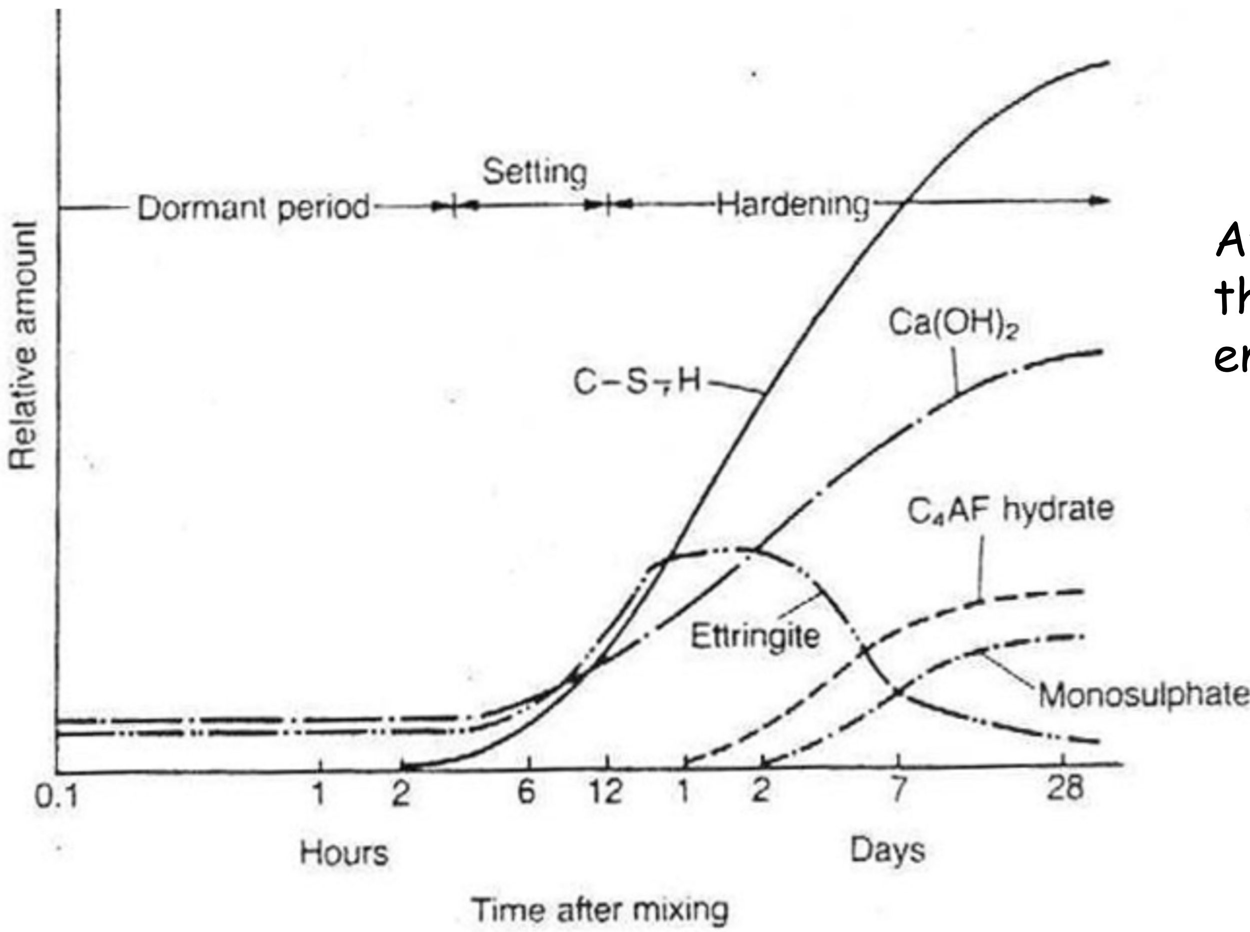


e. Hydration, cont'd - Hydration products



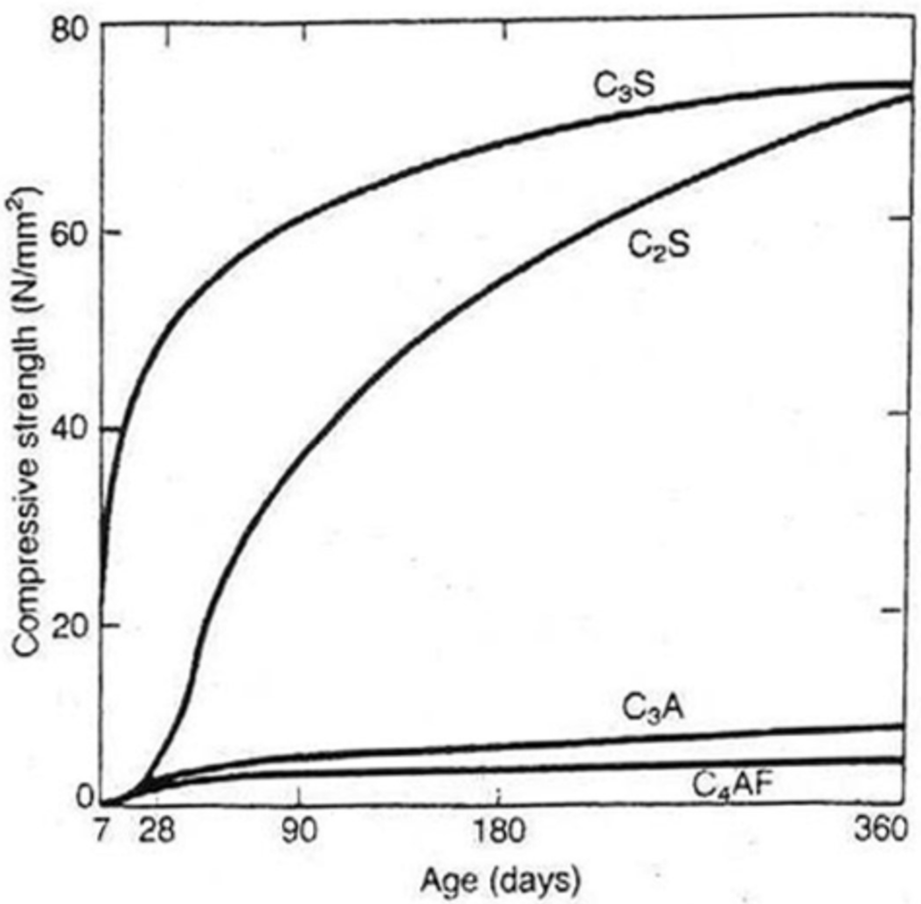
CSH and CH

e. Hydration, cont'd
Typical hydration product development in Portland cement paste



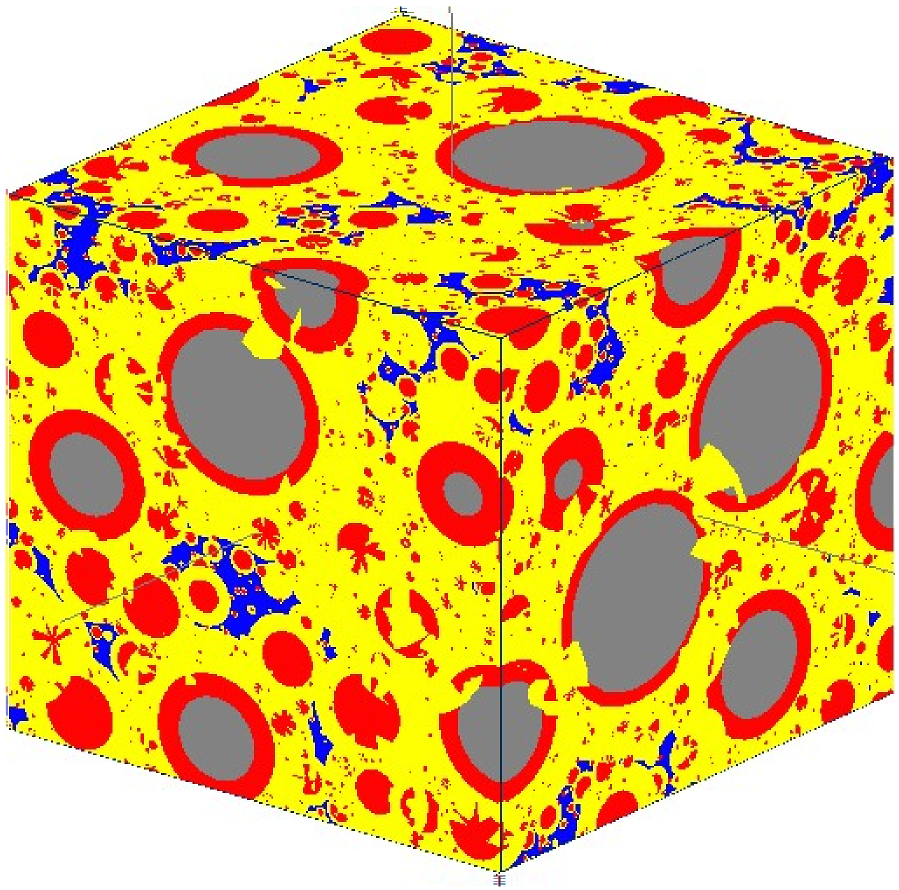
After 1 day CSH dominates, thus; $Ca(OH)_2$ production enhanced

e. Hydration, cont'd
Development of strength of pure compounds from Portland Cement



C_3S and C_2S are the ones contributing the most to the strength development

e. Hydration, cont'd
Model – Hydration of cement paste



f. Structure of hardened cement paste

- Residue of unhydrated cement, at center of original grains
- Hydrates, mainly calcium silicates (C-S-H); also calcium aluminates, sulphoaluminates and ferrites
- Crystals of calcium hydroxide ($Ca(OH)_2$)
- Unfilled spaces between cement grains, called capillary pores

Hardened cement paste; hydrates (cement gel) + unhydrated cement grains + $Ca(OH)_2$ +capillary pores

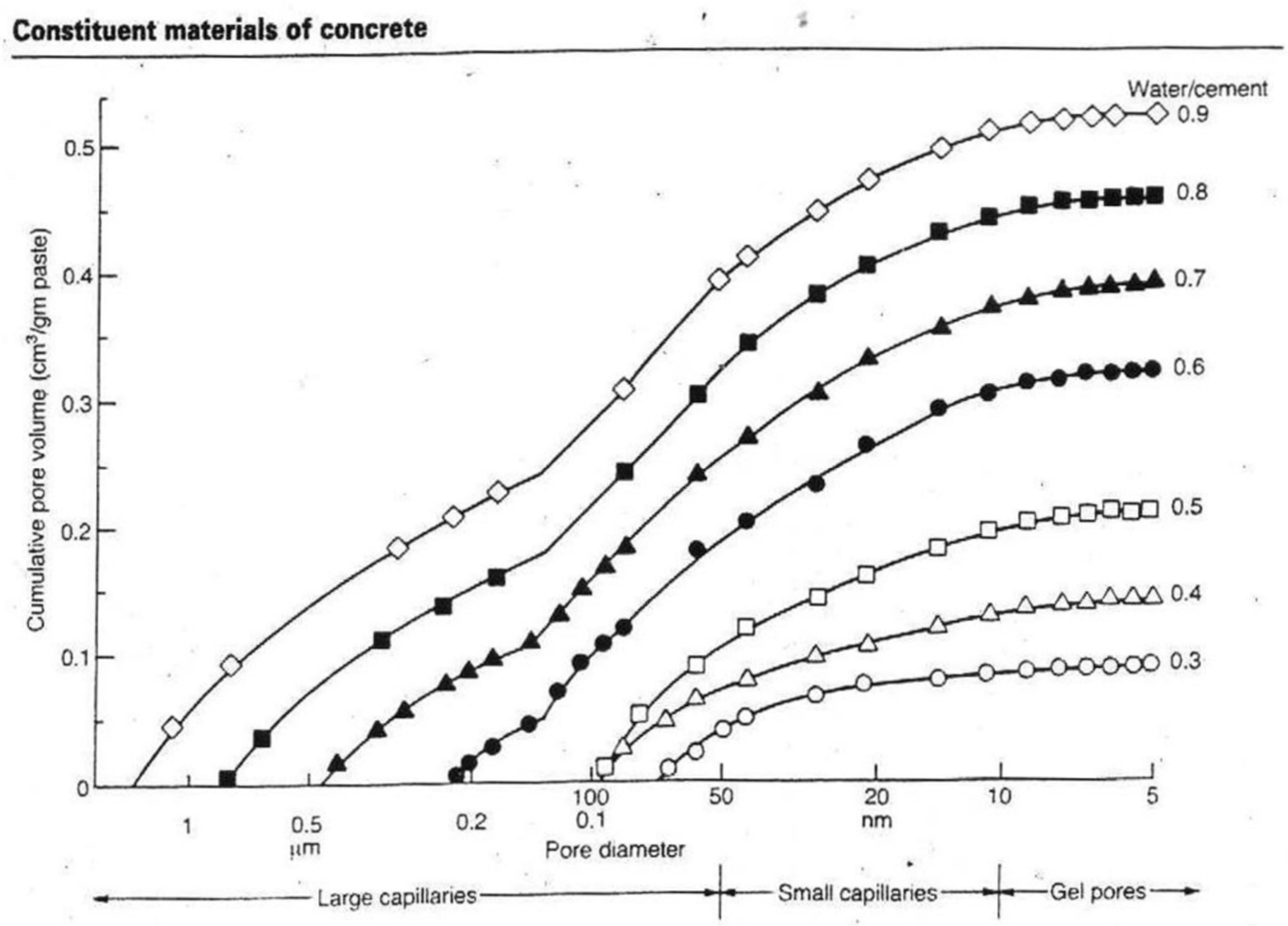
f. Structure of hardened cement paste, cont'd

Pore structure of cement paste

- Capillary pores; volume of capillary pores depends on w/c ratio, approximately 1-2μm in size
- Gel pores; 28 % of cement gel, volume of gel pores doesn't depend on w/c ratio, approximately, 2-3ηm in size

f. Structure of hardened cement paste, cont'd

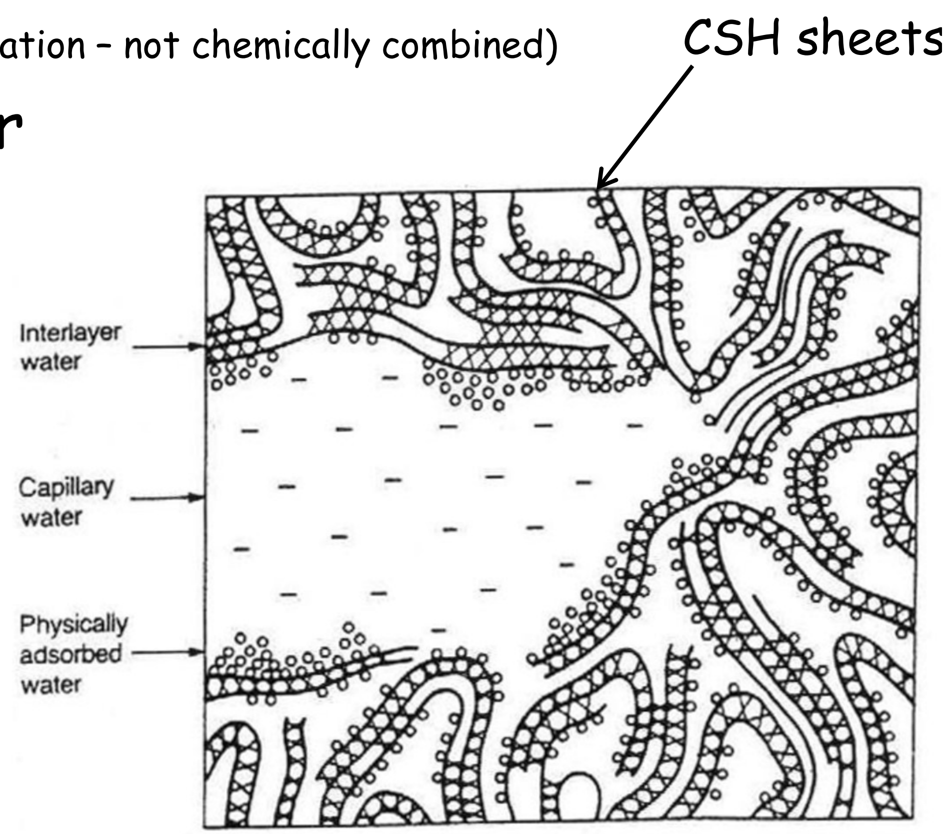
Pore size distribution in 28-day-old hydrated cement paste



f. Structure of hardened cement paste, cont'd

Water in hardened cement paste

- Water held in capillary pores
- Water held in gel pores in a variety of forms;
  - Physically adsorbed water
  - Interlayer water
  - Lattice water (water of crystallization – not chemically combined)
- Chemically combined water



f. Structure of hardened cement paste, cont'd

Water in hardened cement paste

Water vapour: in partially filled larger voids

Capillary water: in capillary pores; bulk water free from attractive forces of solid surfaces.

Adsorbed water: On solid surfaces under influence of surface attractive forces. Lost on drying to 30% RH and this contributes mainly to shrinkage

Interlayer water: In gel pores under influence of two surfaces very strongly held. Lost on drying at elevated temperatures and/or to 10% of RH. Causes in considerable shrinkage.

Chemically combined water: combined with fresh cement in hydration reactions. Not lost on drying. Heating to very high temperatures evolves this water through decomposition of paste.

Shrinkage; decrease in cement paste volume due to loss of humidity

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
    - Cement
    - Admixtures
    - Aggregates
  - Fresh state properties of concrete
  - Deformation of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

Subchapter Outline

Admixtures

1. Chemical admixtures
   a. Related standards and classification
   b. Main types
      i. Accelerating admixtures
      ii. Retarding admixtures
      iii. Water reducing/plasticizing admixtures
      iv. High range water reducing/superplasticizing admixtures
      v. Air – entraining admixtures
2. Mineral admixtures – cement replacement materials (CRMs)

ADMIXTURES

- Chemicals added immediately before or during mixing
- Significantly change fresh, early age or hardened properties to advantage
- Used in very small quantities

1. Chemical admixtures

a. Related standards and classification

TS EN 934-2 (European standard)

ASTM C 494 (American standard)

1. Chemical admixtures

a. Related standards and classification, cont'd

Classification given by TS EN 934-2

1) Admixtures
2) Water reducing/plasticizing admixtures
3) High range water reducing/superplasticizing admixtures
4) Water retaining admixtures
5) Air entraining admixtures
6) Set accelerating admixtures
7) Hardening accelerating admixtures
8) Set retarding admixtures
9) Water resisting admixtures
10) Set retarding/water reducing/plasticizing admixtures
11) Set accelerating/water reducing/plasticizing admixtures
12) Set retarding/high range water reducing/superplasticizing admixtures
13) Viscosity modifying admixtures

1. Chemical admixtures
a. Related standards and classification, cont'd

Classification given by ASTM C 494

1. Type A – Water reducing
2. Type B – Retarding
3. Type C – Accelerating (both setting and early strength development)
4. Type D – Water reducing and retarding admixtures
5. Type E – Water reducing and accelerating
6. Type F – High range water reducing admixtures
7. Type G – Water reducing, high range and retarding admixtures
8. Type S – Specific performance admixtures

1. Chemical admixtures
b. Main types

- 5 main types will be discussed here
  i. Accelerating admixtures
  ii. Retarding admixtures
  iii. Water reducing/plasticizing admixtures
  iv. High-range water reducing/superplasticizing admixtures
  v. Air entraining agents

1. Chemical admixtures
b. Main types, cont'd

i. Accelerating admixtures

- Increased rate of hardening and enhanced early strength
- May allow early removal of formwork
- May reduce curing time for concrete placed in cold weather
- May be used for urgent repair jobs

$CaCl_2$ is a popular accelerator. It may cause increased creep and shrinkage and therefore prohibited in reinforced concrete and pre-stressed concrete due to corrosion of steel in presence of chloride ions. Calcium nitrite, calcium nitrate, calcium formate and sodium formate may be given as other examples for accelerators.

1. Chemical admixtures

b. Main types, cont'd

ii. Retarding admixtures

- Delay setting time
- Counteracts accelerating effect of hot weather (especially for long transportation distances)
- Avoids cold joints and discontinuities by controlling setting in large pours

Sugar, different forms of carbohydrates are examples for some retarders

1. Chemical admixtures
b. Main types, cont'd

iii. Water reducing/plasticizing admixtures

They decrease w/c ratio (% 5-10 up to % 15) without interfering workability and thus result in increases in strength.

Two main groups :

a) Lignosulfonic acids and their salts

b) Hydroxylated carboxylic acids and their salts

1. Chemical admixtures
b. Main types, cont'd
iii. Water reducing/plasticizing admixtures, cont'd

- Plasticizers adsorbe on cement particle surfaces, giving negative charges to the surface and thus particles repel each other, breaking up any flocs and causing a better dispersion and wetting of particles
- This results in increased fluidity and slight increase in strength at same w/c ratio

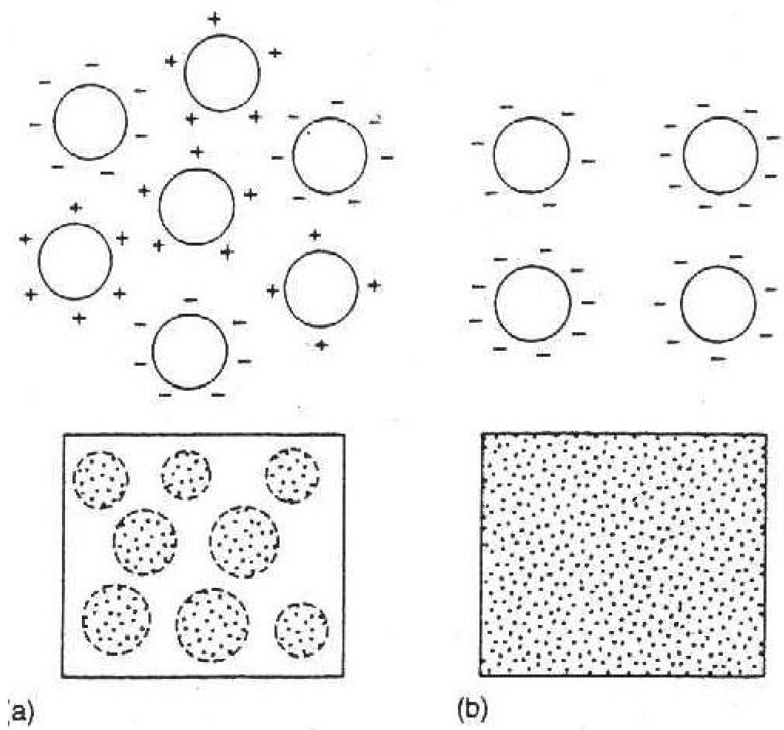


FIGURE 13.10 Schematic of dispersing action of plasticizing admixtures: (a) flocculated particles; (b) dispersed particles after admixture addition (Mindess and Young, 1981).

1. Chemical admixtures
b. Main types, cont'd

iv. High range water reducing/superplasticizing admixtures

They decrease w/c ratio (% 25-35) without interfering workability and thus result in very high increases in strength. Used either to increase workability (% 0.1 - 0.3) or to decrease the amount of w (% 0.5 – 2).

4 main categories :

a) Sulphonated melamin formalydehyde condensates
b) Sulfonated naphthalene-formaldehyde condensates
c) Modified lignosulfonates
d) Sulfonic acid esters and carbohydrate esters

1. Chemical admixtures
b. Main types, cont'd

v. Air entraining agents

- Organic materials which entrain controlled amount of microscopic (less than 0.1mm) bubbles into cement paste of concrete
- Bubbles preserve stability during mixing, transporting, placing, compaction and setting and hardening

  Note; entrained air and entrapped air are different

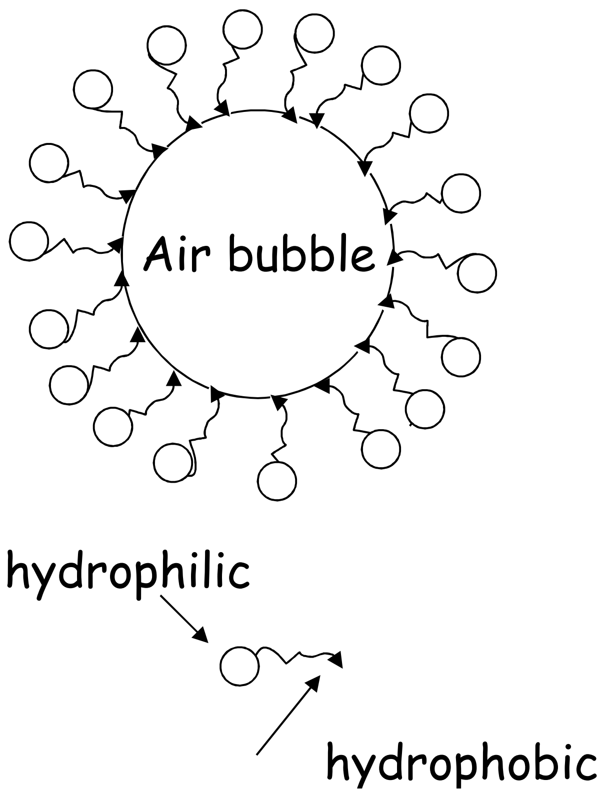
Air entrainment is done for providing freeze-thaw resistance to concrete

- In winter time, water in capillary pores expands on freezing resulting in disruptive internal stresses. Successive cycles of freezing and thawing may lead to progressive deterioration. Entrained air, uniformly dispersed in hcp with a spacing factor of not more than 0.2mm, provide a reservoir for water to expand
- Entrained air volumes of 4-7% by vol. of concrete is required to provide effective protection.

1. Chemical admixtures
b. Main types, cont'd

v. Air entraining agents - Secondary effects of air entrainment

- Increase in workability due to lubricating affect of small air bubbles
- About 6% decrease in strength for each 1% of air. However, improvement in workability may allow to partially offset the loss in strength by reducing water content and thus w/c ratios



- Organic substances reduce surface tension of water and bubbles form during mixing
- Long chain molecules have hydrophilic and hydrophobic ends
- They align themselves radially on surface of air bubble with hydrophilic ends in water and hydrophobic ends in air. Thus they provide air stability

2. Mineral Admixtures - Cement replacement materials (CRM)

Mineral additives that partially replace portland cement
Could be by-products from other industries (Economically advantageous)
They enhance concrete properties in a variety of ways

Pozzolanic behavior

A pozzolanic material is one which contains active silica (SiO_2) and is not cementitious in itself but will, in a finely divided form and in presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form cementitious compounds

Pozzolanic reaction (Secondary reaction)

$$S + CH + H \rightarrow C - S - H$$

2. Mineral Admixtures - Cement replacement materials (CRM)

Types of Cement Replacement Materials

1. Fly ash (pulverized fuel ash); ash from pulverized coal used to fire power stations
2. Ground granulated blast furnace slag (ggbs); slag from scum formed in iron smelting in a blast furnace, ground to a powder
3. Condensed silica fume; sometimes called microsilica; very fine particles of silica condensed from waste gases given off in production of silicon metal
4. Natural pozzolans; some volcanic ashes
5. Calcined clay and shale; clay and shale minerals heat treated
6. Rice husk ash; ash from controlled burning of rice husks after rice grains have been separated

Dictionary definitions:
Pulverize; to reduce to dust or powder, as by pounding or grinding
Smelt ; to melt or fuse (ores) in order to separate the metallic constituents.
Husk; the dry external covering of certain fruits or seeds

2. Mineral Admixtures - Cement replacement materials (CRM), cont'd

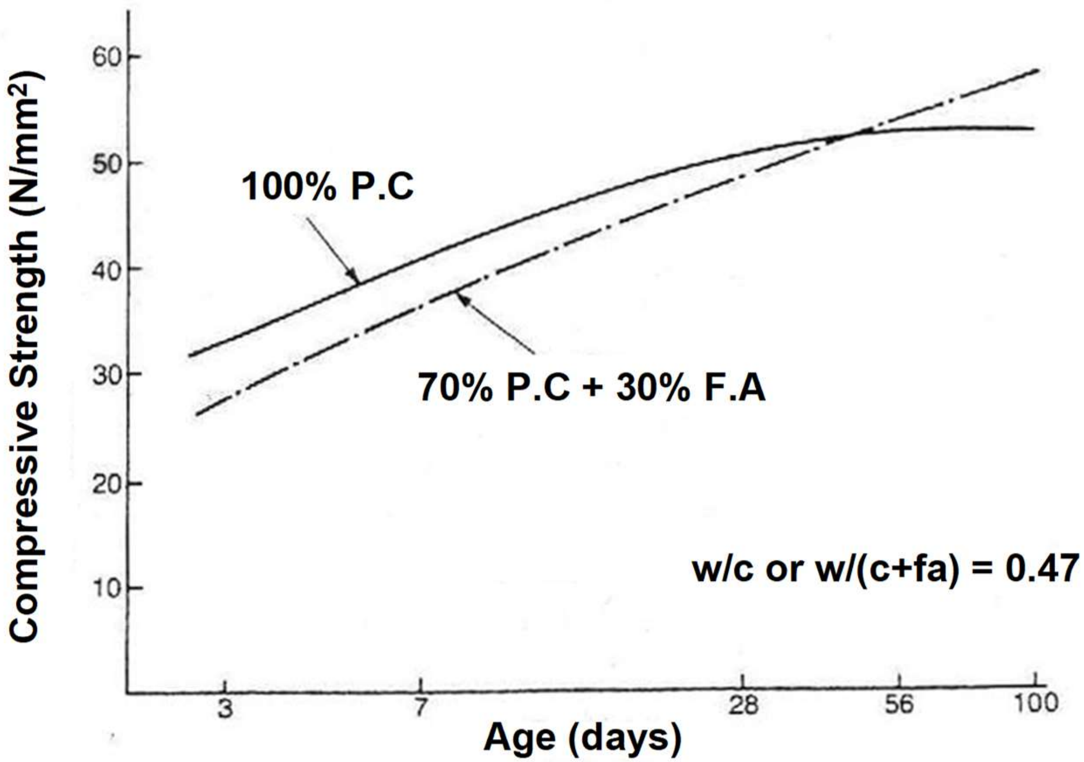
Typical composition and properties of cement replacement materials

Oxide	Fly ash		Ggbs	Silica fume	PC
	Low lime	High lime			
SiO_2	48	40	36	97	20
Al_2O_3	27	18	9	2	5
Fe_2O_3	9	8	1	0.1	4
MgO	2	4	11	0.1	1
CaO	3	20	40	-	64
Na_2O	1	-	-	-	0.2
K_2O	4	-	-	-	0.5
Specific gravity, (gr/cm^3)	2.1		2.9	2.2	3.15
Particle size (µm)	10-150		3-100	0.01-0.5	0.5-100
Specific Surface (m^2/kg)	350		400	15000	350

2. Mineral Admixtures - Cement replacement materials (CRM), cont'd

- High lime fly ash and ground granulated blast furnace slag are not true pozzolanas. They have certain self-cementing due to high CaO content. They may be used at high substitution rates (up to 90%)
- Low lime fly ash is used at most 40% replacement
- Silica fume is used at most 25% replacement (needs superplasticizer to maintain workability)
- Particles of artificial pozzolanas are smooth surfaced and spherical (Thus they improve workability)

2. Mineral Admixtures - Cement replacement materials (CRM), cont'd



- Pozzolanic reaction and then early strength development is slow
- With silica fume, delay is much less due to high surface area and active silica content
- At later ages concretes with cement replacement materials exceed strength of Portland cement only concretes
- Slower pozzolanic reaction reduces porosity
- Pozzolanic reaction enhances transition zone between aggregate and cement paste

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
    - Cement
    - Admixtures
    - Aggregates
  - Fresh state properties of concrete
  - Deformation of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

Subchapter Outline

Aggregates

1. Introduction
2. Aggregates and concrete composite models
3. Types of aggregates
   a) According to origin
   b) According to size
   c) According to density or specific gravity
4. Related standards
5. Grading of aggregates
6. Other properties of aggregates

AGGREGATES
1. Introduction

Disadvantages of hardened cement paste (hcp);

1. Dimensional instability (high creep and shrinkage)
2. High cost

Remedy to disadvantages;

Put aggregates into cement paste → Produce concrete

Aggregates occupy about 70-80% of total concrete volume

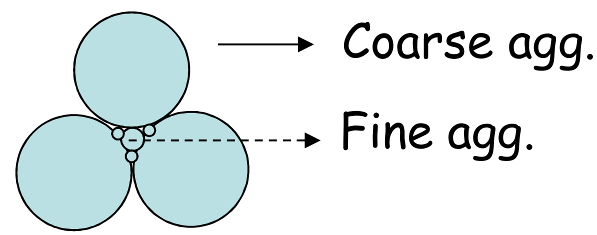
Creep; deformation of concrete under constant stresses
Shrinkage; decrease in volume due to loss of water

1. Introduction, cont'd

Objective;
Use as much aggregate as possible
Use largest possible aggregate size
Use a continuous grading of particle sizes from sand to coarse stones

Thus;
Void content of aggregate mixture
Amount of hcp required

} Minimized



2. Aggregates and concrete composite models

a) Two-phase model for describing deformation behavior
   - Coarse aggregate dispersed in mortar matrix
   - Coarse and fine aggregate dispersed in hcp matrix

b) Three-phase model for considering cracking and strength
   - Aggregates + hcp + transition or interfacial zone (~ 50 μm)
   - (cracking and failure starts from interfacial zone, the weakest phase)

3. Types of aggregates

a) **According to origin**
b) **According to size**
c) **According to density or specific gravity**

a) *According to origin;*
   i. Natural aggregates from natural sand and gravel deposits and crushed rocks
   ii. Specifically manufactured aggregates such as fly ash pellets, granulated blast furnace slag

b) *According to size;*
   i. Fine aggregate; Particle size from 0 to 4 mm
      Ex; natural sand and crushed sand
   ii. Coarse aggregate; Particle size from 4 to 16 or 32 mm
      Ex; gravel, crushed limestone

Dictionary definition:
Pellet; small, rounded or spherical body

c) According to density or specific gravity;

i. Normal density aggregates; natural aggregates,
Ex; gravels, igneous rocks (basalt, granite), sedimentary rocks (limestone, sandstone)
   - Specific gravities; 2.55 – 2.75 gr/cm^3
   - Concrete density; 2250 - 2450 kg/m^3
   - Gravels from deposits in river valleys or coastal waters are directly used after washing and grading, particles are round
   - Bulk rock sources (granite, basalt, limestone) require crushing giving angular and sharp particles

Dictionary definitions:
Igneous; produced under conditions involving intense heat, as rocks of volcanic origin or rocks crystallized from molten magma
Sediment; mineral or organic matter deposited by water, air, or ice.

ii. Lightweight aggregates; pumice (a naturally occurring volcanic rock), artificial lightweight aggregates (sintered fly ash, expanded clay or shale, foamed slag)
   - To produce lower density concretes (less than 2000 kg/m^3) advantages; reduced self-weight, better thermal insulation
   - Reduced specific gravity (less than 2.0 gr/cm^3) due to voids in particles
   - Reduced strength of concrete due to increased porosity

iii. Heavyweight aggregates; minerals like barytes to barium sulphate ore and steel shots
   - To produce high density concrete (3500 to 4500 kg/m^3) (For nuclear radiation shielding)

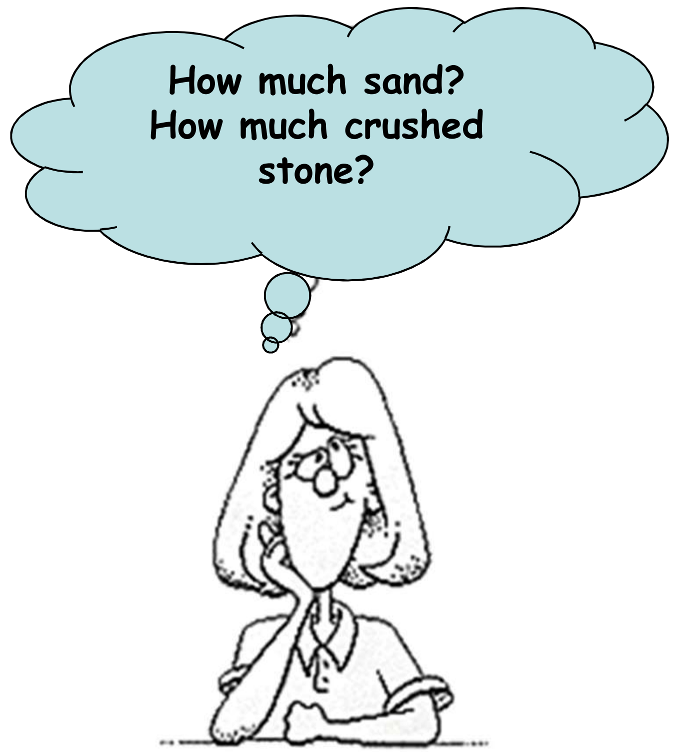
Dictionary definition:
Sintering; to form a coherent mass by heating without melting.
Barytes; a white or colorless mineral (BaSO4); the main source of barium
Ore; a mineral or natural product serving as a source of some nonmetallic substance

4. Related standards

- TS 706 EN 12620 (Aggregates for concrete)
  - Gives types and properties of aggregates
- TS 802 (Concrete mix design calculations)
  - Gives limiting grading curves

5. Grading of aggregates

- Grading or particle size distribution (Why do we need that?)
- Overall objective
  - To calculate suitable grading for good workability and stability (continuous grading → low void content)



5. Grading of aggregates, cont'd

Grading or particle size distribution (Sieve analysis)

- Aggregate samples dried, weighed and passed through a stack of the sieves
  - Sieve sizes in mm (0.25, 0.50, 1, 2, 4, 8, 16, 31.5) – different sieve series are given in TS 706 EN 12620
- Weight of aggregate retained on each sieve measured and converted to percentage retained and then to cumulative
- Then plotted against the sieve size to obtain *grading curve*

Sieve

Sieve Shaker

5. Grading of aggregates, cont'd

Grading curves

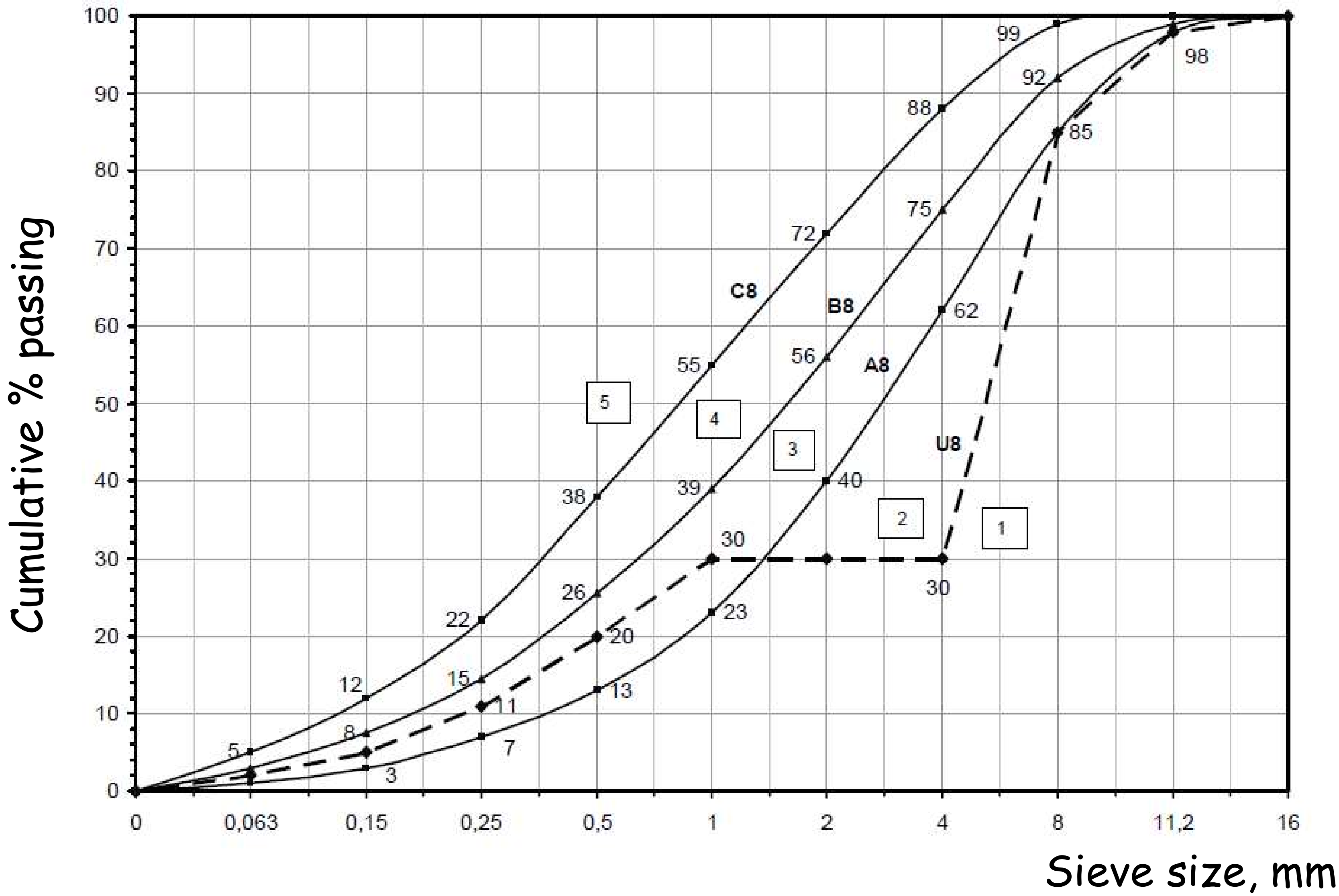
TS 802 define limits inside which the grading curves (next slides) for mixtures must fall.

5 regions are given on the grading curves.

Region 3; the best grading
Region 4; gradings falling into this region can be used
Region 2; gradings falling into this region can be used (only if unavoidable)
Region 5; should not be used (very fine – water requirement is very high)

5. Grading of aggregates, cont'd

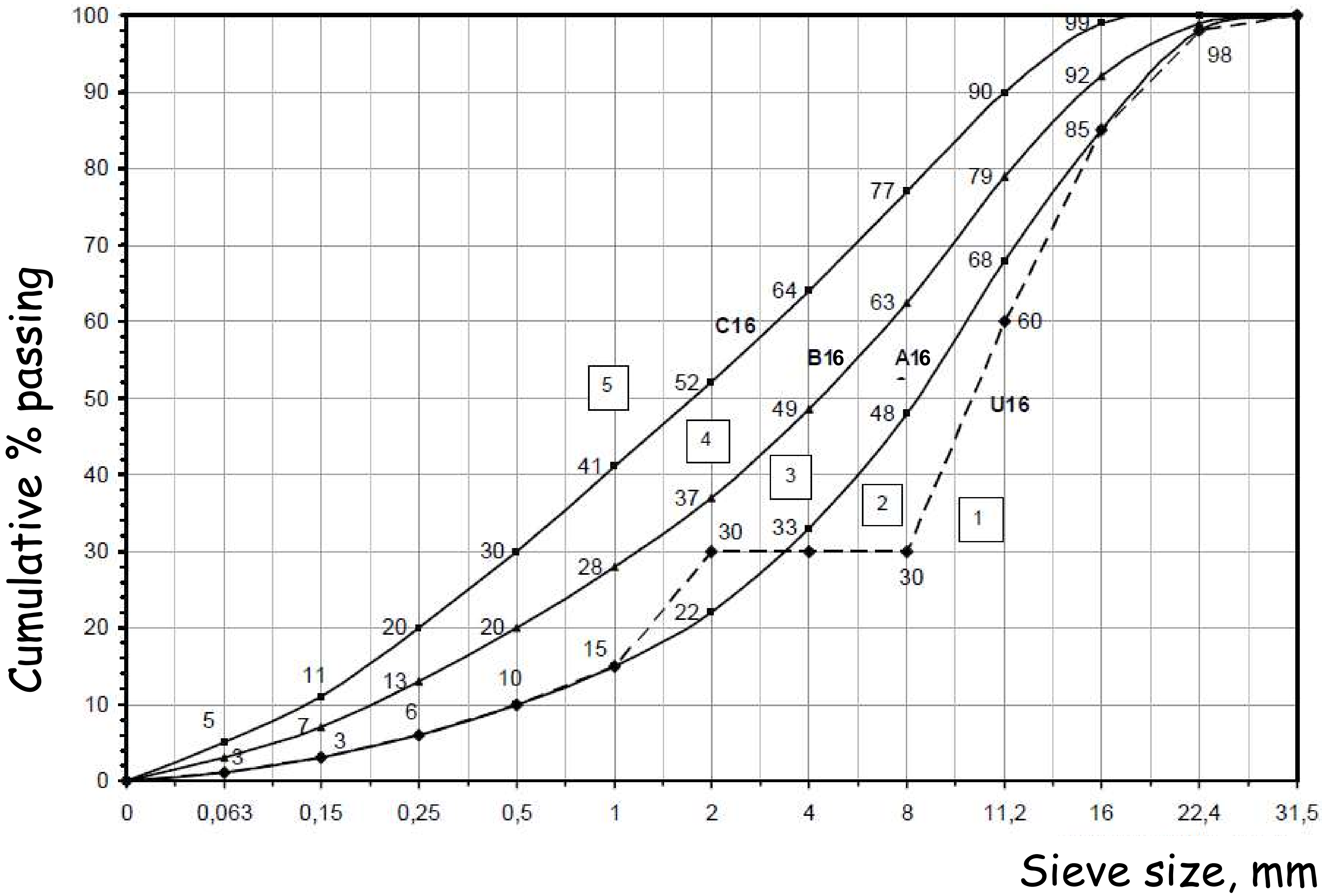
Grading curves



Grading curves for Dmax = 8 mm

5. Grading of aggregates, cont'd

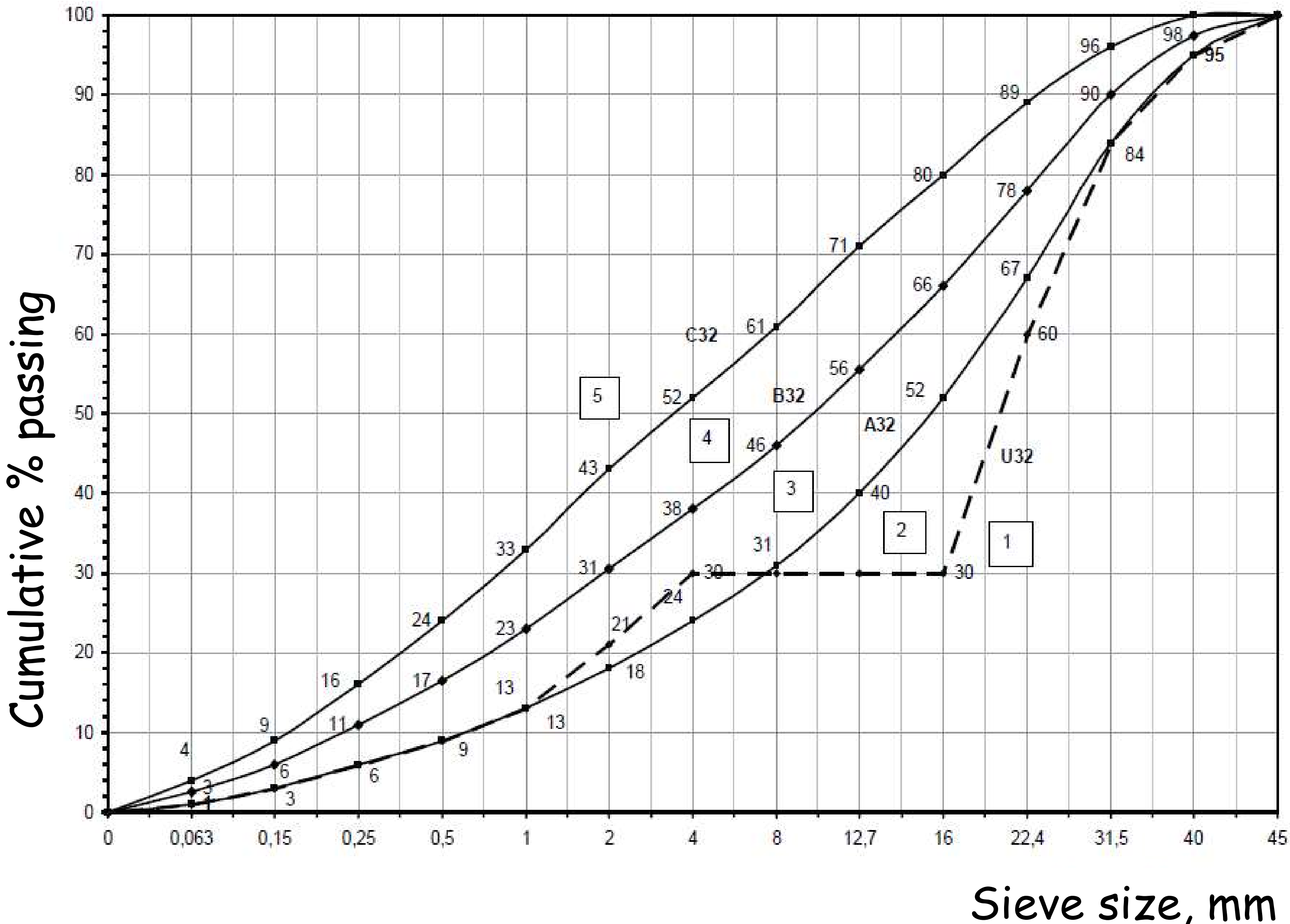
Grading curves



Grading curves for Dmax = 16 mm

5. Grading of aggregates, cont'd

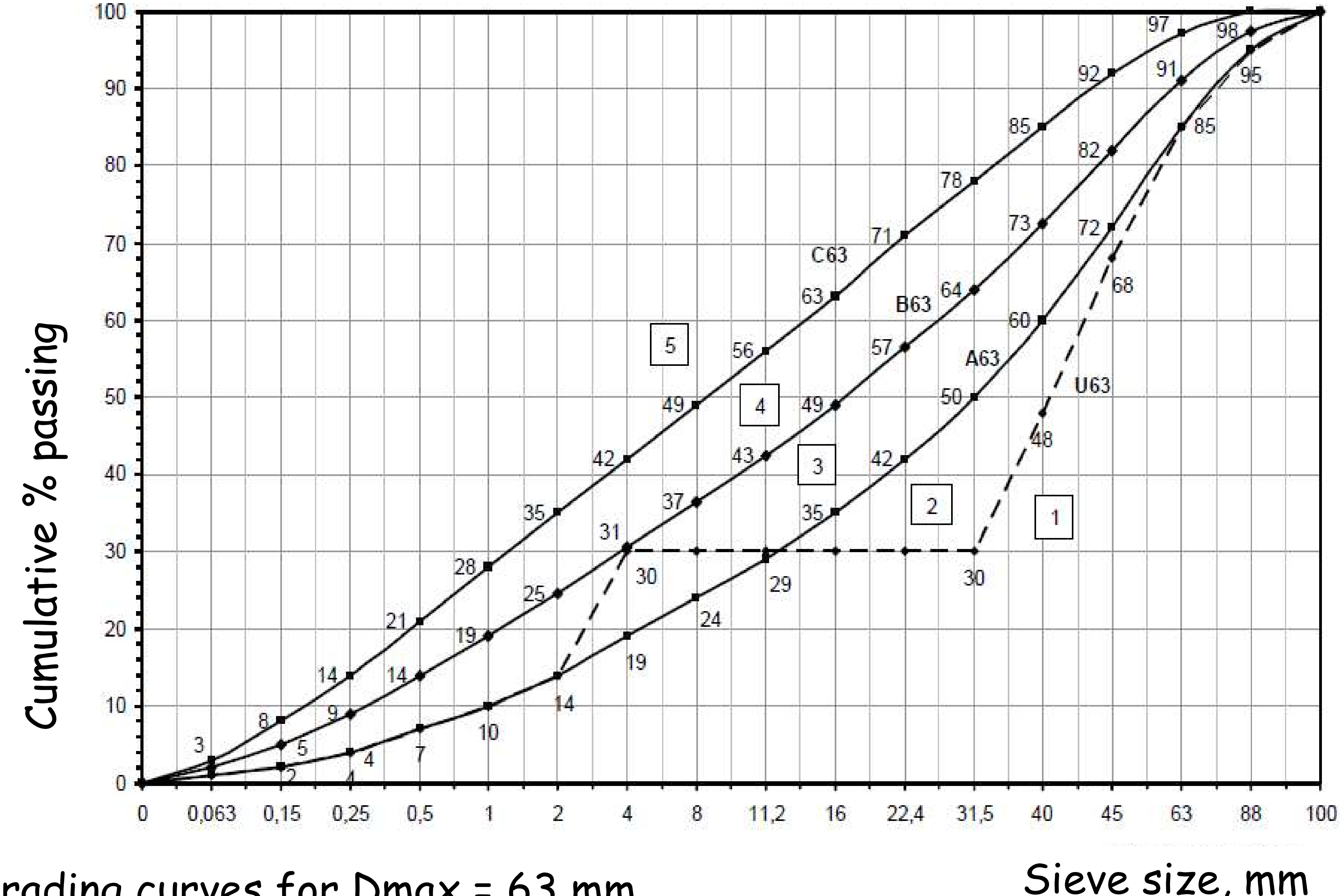
Grading curves



Grading curves for Dmax = 32 mm

5. Grading of aggregates, cont'd

Grading curves



Grading curves for Dmax = 63 mm

5. Grading of aggregates, cont'd

Example problem

Determine mix proportions of sand and crushed stone such that fineness modulus of mixture will be 4.30.

Sieve size (mm) / Material Passed (%)	**0.25**	**0.50**	**1**	**2**	**4**	**8**	**16**	**31.5**
Sand (%)	18	23	28	48	60	90	100	100
Crushed stone (%)	0	0	0	0	5	40	60	100

Fineness modulus; Sum of the cumulative percentages retained on the sieves of the standard series

Fineness modulus ↑ coarser material

5. Grading of aggregates, cont'd

Solution

Fineness Modulus = $\sum$ (cumulative percentage retained)/100

For sand = [800-(18+23+28+48+60+90+100+100)]/100 = 3,33

For crushed stone = [800-(5+40+60+100)]/100 = 5,95

5. Grading of aggregates, cont'd

Solution, cont'd

Mix proportions by vol: a (for sand), b (for crushed stone)

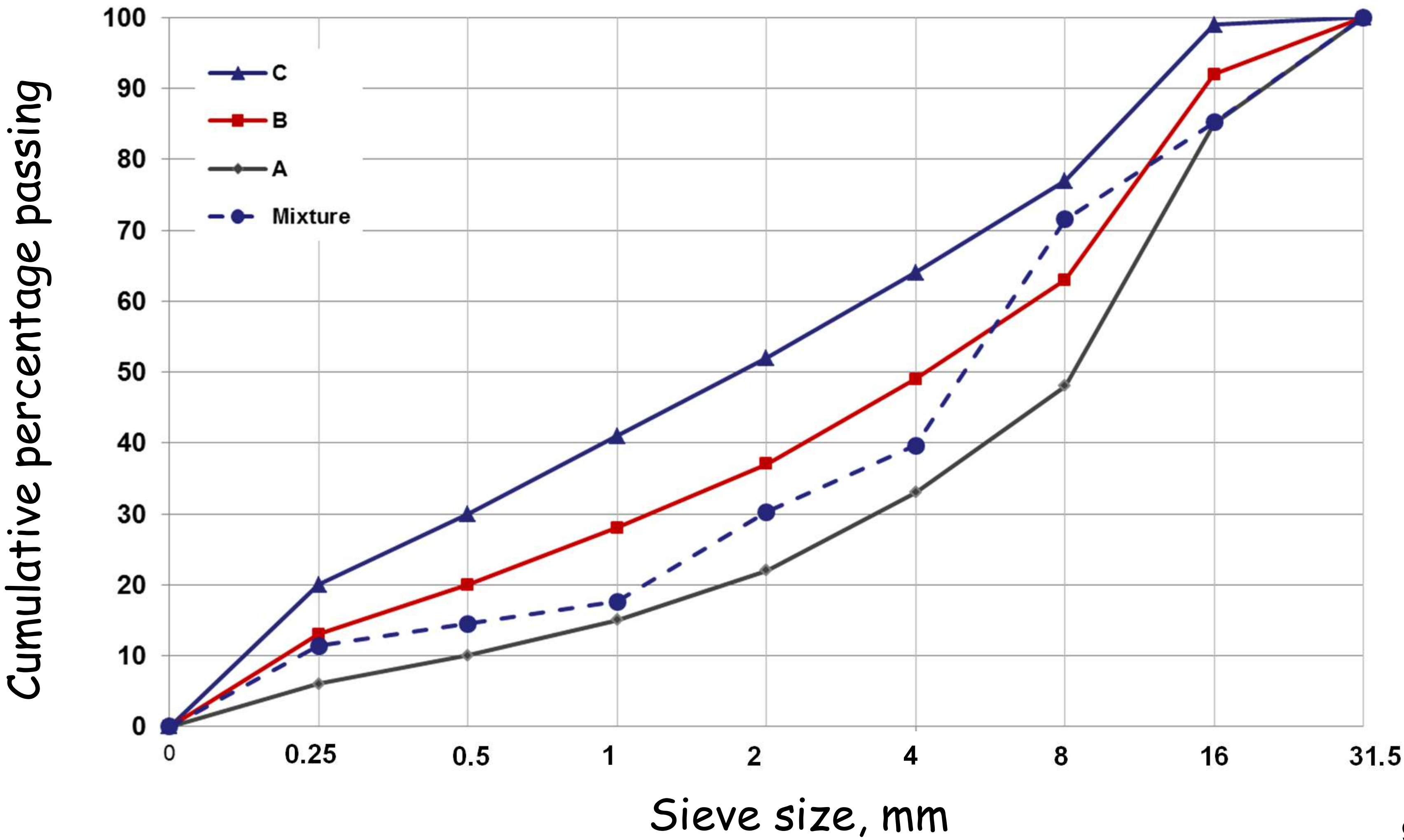
Using law of simple mixtures;

$$\left. \begin{aligned} a + b &= 1 \\ m_1 a + m_2 b &= m_m \end{aligned} \right\} \quad \left. \begin{aligned} a + b &= 1 \\ 3.33\,a + 5.95\,b &= 4.30 \end{aligned} \right\} \quad \begin{aligned} a &= 0.63 \\ b &= 0.37 \end{aligned}$$

Sieve size (mm) / Material Passed (%)	**0.25**	**0.50**	**1**	**2**	**4**	**8**	**16**	**31.5**
Sand **(0.63)**	11.3	14.5	17.6	30.2	37.8	56.7	63	63
Crushed stone **(0.37)**	0	0	0	0	1.9	14.8	22.2	37
Mixture	11	15	18	30	40	72	85	100

5. Grading of aggregates, cont'd
Solution, cont'd

Grading curve of the mixture (sand+crushed s.) together with the limiting A, B and C curves



5. Grading of aggregates, cont'd

In case of more than two aggregate fractions

$$\left.\begin{aligned} a+b+c&=1 \\ P_i^1 a + P_i^2 b + P_i^3 c &= P_i^m \\ P_j^1 a + P_j^2 b + P_j^3 c &= P_j^m \end{aligned}\right\}$$

Can be extended to as many equation as number of size fractions which provides full conformity to the desired grading curve

Ideal (desired) grading curve

Fuller parabola

$$P_i = 100\sqrt{\frac{d_i}{D_i}}$$

where;
P_i = % passing from i^{th} sieve
d_i = opening size of i^{th} sieve
D_{max}= Max particle size
(sieve size through which 100% of aggregate passes)

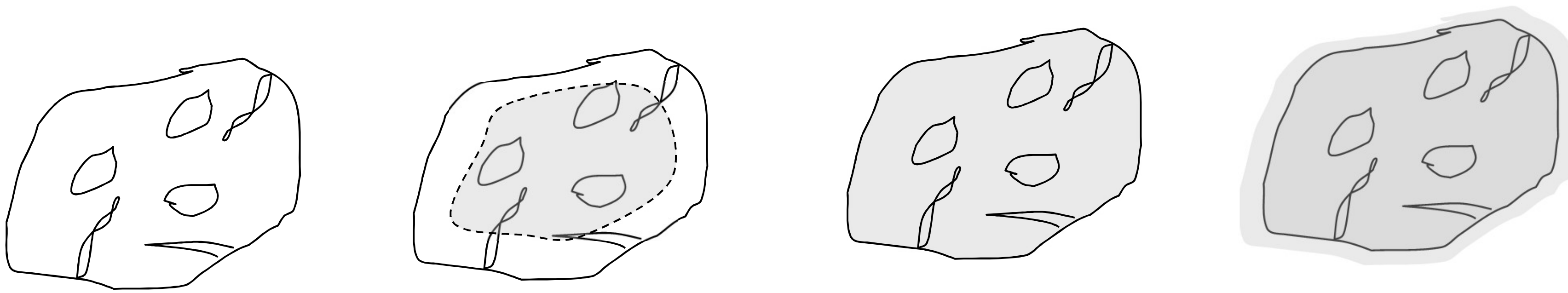
- Use fineness modulus of the ideal grading curve and aim to approach to this value for the mixture (this is a convenient method especially if there are only 2 types of aggregates)
- Select 2 sieve sizes and fix the percent passing from these two sieve sizes for the mixture curve based on ideal curve.

6. Other properties of aggregates

1) Porosity and absorbtion

Normal weight aggregates contain pores (typically 1-2 % by volume)
Particles can absorb and hold water

Aggregate Moisture Conditions



Completely (oven dry) All pores empty	Air dry Pores partially filled	Saturated surface dry All pores full but no excess water	Saturated or wet excess water
	Field conditions	Possible only in lab. conditions	Field conditions
Absorb some of mix water in fresh concrete	Absorb some of mix water in fresh concrete	No absorbtion and no addition	Add to mix water in fresh concrete

6. Other properties of aggregates, cont'd

- Amount of water available for cement hydration, i.e. non-absorbed or free water is of prime importance
- Therefore, to ensure the required free water/cement ratio, it is necessary to allow for the aggregate moisture condition
- When calculating the amount of mix water;
  - If aggregate is drier than SSD, extra water must be added
  - If it is wetter, then less mix water is required

2) Elastic properties and strength

- Elastic properties of aggregates have major influence on elastic properties of concrete
- Strength of normal weight aggregates are higher than haredened cement paste and do not have major influence on strength of normal strength concrete
- In high-strength concrete (greater than 70-80 MPa), strength of aggregates and effect of transition zone between aggregate and hcp become seriously important

6. Other properties of aggregates, cont'd

3) Surface characteristics

- Surface texture have greater influence on the flexural strength than on the compressive strength of the concrete (rougher texture results in a better adhesion)
- Surface cleanliness is also important for adhesion (surface should be kept clear of the materials such as mud, clay etc.)
- Better adhesion » stronger *interface* between aggregate and hcp

Stronger interface zone » higher mechanical performance

Example 2

Sieve analysis test results for three available aggregates are given as:

	0.25	0.5	1.0	2.0	4.0	8.0	16.0	mm
Sand	15	40	83	98	100	100	100	% passing
Sandy gravel	5	10	30	60	70	85	100	% passing
Crushed stone	0	0	0	0	0	5	100	% passing

Concrete will be produced with aggregate mixture grading conforming to an ideal grading curve given by $P = 100\,(d/D)^{1/2}$

Where, P = % passing the sieve
d = sieve size
D = maximum particle size of aggregate mixture

Considering the possible combinations of these three aggregates, determine the grading curve of the aggregate mixture that best conforms to the ideal curve. Discuss your result and explain your reasoning.

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
  - Fresh state properties of concrete
  - Deformation of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

Subchapter Outline

Fresh state properties of concrete

1. Workability
2. Workability measurement methods
3. Behavior of fresh concrete after placing and compacting
   i. Segregation and bleeding
   ii. Plastic settlement
   iii. Plastic shrinkage
4. Curing concrete
5. Maturity

Fresh state / early age properties of concrete

Fresh state properties affect hardened state properties of concrete

Fresh concrete: from time of mixing to end of time concrete surface finished in its final location in the structure

Operations: batching, mixing, transporting, placing, compacting, surface finishing

Treatment (curing) of in-placed concrete 6-10 hours after casting (placing) and during first few days of hardening is important

1. Workability

Main properties of fresh concrete during mixing, transporting, placing and compacting

- Fluidity or consistency: capability of being handled and of flowing into formwork and around any reinforcement, with assistance of compacting equipment
- Compactability: air entrapped during mixing and handling should be easily removed by compaction equipment, such as poker vibrators
- Stability or cohesiveness: fresh concrete should remain homogenous and uniform. No segregation of cement paste from aggregates (especially coarse ones)

Fluidity & compactability known as WORKABILITY

Higher workability concretes are easier to place and handle but obtaining higher workability by increasing water content decreases strength and durability

1. Workability, cont'd

Compaction of concrete **Finishing of concrete**

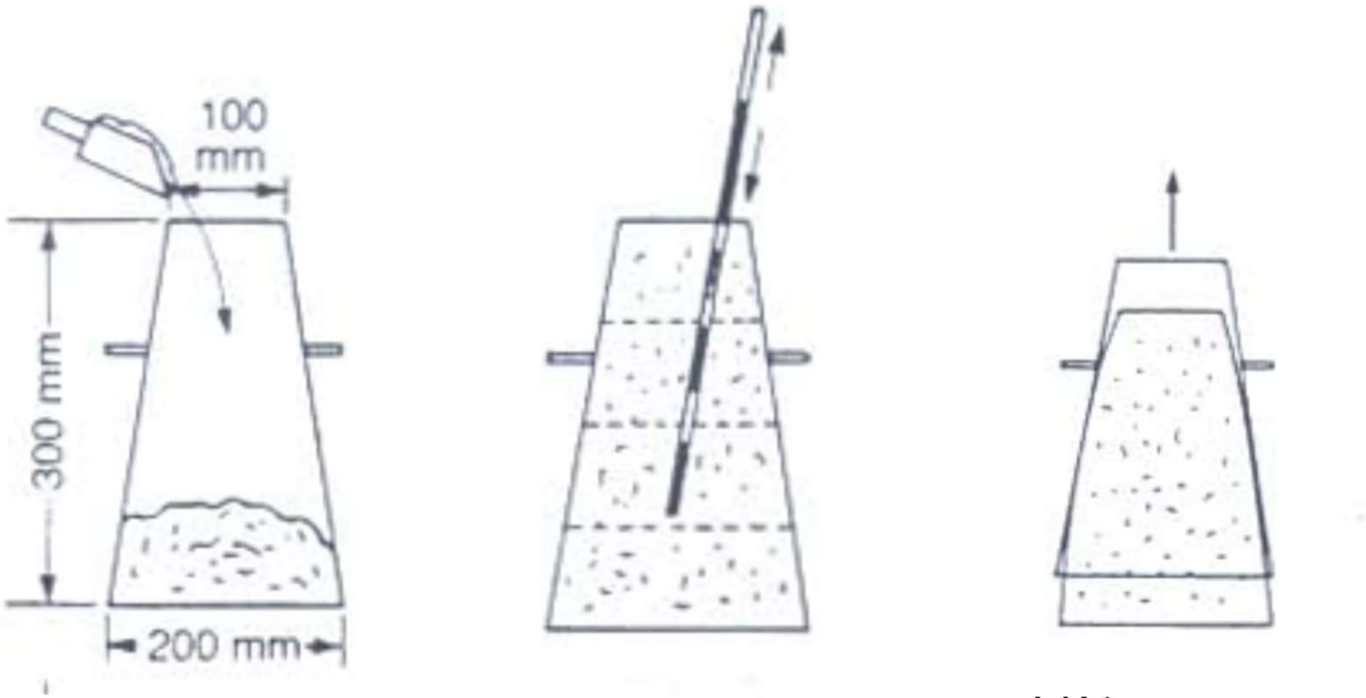
Fig ref :
https://www.google.com/search?q=compaction+of+concrete&rlz=1C1EODB_enTR532TR534&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjR0qSv66HgAhXBTRUIHas7D_AQ_AUIDigB&biw=1920&bih=938#imgrc=9P7mTskScseoZM:

2. Workability measurement methods

a) Slump test
b) Mini-slump test
c) Compacting factor test
d) Vebe test
e) Flow table test

2. Workability measurement methods, cont'd

a) Slump test - simplest and crudest test (standardized in ASTM C 143 and EN 12350-2)



Fill concrete into frustum of a steel cone in three layers

Hand tap concrete In each layer

Litt cone up
Define slump as downward Movement of the concrete

2. Workability measurement methods, cont'd

a) Slump test

Lift cone up

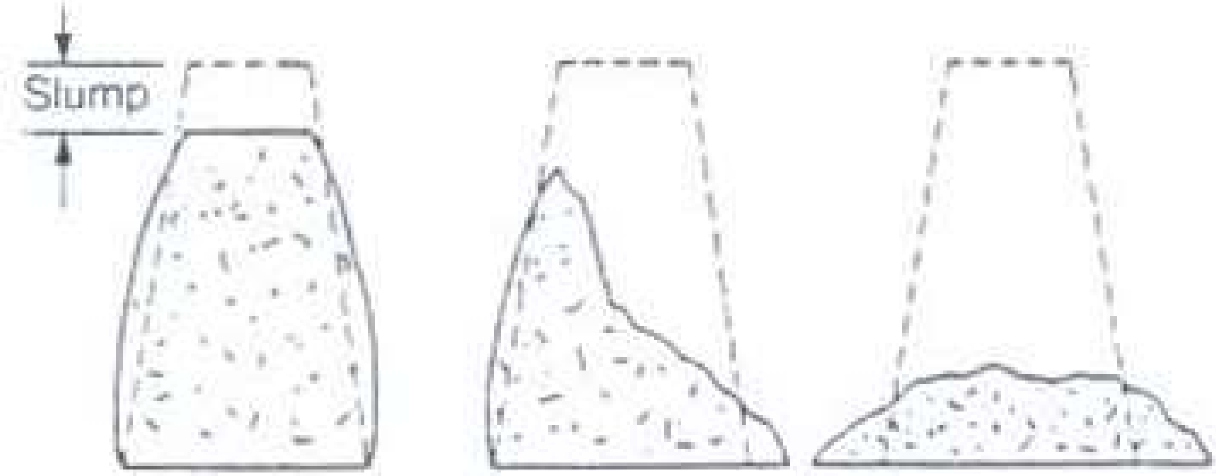
Define slump as downward movement of the concrete

Fig; http://www.arche.psu.edu/thinshells/module%20III/concrete_material_files/image002.gif

Fig; http://myphliputil.pearsoncmg.com/media/nccer_carpentry_2/module03/fg03_00900.gif

2. Workability measurement methods, cont'd

a) Slump test



True
Valid slump measurement 0-175 mm

Shear
Mixes having tendency to segregate – repeat test

Collapse
Slumps greater than 175 mm - self-leveling concrete

Consistency grade	Slump (mm)	Recommended method of compaction
Stiff, K1	0 - 60	Mechanical compaction like vibration
Plastic, K2	60 – 130	Mechanical or hand compaction (rodding, tampering)
Flowing, K3	130 – 200	Hand compaction or no compaction
Self compacting, K4	≥ 200	No compaction

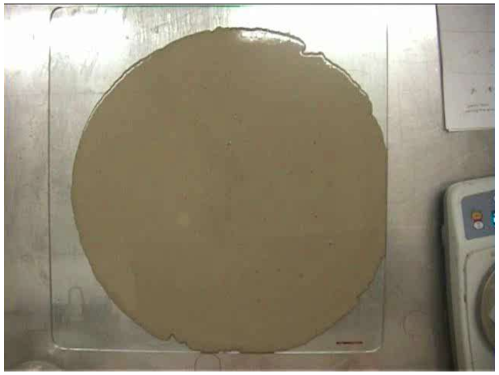
2. Workability measurement methods, cont'd

b) Mini slump test

- Used for workability testing of cement pastes
- Mini slump cone is a small version of slump cone
- The cone is placed in the center of a piece of glass, paste is cast into cone and then the cone is lifted to measure the average spread of paste.

w/b : 0.2 sp:%2

w/b : 0.22 sp:%2

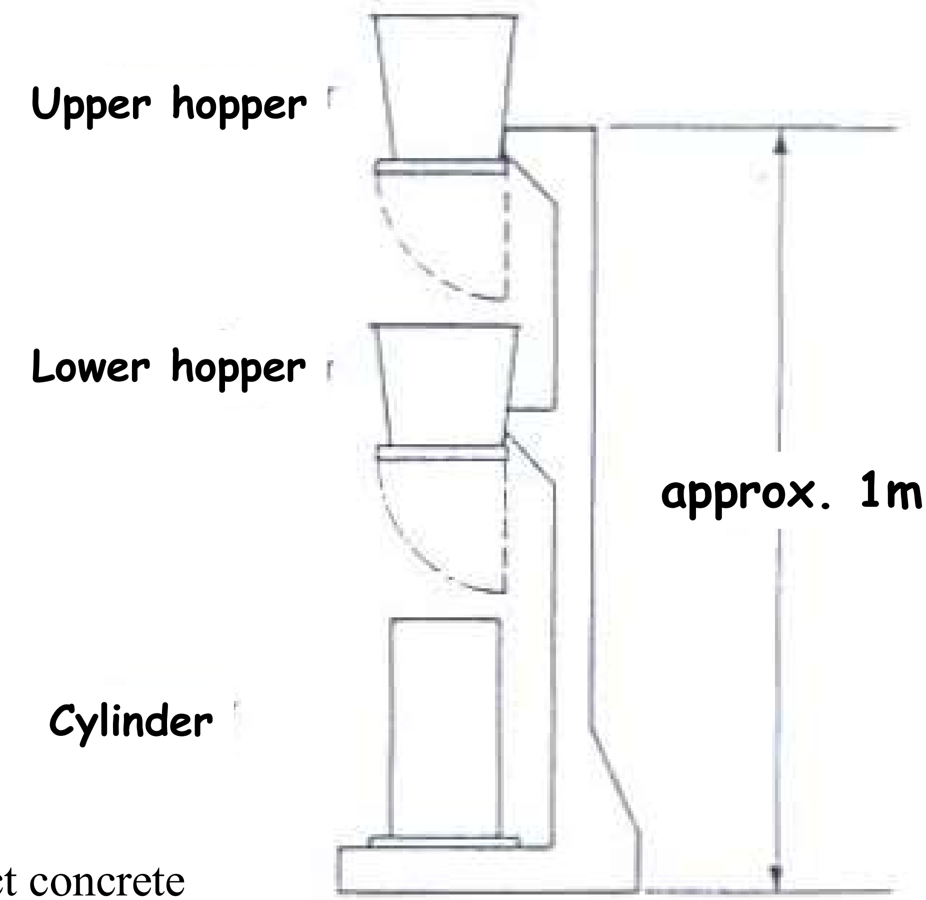


2. Workability measurement methods, cont'd

c. Compacting factor test

(to distinguish between low slump mixes)

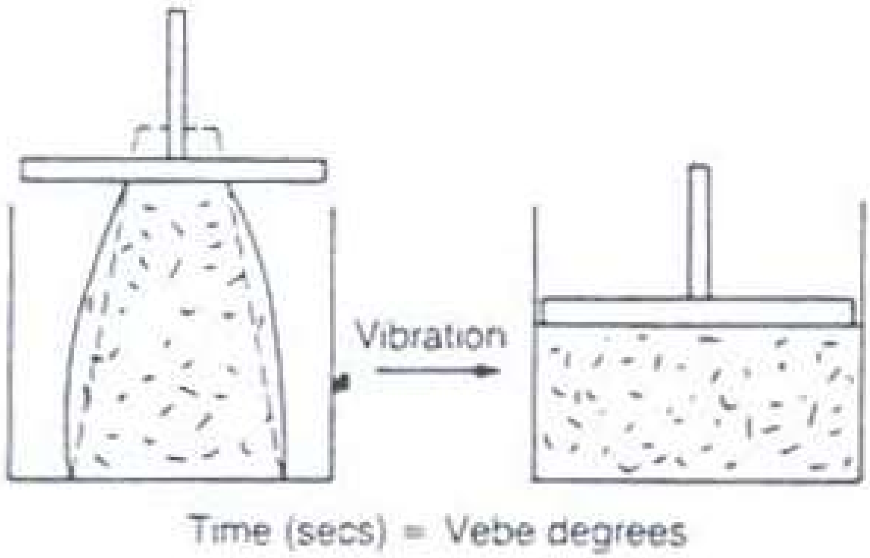
1. Concrete is placed in an upper hopper
2. Dropped into a lower hopper to bring it to a standard state and then allowed to fall into a standard cylinder.
3. The cylinder and concrete weighed (partially compacted weight)
5. The concrete is fully compacted, extra concrete added and then conrete and cylinder weighed again (fully compacted weight)



$$\text{Compacting factor} = \frac{\text{weight of partially compact concrete}}{\text{weight of fully compact concrete}}$$

2. Workability measurement methods, cont'd

d) Vebe test



1. A slump test is performed in a container
2. A clear perspex disc, free to move vertically, is lowered onto the concrete surface
3. Vibration at a standard rate is applied

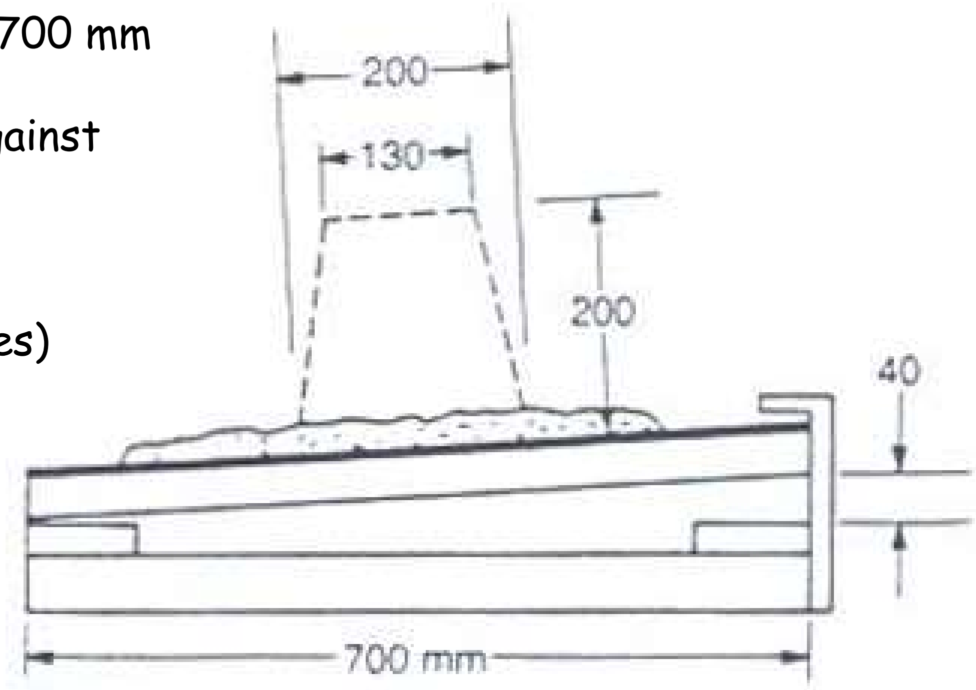
<u>Vebe time</u> is defined as the time taken to complete covering of the underside of the disc with concretecontainer

2. Workability measurement methods, cont'd

e) Flow table test
(to differentiate between high workability mixes)

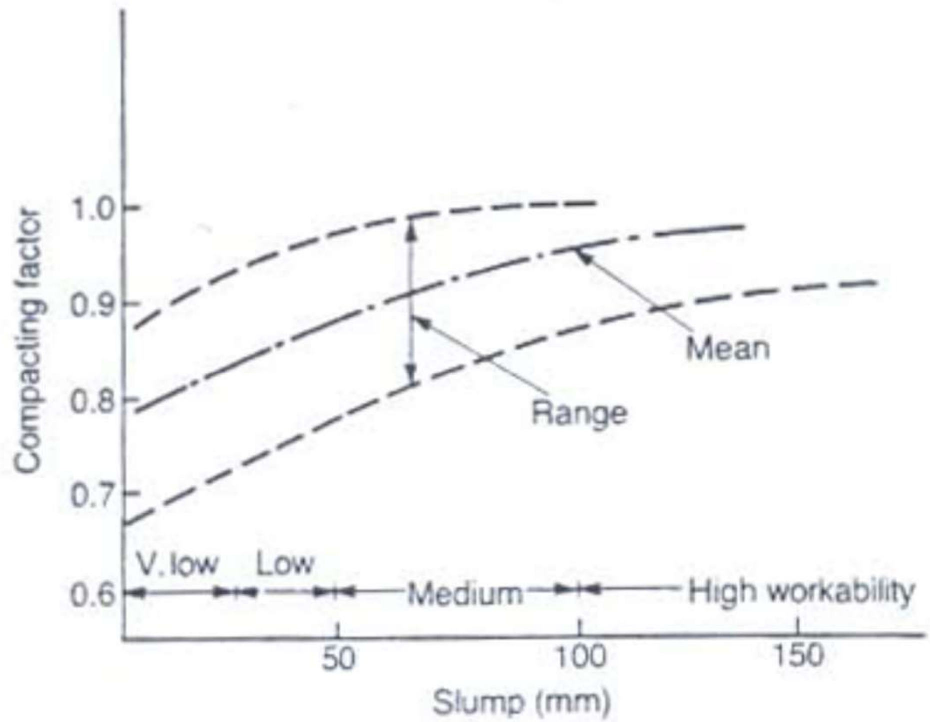
i. A conical mould is used to produce a sample of concrete in the centre of a 700 mm square board, hinged along one edge
ii. The free edge of the board is lifted against the stop and dropped 15 times

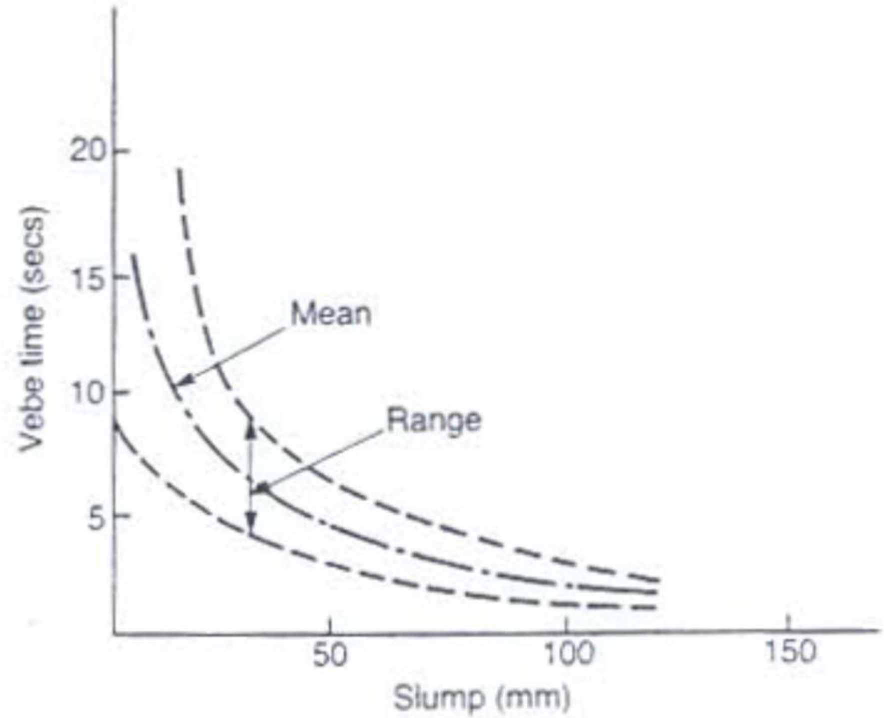
Flow = final diameter of the concrete
(mean of two measurements at right angles)



2. Workability measurement methods, cont'd

Correlations between compacting factor, Vebe time and slump





Some degree of correlation between the results exist, however the correlation is quite broad since each tests measures the response to different conditions

3. Behavior of fresh concrete after placing and compacting

i. Segregation and Bleeding

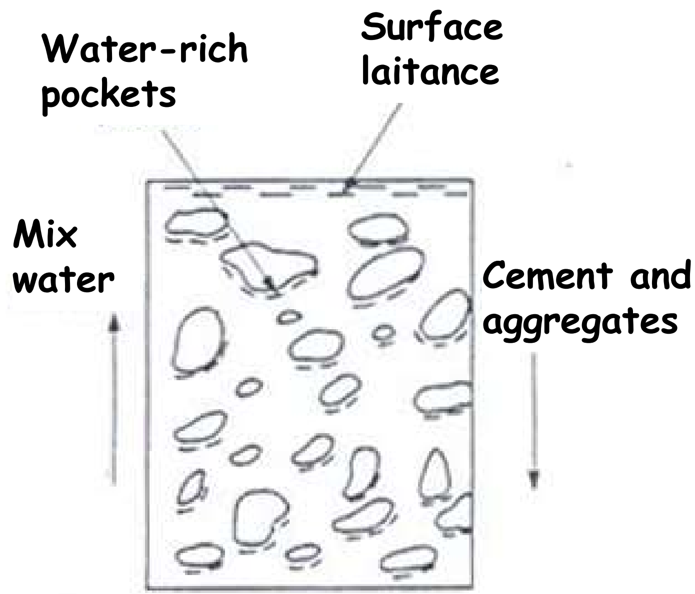
From placing to final set, concrete is in a plastic, semi-fluid state
Heavier particles (aggregates) have tendency to move down (SEGREGATION)
Mix water has a tendency to move up (BLEEDING)

3. Behavior of fresh concrete after placing and compacting

i. Segregation and Bleeding, cont'd

Bleeding

A layer of water (~ 2 % or more of total depth of concrete) accumulates on surface, later this water evaporates or re-absorbed into concrete



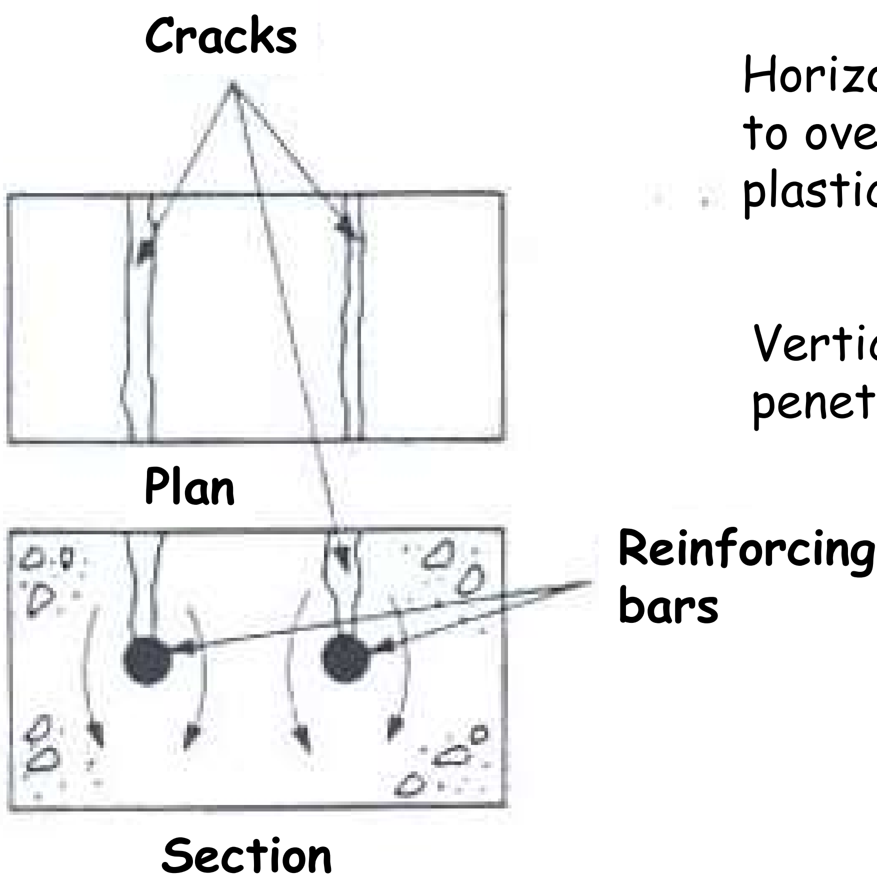
Other effects of bleeding;

Surface laitance; water rich concrete layer hydrating to a weak structure (not good for floor slabs that need to have hard wearing surface)

Water-rich pockets; upward migrating water can be trapped under coarser aggregate particles causing loss of strength and local weakening in transition zone

3. Behavior of fresh concrete after placing and compacting

ii. Plastic settlement

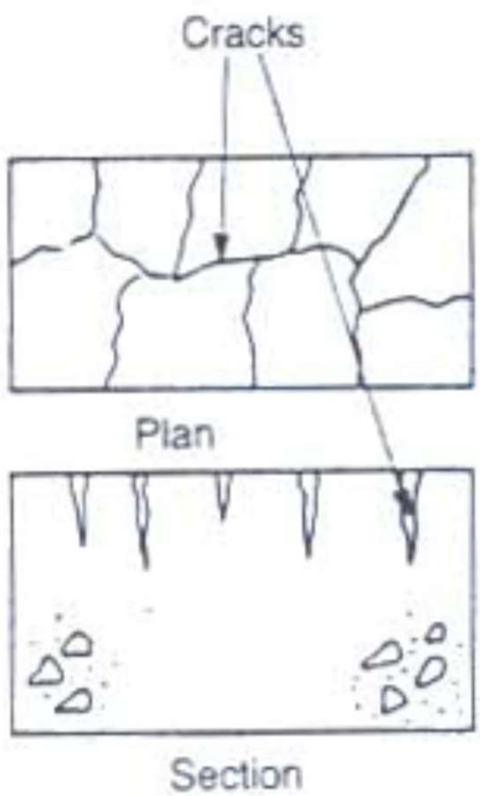


Horizontal reinforcing bars may put restraint to overall settlement of concrete. Then plastic settlement cracking can occur.

Vertical cracks form along line of the bars, penetrating from surface to bars

3. Behavior of fresh concrete after placing and compacting

iii. Plastic shrinkage



- On an unprotected surface, bleed water evaporates.
- If rate of evaporation > rate of bleeding, then surface dries (water content reduces on surface) and plastic shrinkage will occur
- Restraint of walls of concrete causes tensile strains in near surface region
- Fresh concrete has almost zero tensile strength, thus, plastic shrinkage cracking results cracking is in fairly regular "crazing" form

Plastic shrinkage cracking will be increased by greater evaporation rates of the surface water which occurs, i.e. with **higher concrete or ambient temperatures, or if the concrete is exposed to wind**

3. Behavior of fresh concrete after placing and compacting

Methods of reducing segregation and bleed and their effects

CAUSES OF BLEEDING	REMEDIES
Poorly graded aggregate with a lack of fine material with particle size < 300μm	1. increase sand content 2. Air entrain concrete as substitute for fine materials
High workability mixes	Provide high workability with superplasticizers rather than high water contents
	Use very fine materials such as silica fume

3. Behavior of fresh concrete after placing and compacting

REMEDIES for PLASTIC SETTLEMENT or PLASTIC SHRINKAGE CRACKS

Revibrate surface region, particularly in large flat slabs

Apply good curing that stops moisture loss from surface as soon as after placing is possible and for first few days of hardening

4. Curing concrete

Curing; proctection of concrete from moisture loss from as soon after placing as possible, and for the first few days of hardening

Curing methods

- Spraying or ponding surface of concrete with water
- Protecting exposed surfaces from wind and sun by windbreaks and sunshades
- Covering surfaces with wet hessian and/or polythene sheets
- Applying a curing membrane, a spray-applied resin seal, to the exposed surface to prevent moisture loss

4. Curing concrete, cont'd

Effect of curing temperature

Hydration reactions between cement and water are temperature-dependent and rate of reaction increases with curing temperature

- At early ages rate of strength gain increases with curing temperature
  - (higher temperatures increases rate of reaction, thus more C-S-H gel is produced at earlier times, achieving a higher gel/space ratio and thus higher strength)
- At later ages, higher strength are obtained from concrete cured at lower temperatures
  - (C-S-H gel is more rapidly produced at higher temperature and is less uniform and hence weaker than produced at lower temperatures)
- Standard curing temperature is $22 \pm 1\,°C$
- Hydration proceeds below $0\,°C$, stop completely at $-10\,°C$

5. Maturity

Cement hydration depends on both time and temperature

$Maturity = \Sigma\, t.(\mathrm{T} + 10)$ → shows correlation with strength

T= -10 °C is datum line
At T= -10 °C, hydration reactions stop, no maturity developed
t (hours), T (°C)
Useful in estimating strength of concrete in a structure from strength of laboratory samples cured at different temperatures

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
  - Fresh state properties of concrete
  - Deformation and dimensional stability of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

Subchapter Outline

Deformation and dimensional stability of concrete

1. Types of deformations
2. Elastic Behavior of Concrete
    i. Modulus of elasticity of concrete
    ii. Poisson's ratio
    iii. Models for concrete behavior
3. Shrinkage
    i. Drying shrinkage
    ii. Plastic shrinkage
    iii. Autogenous shrinkage
    iv. Carbonation shrinkage
    v. Thermal shrinkage?
4. Creep
5. Thermal properties of concrete

Ref; P. Kumar Mehta, Paulo J.M. Monteiro, Concrete, Microstructure, Properties and Materials

Deformation and dimensional stability of concrete

1. Types of deformations

a) Due to environmental effects (e.g. moisture movement and heat)
As a result shrinkage occurs; deformation due to loss of water from concrete

b) Due to applied stresses (e.g. short and long term)
As a result creep occurs : deformations under sustained load

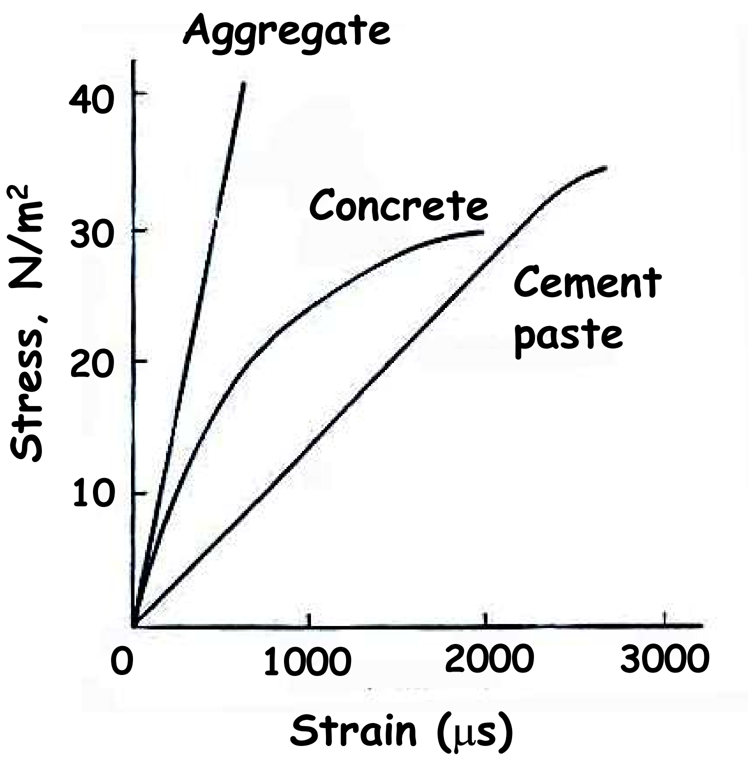
Concrete members are restricted in different ways (e.g. subgrade friction, end members, reinforcing steel).

Shrinkage and creep result in deformations → if deformations are restricted, concrete members crack when tensile strength of concrete is exceeded. ***Elastic properties of concrete plays an important role (NEXT SLIDE)***

2. Elastic behavior of concrete

i. Modulus of elasticity of concrete

Elasticity; modulus of elasticity can be determined from stress-strain data



Stress-strain behavior of both aggregates and cement paste is substantially linear almost up to maximum

Composite concrete with intermediate stiffness is markedly non-linear. The reason for non-linear behavior of concrete is explained based on microcracking in concrete. *(Details will be given later)*

Fig. Stress-strain relationships for cement paste, aggregates and concrete

2. Elastic behavior of concrete, cont'd

i. Modulus of elasticity of concrete

Modulus of elasticity of paste can be estimated based on following equation.

$$E_p = E_g\,(1\text{-}p_c)^3$$

E_p = modulus of elasticity of paste

E_g = modulus of elasticity when $P_c = 0$ (represents the modulus of elasticity of the gel)

p_c = capillary porosity

Modulus of elasticity increases with age and decreasing w/c. Thus, increasing compressive strength of concrete results in increased modulus of elasticity

2. Elastic behavior of concrete, cont'd

i. Modulus of elasticity of concrete

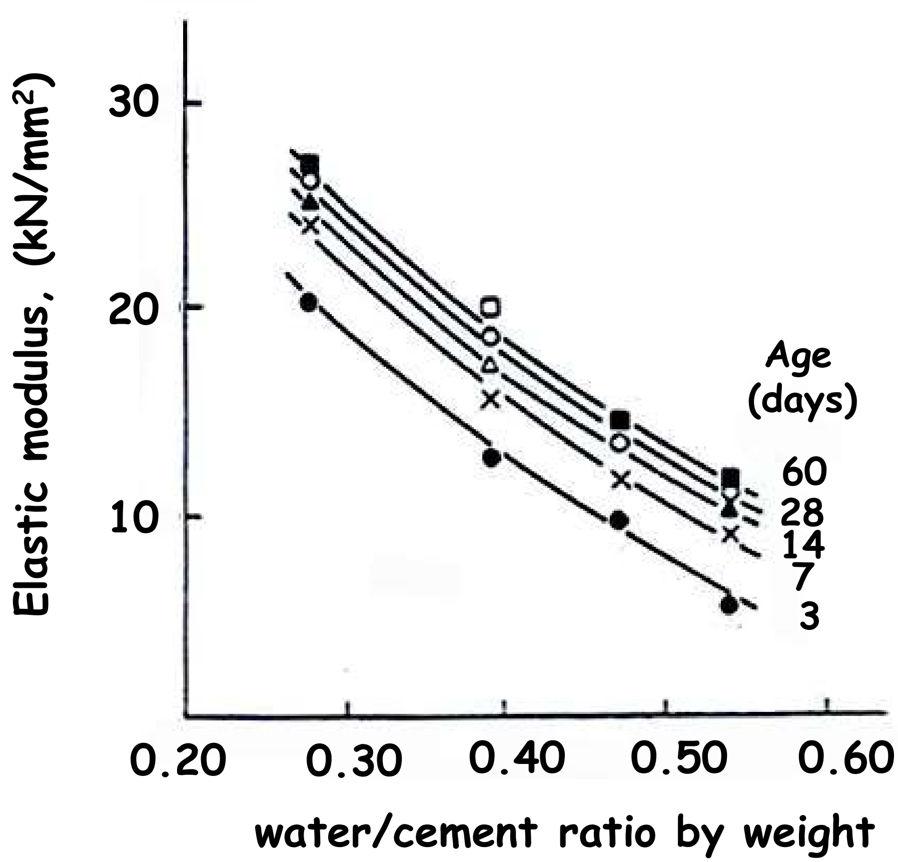
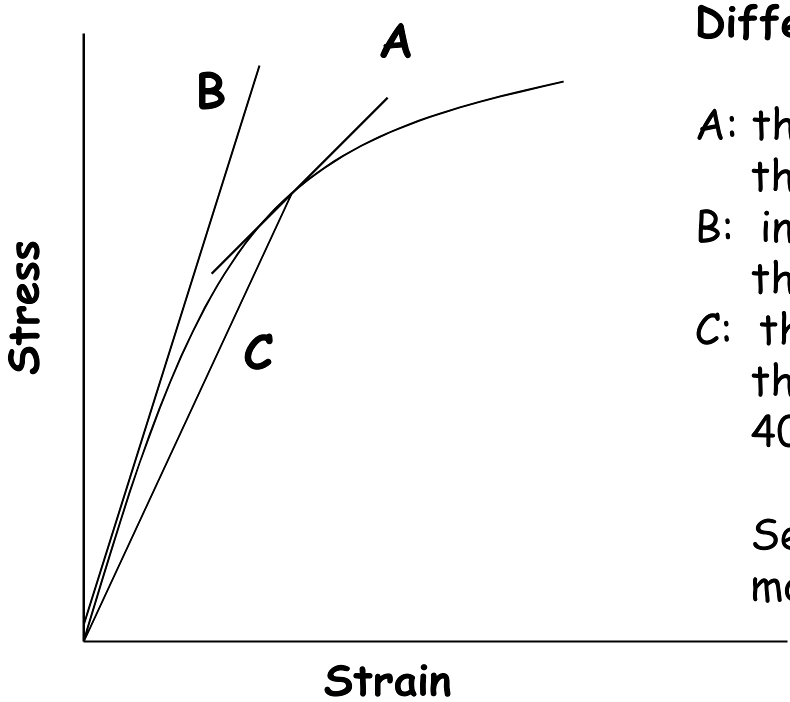


Fig. Effect of w/c and age on the elastic modulus of hcp

2. Elastic behavior of concrete, cont'd

i. Modulus of elasticity of concrete



Different definitions for elastic modulus,

A: the tangent modulus; slope of a line drawn tangent to the curve at any point on the curve
B: initial tangent modulus; slope of a line drawn from the origin
C: the secant modulus; the slope of the line drawn from the origin to a point on the curve corresponding to a 40% stress of the failure load

Secant modulus is preferred since it is known to give more realistic results.

2. Elastic behavior of concrete, cont'd

i. Modulus of elasticity of concrete

According to the testing method,
- static modulus of elasticity (destructive test)
- dynamic modulus of elasticity (non-destructive test)

- Static modulus of elasticity: secant modulus is calculated from readings of strain at a stress at 40% of ultimate strength. Cylindrical or prismatic specimens are used and loaded longitudinally with a static load
- Dynamic modulus of elasticity: dynamic test is applied to a prismatic specimen and dynamic elastic modulus is calculated as (non-destructive test)

$$E_d = 4n^2 l^2 \rho$$

n: fundamental resonant frequency
l: length of specimen
ρ: density of concrete

Dynamic modulus of elasticity approximates to the initial tangent modulus (line B). It is higher than secant modulus.

2. Elastic behavior of concrete, cont'd

i. Modulus of elasticity of concrete

Some of the proposed relations for prediction of E;

$$E_{cj} = 3250\sqrt{f_{ckj}} + 14000$$

given by TS 500 (Feb 2000)

E_{cj} ; static modulus of elasticity for normal weight concrete (MPa) – j specifies age (days)
w_c ; concrete unit weight (1500-2500kg/m^3)
f_{ckj} ; characteristic cylinder compressive strength (MPa) – j specifies age (days)

$$E_c = w_c^{1,5} x 0,043\sqrt{f_c'}$$

given by ACI Building Code 318

E_c ; static modulus of elasticity (MPa)
w_c ; concrete unit weight (1500-2500kg/m^3)
f_c ; 28 day compressive strength (MPa)

2. Elastic behavior of concrete, cont'd

ii. Poisson's ratio

for water-saturated cement paste, $0.25 \leq \mu \leq 0.30$ on drying it reduces to 0.2
μ is largely independent of w/c, age and strength

Anson proposed the following relation;

$$\mu_c = \mu_p (1 - V_a)^n$$

for $\mu_p = 0.22$, $n = 0.42$

μ_c = poisson ratio of concrete
μ_p = poission ratio of cement paste
V_a = volume of aggregates

3. Shrinkage of concrete

i. Drying shrinkage
ii. Plastic shrinkage
iii. Autogenous shrinkage
iv. Carbonation shrinkage
v. Thermal shrinkage

Shrinkage is expressed as a linear strain through determination of length change

3. Shrinkage of concrete

i) Drying shrinkage

Removal of physically adsorbed water from C-S-H when concrete is exposed to ambient humidities below saturation. Shrinkage values up to $4000*10^{-6}$ strain can be observed.

- If the component/specimen is restricted, tensile stresses will develop and cracks will occur when developed stresses exceed the tensile strength of newly cast concrete

i) Drying shrinkage, cont'd

Factors affecting drying shrinkage

a) Materials and mix proportions

Drying shrinkage of concrete $<$ drying shrinkage of cement paste

Aggregates are dimensionally stable and they put restraint to shrinkage deformation of hcp in concrete

Degree of restraint depends on;

- aggregate volume concentration
- modulus of elasticity of aggregate

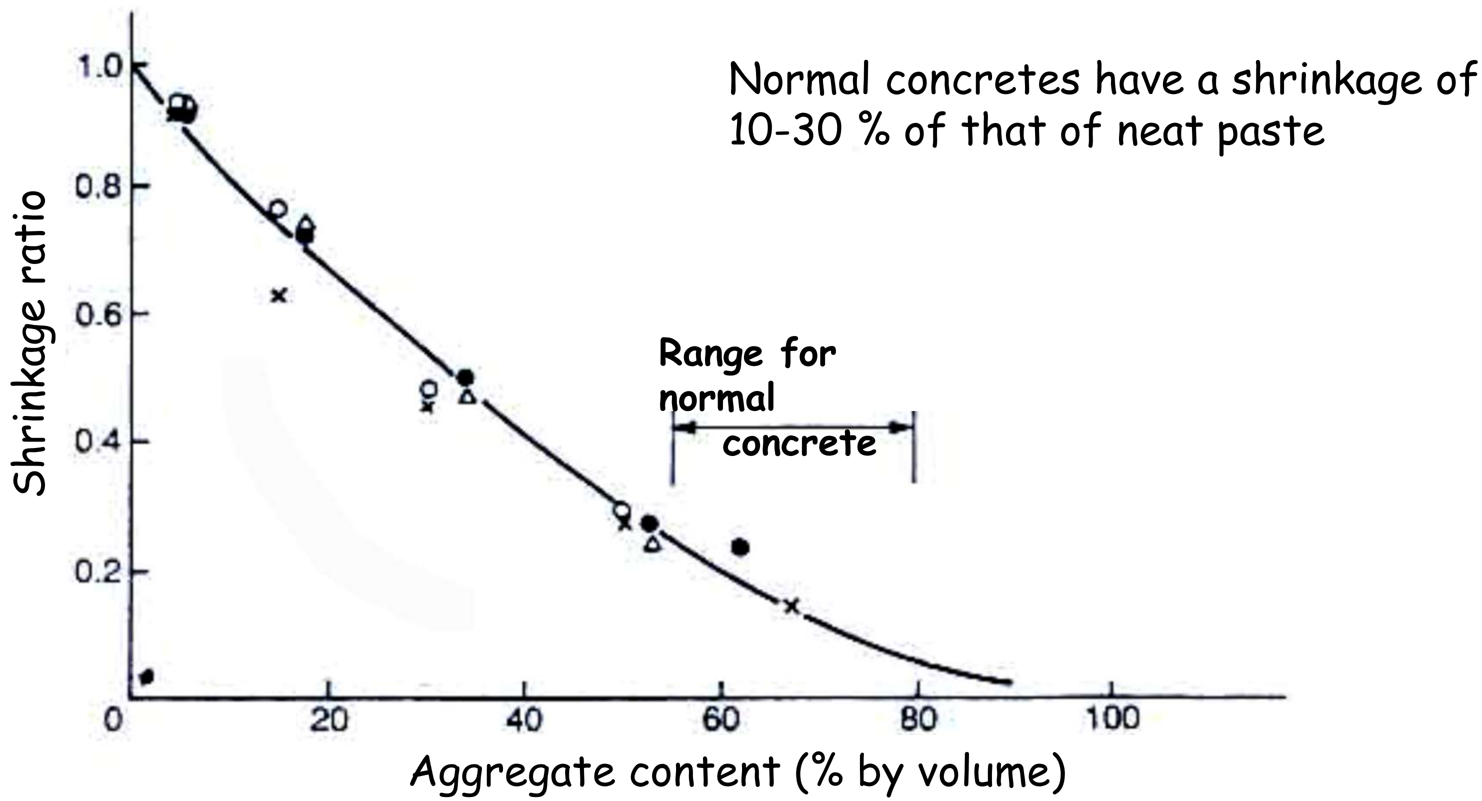
In hcp; unhydrated cement grains also act as a restraint

i) Drying shrinkage, cont'd

Factors affecting drying shrinkage, cont'd

a) Materials and mix proportions, cont'd

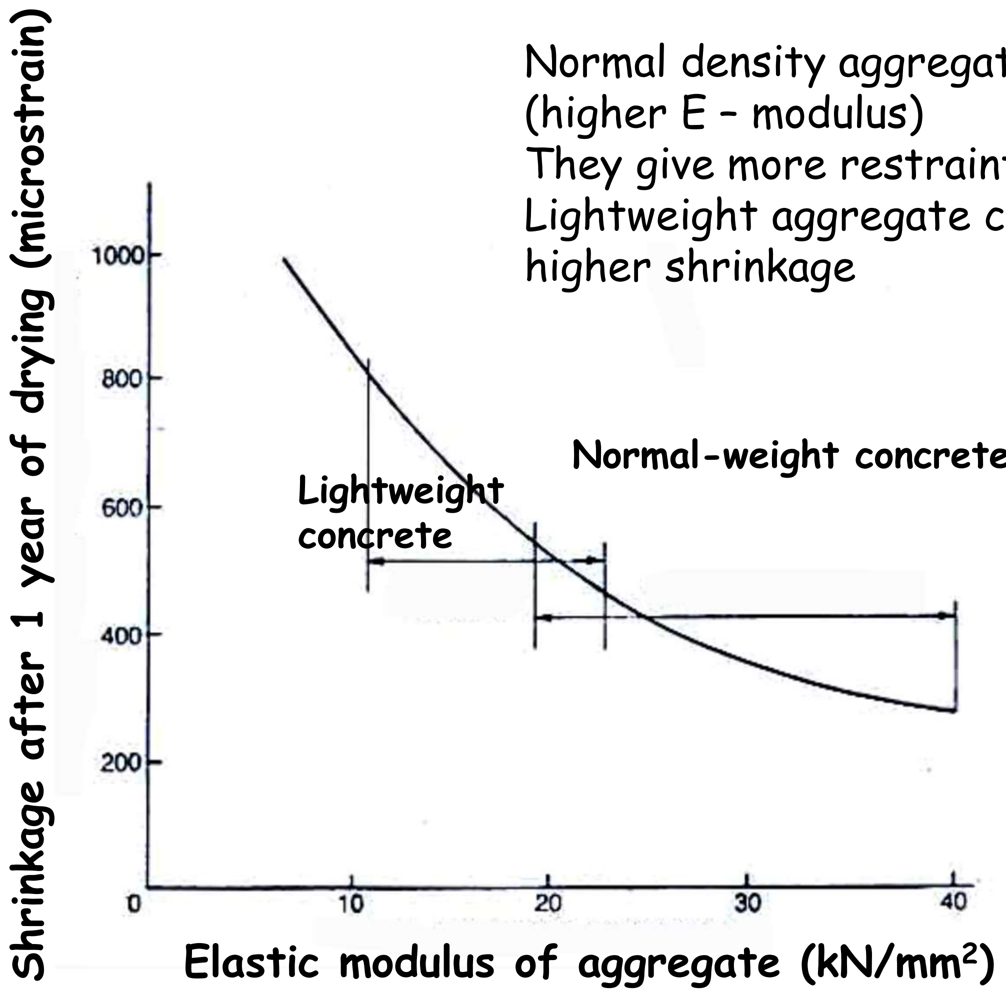
Influence of aggregate content in concrete on the ratio of the shrinkage of concrete to that of neat cement paste



i) Drying shrinkage, cont'd

Factors affecting drying shrinkage, cont'd

a) Materials and mix proportions, cont'd



Normal density aggregates have higher stiffness (higher E – modulus)
They give more restraint to concrete
Lightweight aggregate concretes tend to have higher shrinkage

i) Drying shrinkage, cont'd

Factors affecting drying shrinkage, cont'd

a) Materials and mix proportions, cont'd

Combined effects of aggregate volume ratio and stiffness

$$\varepsilon_{c_{sh}} = \varepsilon_{p_{sh}} (1 - g)^n$$

$\varepsilon_{c_{sh}}$ = shrinkage strain of concrete

$\varepsilon_{p_{sh}}$ = shrinkage strain of hcp

g = aggregate volume content

$$n = \frac{3(1 - \mu_p)}{1 + \mu_p + 2(1 - 2\mu_a)\frac{E_p}{E_a}} = 1.2 - 1.7$$

μ_p = poissons ratio of hcp

μ_a = poissons ratio of aggregates

E_p = modulus of elasticity of paste

E_a = modulus of elasticity of aggregates

i) Drying shrinkage, cont'd

Factors affecting drying shrinkage, cont'd

b) Effect of specimen geometry

- ✓ Size and shape of concrete specimen influence rate of drying and degree of restraint from the core, e.g. a member with a large surface area to volume ratio will dry and shrink more rapidly
- ✓ Restraint from central core of a concrete element which has higher moisture content than the surface puts the surface into tension. Thus, under these tensile stresses, surface cracking may occur

c) Other factors

- ✓ C_3A and sulphate content of cement affect the shrinkage, also, alkali content and fineness has a significant effect

ii) Plastic shrinkage

Occurs when the loss of water from the surface exceeds the rate at which bleed water is appearing. Environmental factors such as ambient temperature, humidity and wind speed are effective. The values up to $10000*10^{-6}$ strain may be observed with an increased wind speed.

Prevention; avoid high rates of evaporation, use good quality concrete with a well selected granulometry.

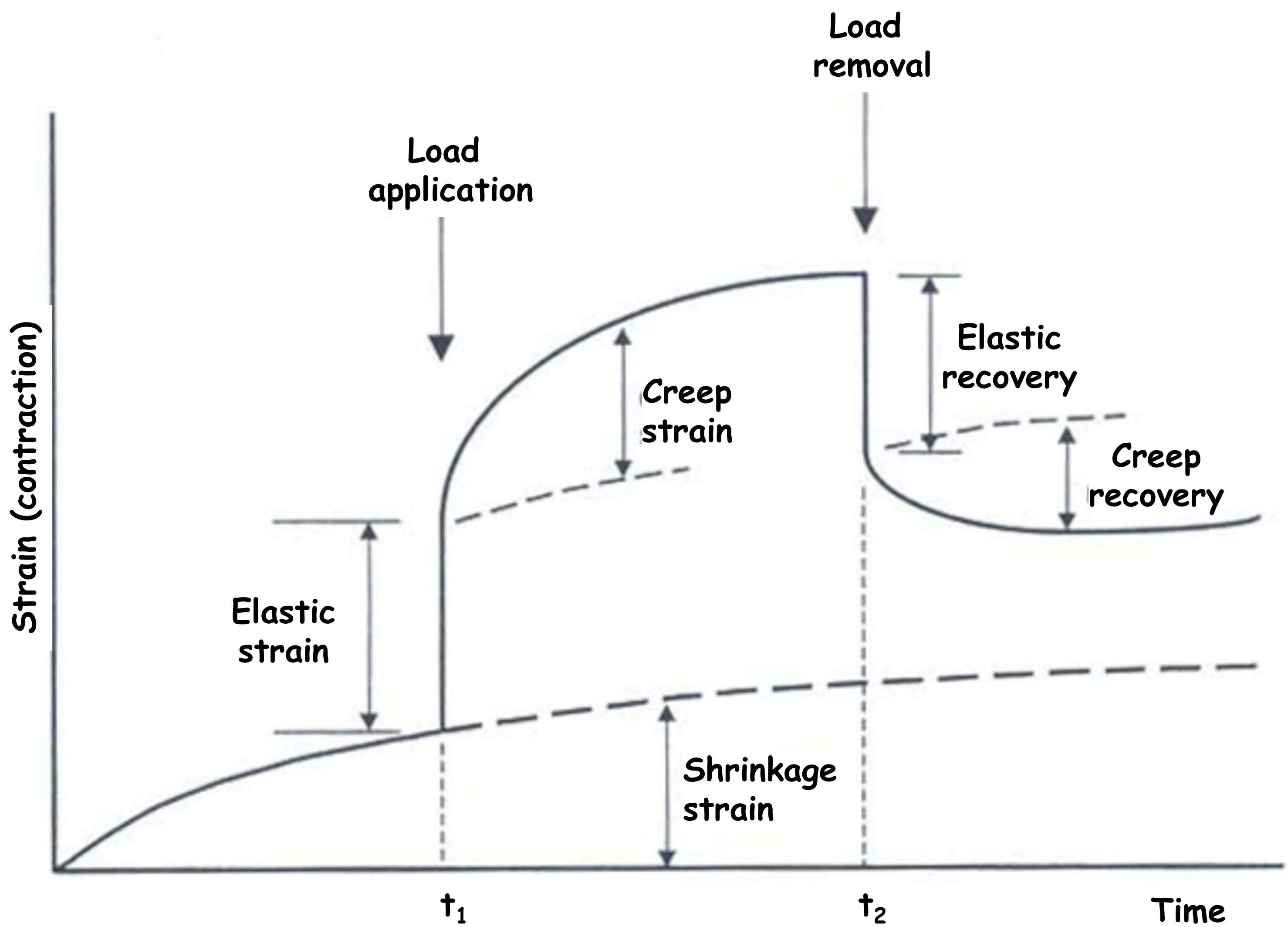
4. Creep

Creep; gradual increase in strain with time under a given level of sustained stres

Magnitude of creep strains is as great or greater than elastic strains on loading. Therefore, they have a significant influence on structural behavior.

4. Creep, cont'd

The response of concrete to a compressive stress applied in a drying environment



4. Creep, cont'd

- **I** → **before** t_1→ net contraction in volume known as shrinkage due to drying, t_1→ stress is applied and held constant, t_2→ stress is removed (without stress it follows dotted extension beyond t_1 difference between solid and dotted curves shows effect of loading)
- **II** → **on loading** → immediate strain response (proportional to stress for low stress level)
- **III** → Compressive strain increases at a decreasing rate, this increase, after allowing for shrinkage represents creep strain
- **IV** → **Upon unloading**, immediate strain recovery is less than immediate strain on loading.
- **V** → Time-dependent creep recovery

5. Thermal properties of concrete

Cement paste and concrete expand on heating

Thermal expansion coefficient is needed in two main situations;

1. To calculate stresses due to thermal gradients arising from heat of hydration
2. To calculate overall dimensional changes in structures

Thermal expansion of cement paste

- Coefficient of thermal expansion of hcp=10 -20 x 10^{-6} / °C
- The value depends on moisture content
- Disturbance of equilibrium between water vapor, free water, freely adsorbed water, water in areas of hindered adsorption and forces between layers of gel solids will determine the behavior of cement paste upon being heated.

5. Thermal properties of concrete, cont'd

Thermal expansion of concrete

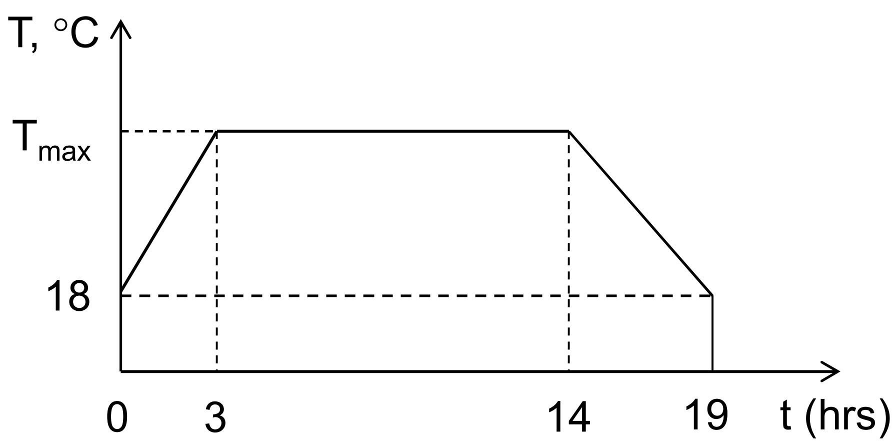
- Coefficient of thermal expansion of most rocks = 6 - 10 x 10^{-6} / °C
- Therefore, coefficient of thermal expansion of concrete is less than that of hcp
- Since aggregate occupies 70- 80 % of concrete volume, effect of humidity is very much reduced, therefore, we assume a constant coefficient of thermal expansion for concrete. This value depends on concrete mix proportions, cement paste content and aggregate type.
- At temperatures higher than ~ 60 °C, differential stresses set up by different thermal expansion coefficients of paste and aggregate can lead to internal microcracking

Example problems

1) In a precast concrete plant, beams have been heat treated according to the given cycle. Specimens for determining the potential strength of concrete are cured in a moist environment at 22°C for 28 days in the laboratory. It is considered that the strength of concrete is related to its maturity as

$$f_c = -25 + 20 \log M$$

Where M is in °C.days and f_c is the potential strength of concrete in MPa. Prestressing of the precast beams is done when the concrete strength for the beams reach to at least 20% of its potential value. Determine the T_{max} for the heat cycle applied so that the beams can be prestressed afterwards.



Example problems

2) A concrete composite is produced by using cement paste and aggregate with below properties:

Cement paste: μ = 0.20 ε_{sh} = 0.003

Aggregate: μ = 0.22 E = 60 GPa

n: 1.622

Modulus of elasticity and shrinkage of this composite are to be modeled by the following equations;

$$\frac{1}{E_c} = \frac{V_a}{E_a} + \frac{(1-V_a)}{E_p} \qquad \varepsilon_{c_{sh}} = \varepsilon_{p_{sh}}(1-g)^n$$

Modulus of elasticity of this concrete has been measured as 30.2 GPa. Estimate the shrinkage of this concrete.

Example problems

3) Modulus of elasticity of the hardened cement paste, the aggregate and the concrete are measured as 15 GPa, 50 GPa, and 30 GPa, respectively. It is observed that the modulus of elasticity of this concrete is best estimated by the equal strain composite model. Using the linear relation, calculate the creep of the concrete given that the creep of the hardened cement paste is 2000×10^{-6}. (n: 1.622)

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
  - Fresh state properties of concrete
  - Deformation and dimensional stability of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

Subchapter Outline

STRENGTH AND FAILURE OF CONCRETE

1) **Strength tests**
   a) Compressive strength test
   b) Tensile tests
      i. Direct tension test
      ii. Flexural test
      iii. Splitting tensile test
2) **Factors influencing strength**
   a) Transition zone
   b) Water to cement ratio
      i. Prediction of concrete strength
   c) Effect of age
   d) Effect of humidity
   e) Effect of aggregate properties, size and volume concentration
3) **Cracking and fracture in concrete**

STRENGTH AND FAILURE OF CONCRETE

Strength of concrete is most important because structural elements must carry imposed loads safely

In loading test: max stress = strength of specimen

Under compressive loading, at max stress, test specimen is still whole (with extensive internal cracking). Complete breakdown subsequently occurs at higher strains and lower stress

Also, strength is related to: elastic modulus, durability (permeability)

Different types of loading in structures result in different modes of failure

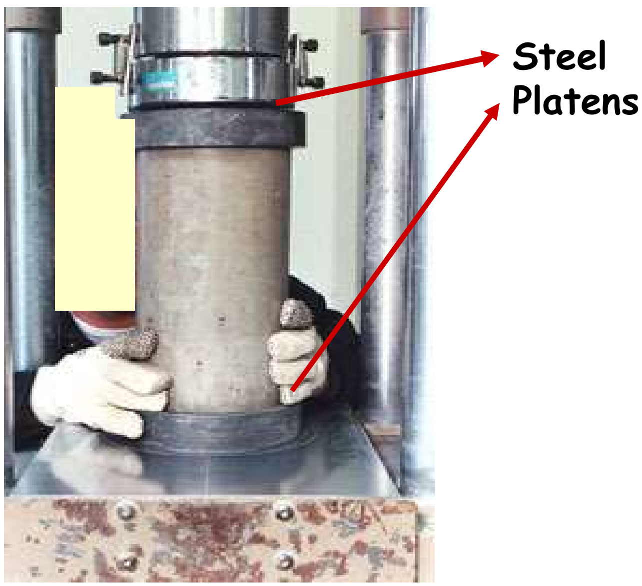
Relevant strengths: Compressive, tensile, torsional (shear), fatigue, impact, strength under multiaxial loading

http://www.ame-geolab.com/CRIB%20MATERIAL%20PHOTOGRAPHS%20testing%20013.jpg

1. Strength tests

a) Compressive strength test: cubes or cylinder specimens are used
Cubes: 100x100x100 mm or 150x150x150 mm
Cylinder: D= 100mm, H= 200mm or D=150mm, H= 300mm

Steel moulds are used, concrete compacted, top surface smoothed



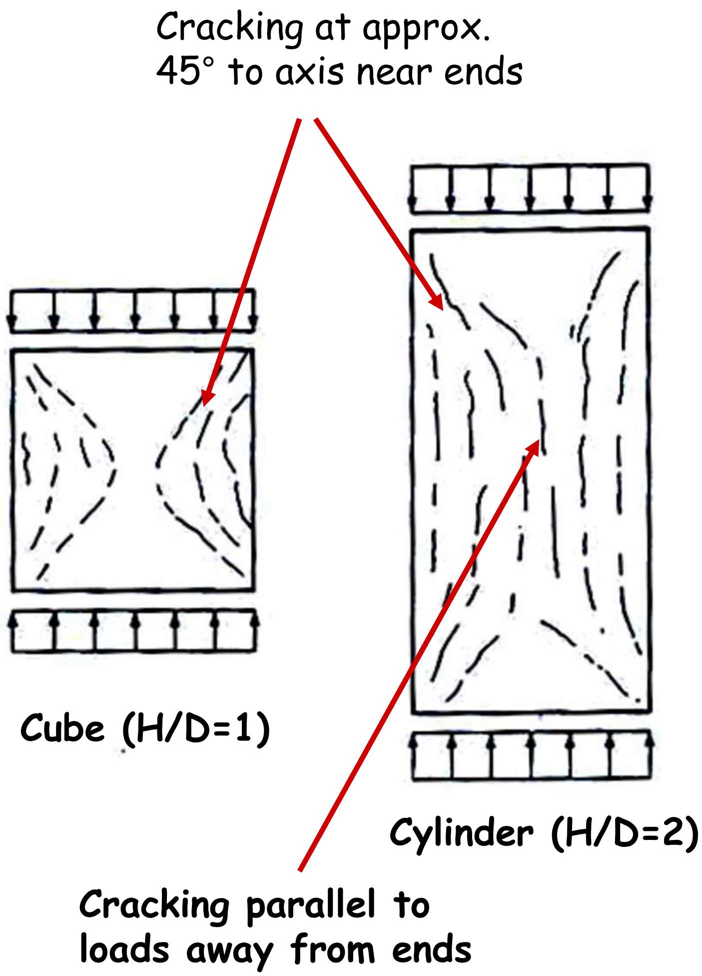
1. Cube or cylinder is placed between steel platens of loading machine
2. Load is increased to its ultimate value in a few minutes

- *Cubes are loaded on two parallel smooth steel moulded surfaces*
- *Cylinders are loaded on top and bottom surfaces. Top surface is a trowelled surface. Therefore it must be capped either with plaster paste or with molten sulfur*

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Cracking patterns during testing of concrete specimens in compression

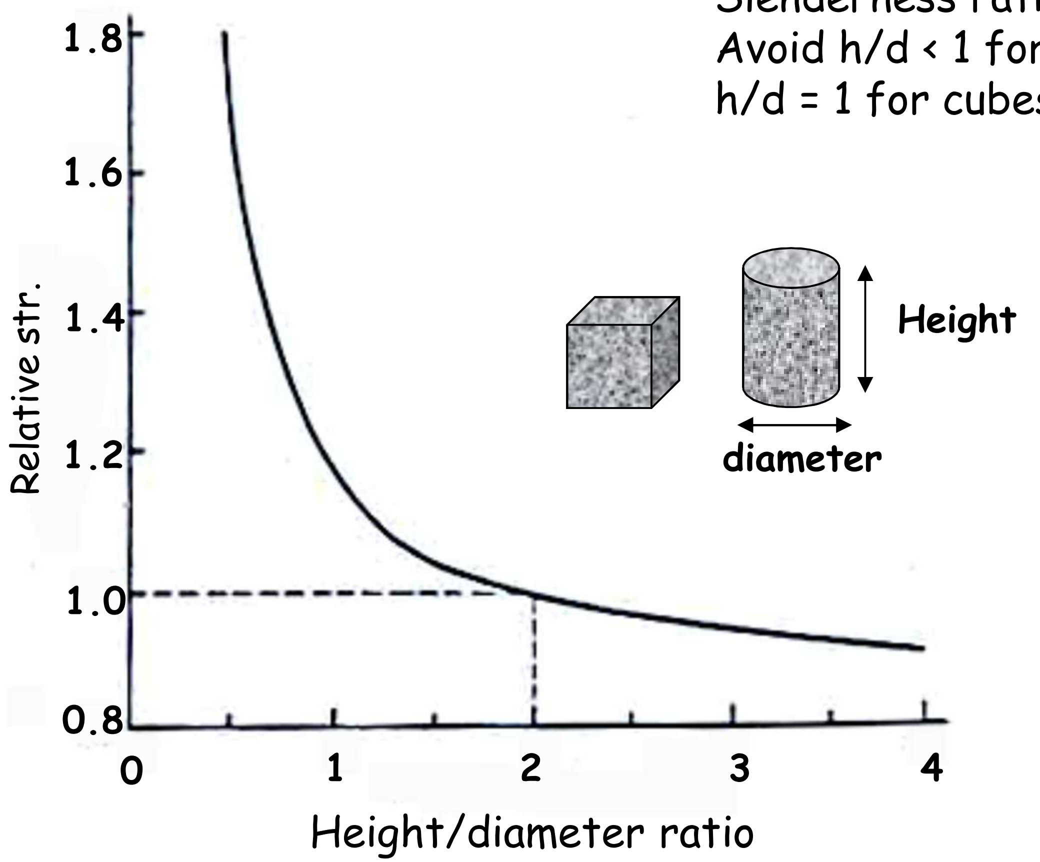


- Cracking pattern of cubes and cylinders show that CUBES are not in uniaxial loading
- This is due to end restraint because of friction between loading platens and concrete surface. This induces lateral tensile stress in both platen and concrete due to Poisson effect. Concrete is in a triaxial stress state with consequent higher strength compared to uniaxial stress case
- IN CYLINDERS, there is a centre portion not affected from end restraint. Thus, this central zone is in uniaxial stress state. *Therefore, cylinder strength ≅ 0.80 cube strength*

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Slenderness ratio (h/d) affects strength
Avoid h/d < 1 for test specimens
h/d = 1 for cubes, h/d = 2 for cylinders



General relationship between height/diameter ratio and compressive strength of a concrete cylinder, (Gonnerman, 1925)

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Concrete strength classes as given by (TS 500)

Concrete Class	Characteristic Compressive Strength, f_{ck} (MPa)	Equivalent Cube(150mm) Compressive Strength (MPa)	Characteristic Axial Tensile Strength, f_{ctk} (MPa)	28-day Modulus of Elasticity, E_c (MPa)
C16	16	20	1,4	27 000
C18	18	22	1,5	27 500
C20	20	25	1,6	28 000
C25	25	30	1,8	30 000
C30	30	37	1,9	32 000
C35	35	45	2,1	33 000
C40	40	50	2,2	34 000
C45	45	55	2,3	36 000
C50	50	60	2,5	37 000

↓ 28th day strength measured on cylinders with a diameter and height of 15cm and 30cm, respectively.

↓ Equivalent 28th day cube strength for cubes with an edge length of 15cm. (TS500/T2)

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Compressive strength classes as given by EN 206 (EN 206 – July 2014) – next slides.

$f_{ck,cyl}$; the characteristic compressive strength at 28 days of 150 mm diameter by 300 mm cylinders

$f_{ck,cube}$; the characteristic compressive strength at 28 days of 150 mm cubes tested in accordance with EN 12390-3 may be used for classification.

NOTE ; in special cases intermediate strength levels between those given in tables may be used.

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Compressive strength classes for normal-weight and heavy-weight concrete as given by EN 206.

Compressive strength class	Minimum characteristic cylinder strength $f_{ck,cyl}$ N/mm^2	Minimum characteristic cube strength $f_{ck,cube}$ N/mm^2
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Compressive strength classes for light-weight concrete as given by EN 206.

Compressive strength class	Minimum characteristic cylinder strength $f_{ck,cyl}$ N/mm^2	Minimum characteristic cube strength[a] $f_{ck,cube}$ N/mm^2
LC8/9	8	9
LC12/13	12	13
LC16/18	16	18
LC20/22	20	22
LC25/28	25	28
LC30/33	30	33
LC35/38	35	38
LC40/44	40	44
LC45/50	45	50
LC50/55	50	55
LC55/60	55	60
LC60/66	60	66
LC70/77	70	77
LC80/88	80	88

a Other values may be used if the relationship between these and the reference cylinder strength is established with sufficient accuracy and is documented.

1. Strength tests, cont'd

a) Compressive strength test, cont'd

Factors that affect compressive strength of concrete

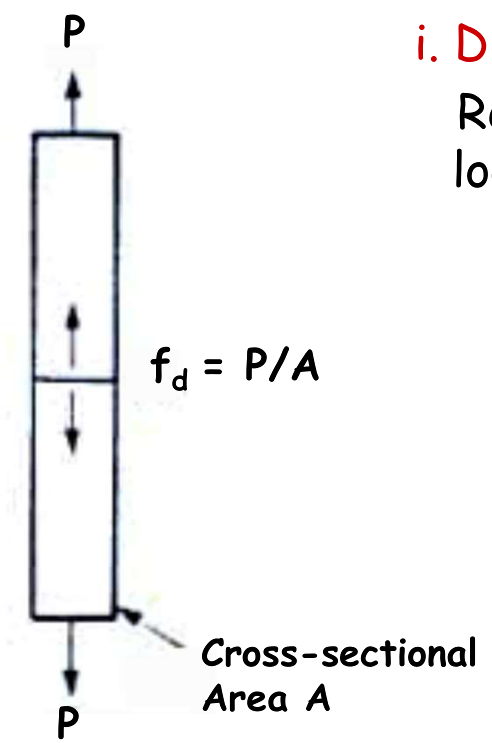
- Age
- Shape and size (slenderness ratio)
  - h/a : 2 – cylinder
  - h/a : 1 – cube $fc_{cylinder} < fc_{cube}$
- Surface roughness (platens of equipment and specimen should be in a perfect contact otherwise stress accumulates on the elevated parts)
- Loading rate
  - If faster than desired → higher strength
  - If lower than desired → lower strength
- Number of specimens; at least 3 specimens should be tested and average of the 3 should be used.

1. Strength tests, cont'd

b) Tensile strength test, cont'd

Tensile behavior of concrete can be evaluated by;

i. Direct tension test
ii. Flexural test
iii. Splitting tensile test



i. Direct tension test

Results are not very dependable (due to eccentric loading and failure at grips)

1. Strength tests, cont'd

b) Tensile strength test, cont'd

i. Direct tension test, cont'd

- Tensile strength of concrete can be found based on the axial tension tests.
- f_{ctm}: mean tensile strength
- f_{ctk}: characteristic tensile strength;

f_{ctk}: TS500 specifies that characteristic strength values are lower limits with confidence degree of 90%. That is, only 10% of the specimens taken from the produced concrete may have tensile strengths below these design strengths (i.e. 1 out of 10).

1. Strength tests, cont'd

b) Tensile strength test, cont'd

i. Direct tension test, cont'd

- F_{ctk} can be calculated by using the following equation;

$$f_{ctk} = 0,35\sqrt{f_{ck}} \quad (MPa)$$

TS 500

f_{ctk} → Characteristic axial tensile strength

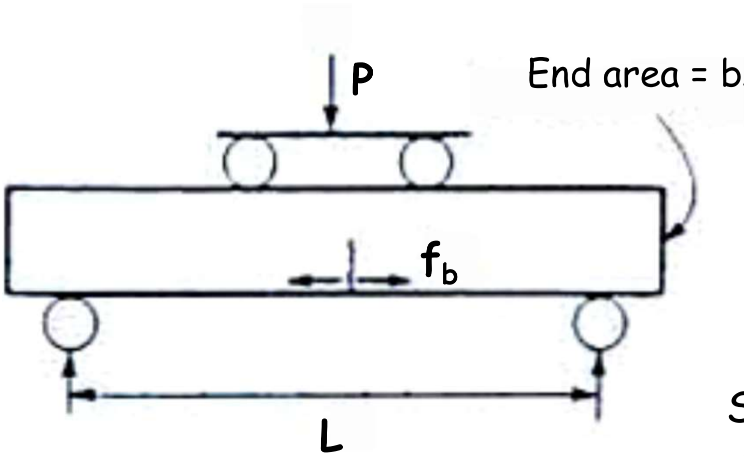
f_{ck} → Characteristic compressive strength

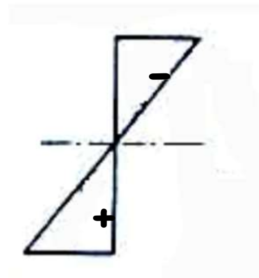
Concrete Class	Characteristic Compressive Strength, f_{ck} (MPa)	Equivalent Cube(150mm) Compressive Strength (MPa)	Characteristic Axial Tensile Strength, f_{ctk} (MPa)	28-day Modulus of Elasticity, E_c (MPa)
C16	16	20	1,4	27 000
C18	18	22	1,5	27 500
C20	20	25	1,6	28 000
C25	25	30	1,8	30 000
C30	30	37	1,9	32 000
C35	35	45	2,1	33 000
C40	40	50	2,2	34 000
C45	45	55	2,3	36 000
C50	50	60	2,5	37 000

1. Strength tests, cont'd

b) Tensile strength test, cont'd

ii. Flexural test





Stress distribution

Prism specimens (100x100x400mm or 150x150x600mm)

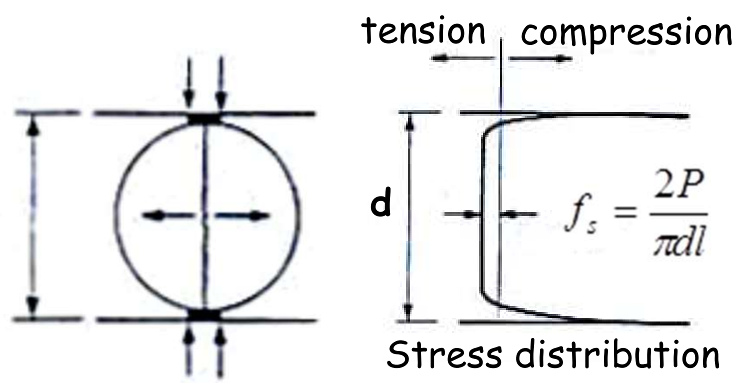
Modulus of rupture = $f_b = \dfrac{PL}{bd^2}$

- Load is applied at third points
- Failure occurs when flexural tensile crack at bottom of beam propagates upwards throughout beam
- Modulus of rupture > direct tensile strength

1. Strength tests, cont'd

b) Tensile strength test, cont'd

iii. Splitting tensile test



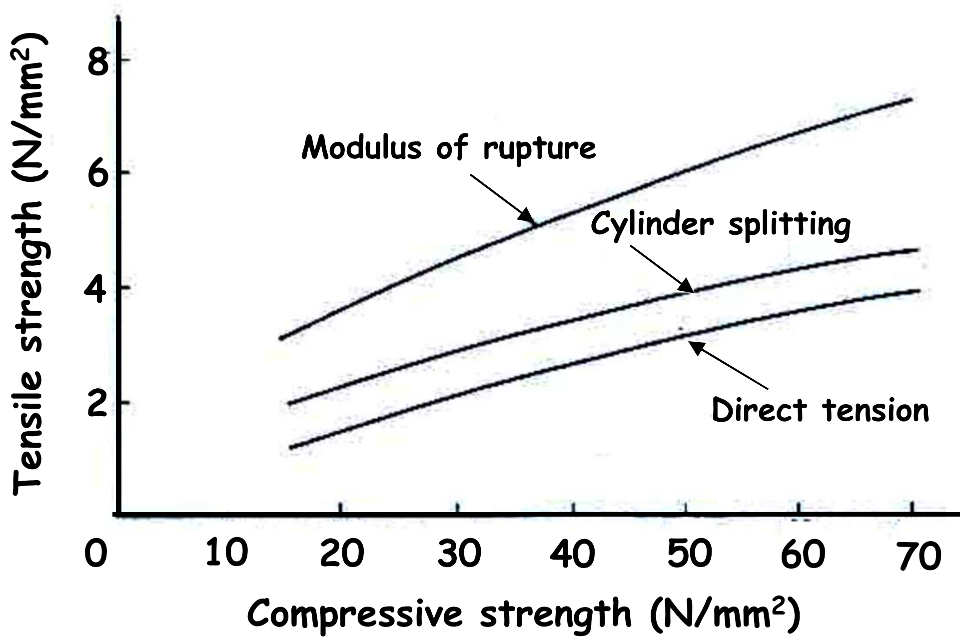
- Cylinder specimen (ϕ150mm, height 300mm)
- Placed on its side in a compression testing machine and loaded across its vertical diameter
- Stress distribution on a plane of vertical diameter is a near uniform tension
- Failure occurs by split or crack along this plane

For the same compressive strength:

Modulus of rupture > cylinder splitting > direct tension

1. Strength tests, cont'd

b) Tensile strength test, cont'd

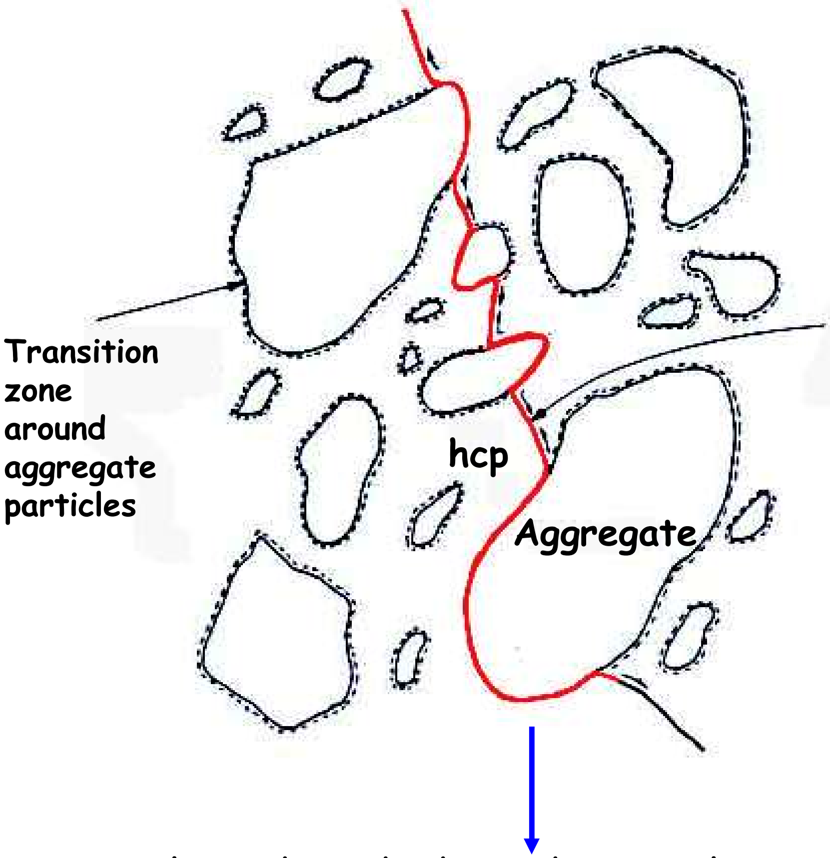


Typical relationships between tensile and compressive strengths of concrete

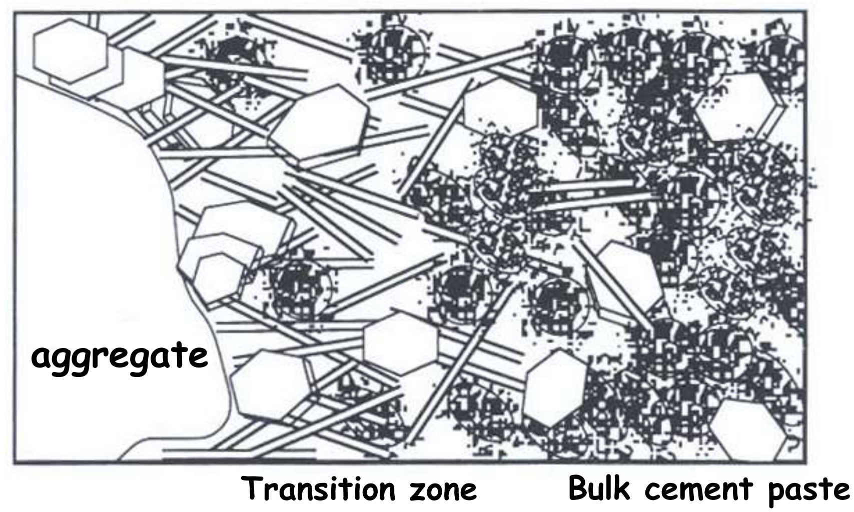
2. Factors influencing strength

a) Transition Zone

Transition zone (~50μm wide) is the weakest phase, cracking and failure initiate in this zone Due to drying shrinkage, cracks are present before loading. As loading increases in compression or tension, cracks in this zone start propagating into hcp, resulting in paths through concrete.



Typical crack path through normal strength concrete



Use 3-phase model when considering strength of concrete (slide 72)

2. Factors influencing strength, cont'd

b) Water/cement ratio:

Strength of concrete depends on;

- Strength of hcp
- Strength of aggregates
- Strength of transition zone

Strength of hcp is governed by

- Porosity (indirectly depending on w/c)
- degree of hydration

Strength of transition zone is dependent on;

- w/c

2. Factors influencing strength, cont'd

b) Water/cement ratio, cont'd

Prediction of Concrete Strength

Various relationships are given by several researchers

Abrams; $$f_c = \frac{k_1}{k_2^{W/C}}$$

when W/C (by wt)
k_1 & k_2 empirical constants depending on age, curing regime, type of cement, entrained air, test method, aggregate type and size

Graf; $$f_c = \frac{f_{cc}}{K_G (W/C)^2}$$

where f_{cc} = compressive strength of cement
K_G = empirical constant related to testing condition
K_G = 4-8, average = 6

2. Factors influencing strength, cont'd

b) Water/cement ratio, cont'd

Prediction of Concrete Strength, cont'd

Feret;

$$f_c = K_F \left(\frac{c}{c+w+v}\right)^2$$

when c, w, v $\rightarrow$ volumes of cement, water, and air voids in $1cm^3$ of concrete

K_F = empirical constant depending on age, type and amount of cement

K_F = 80 – 300 MPa

for 7 days strength K_F = 150 MPa

for 28 days strength K_F = 180 MPa

Bolomey;

$$f_c = K_B \left(\frac{C}{W+v} - k`\right)$$

where C, W$\rightarrow$ weights of cement and water

v $\rightarrow$ volume of air voids

K_B = empirical constant depending on age, type and amount of cement

K_B = 7 – 35 MPa

for 7 days strength K_B = 15 MPa

for 28 days strength K_B = 19 MPa

k` =0.5

2. Factors influencing strength, cont'd

b) Water/cement ratio, cont'd

Prediction of Concrete Strength, cont'd

- Mix design methods use one of these formulas or curves or tables based on these equations to estimate w/c required for a given strength
- To achieve a homogenous, cohesive concrete without significant segregation $w/c < 1$
- $0.4 < w/c < 0.7$ $\rightarrow$ produce concretes of normal to medium strength (20-50 MPa)
- $w/c \approx 0.20 - 0.30 \rightarrow$ high or very high strength concretes are produced (70 - 150 MPa)
  - by using superplasticizer to achieve adequate workability
  - by incorporating silica fume at 5-10 % cement replacement to improve properties of transition zone while also increasing strength of cement paste to a limited degree
  - by selecting aggregate having high inherent strength and good bond characteristics

With this approach, at $w/c \leq 0.26$, compressive strengths > 130 MPa are achieved and placed with conventional mixing, transporting and compaction methods, but with extreme care given to high standards of site practice and supervision and quality control

2. Factors influencing strength, cont'd

c) Effect of age

Hydration reaction continues in time with decreasing rate

Thus even after years, in presence of moisture, there will be some strength increase

d) Effect of humidity

Curing in water results in higher strength compared to air curing

Moisture all through the life of concrete provides higher strengths

2. Factors influencing strength, cont'd

e) Effect of aggregate properties, size and volume concentration

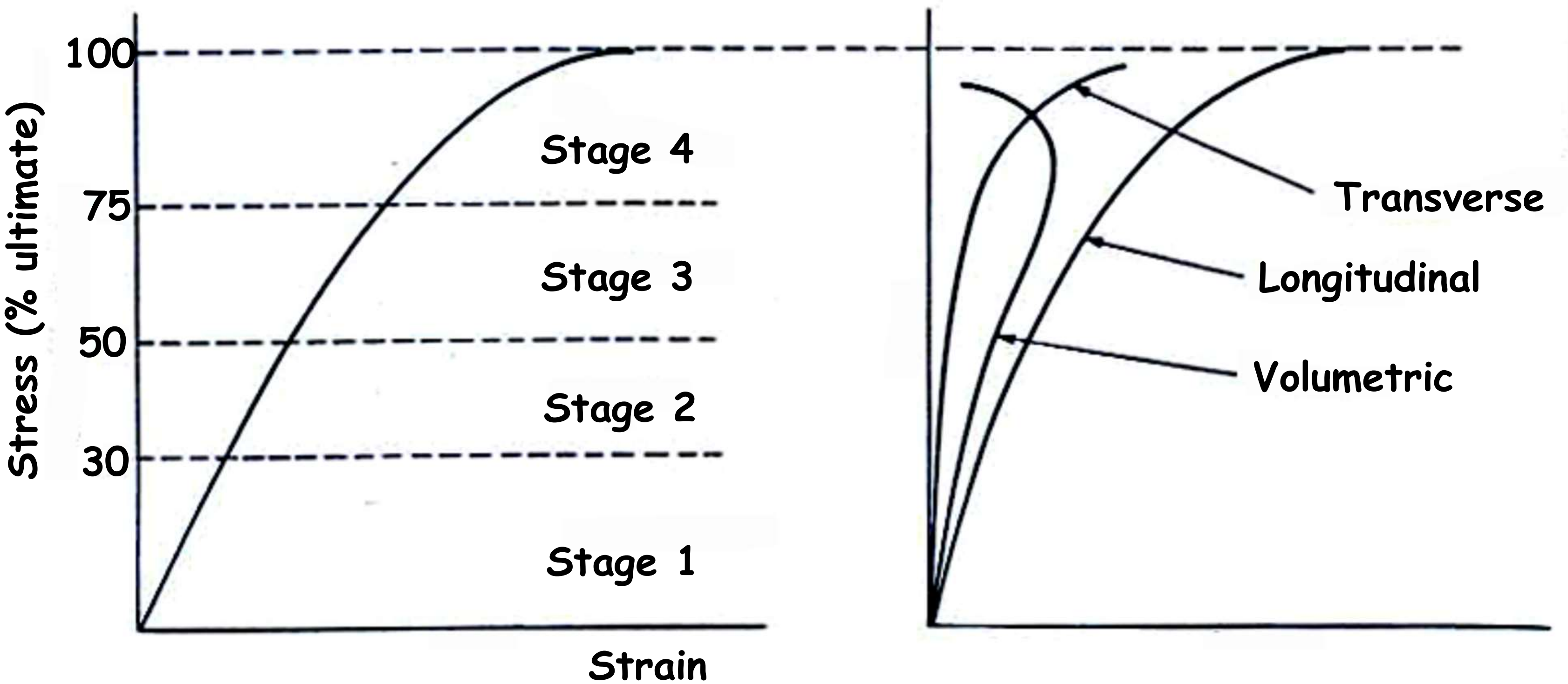
Aggregate strength becomes important in high strength concretes. WHY??

Increased surface roughness improves bonding due to mechanical interlocking. Thus concretes with crushed rock aggregates have about 15 % higher strengths than concretes with smooth gravel aggregates.

Larger maximum aggregate size reduces strength at lower w/c. In high strength concretes, D_{max} is limited to 8 or 16 mm.

Increasing volumetric proportion of aggregate in the mix, at a constant w/c, produce a relatively small increase in concrete strength. There is a maximum limit to aggregate content (~ 80) for practical concretes.

3. Cracking and fracture in concrete



Stress – strain behavior of concrete under compressive loading:
a) from Glucklich (1965);
b) From Newman (1966).

3. Cracking and fracture in concrete, cont'd

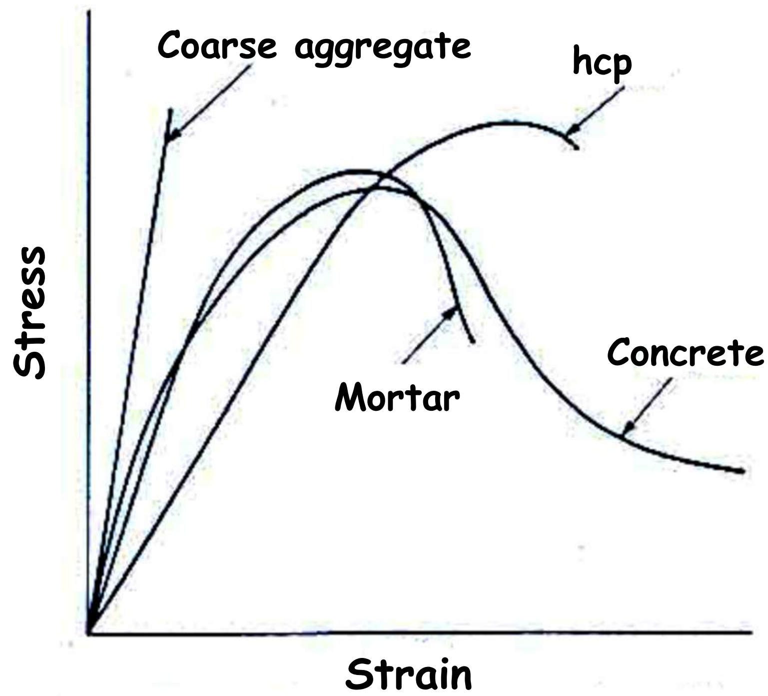
Stage 1: Below 30% of ultimate load transition zone cracks remain stable, stress-strain curve is approximately linear

Stage 2: Between 30-50% of ultimate load. Cracks increase in length, width and number. However, they still remain stable, non-linearity is observed.

Stage 3: Above 50% of ultimate load, cracks start to spread into matrix, towards 75% of ultimate load, cracks become unstable and curve further deviates from linearity

Stage 4: Unstable crack growth and propagation is frequent, leading to high strains. Transverse strains start increasing faster than longitudinal strains resulting in an overall increase in volume

3. Cracking and fracture in concrete, cont'd



Typical stress-strain characteristics of aggregate, hardened cement paste, mortar and concrete under compressive loading

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
  - Fresh state properties of concrete
  - Deformation and dimensional stability of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

DURABILITY of CONCRETE

Durability: ability of a material to remain serviceable for at least the required lifetime of the structure

- Concrete is not inherently of high durability
- Degradation of concrete arises from;
    - Environment to which concrete is exposed
    - Internal causes within concrete

DURABILITY of CONCRETE

The various actions that affect durability

1) Physical actions; effects of high temperature, differences in thermal expansion coefficients of aggregate and cement paste, freeze – thaw damage, etc.
2) Chemical actions; alkali – silica, alkali carbonate reactions, chlorides, sulphates, etc.
3) Mechanical; impact, abrasion, erosion, cavitation, etc.

DURABILITY of CONCRETE

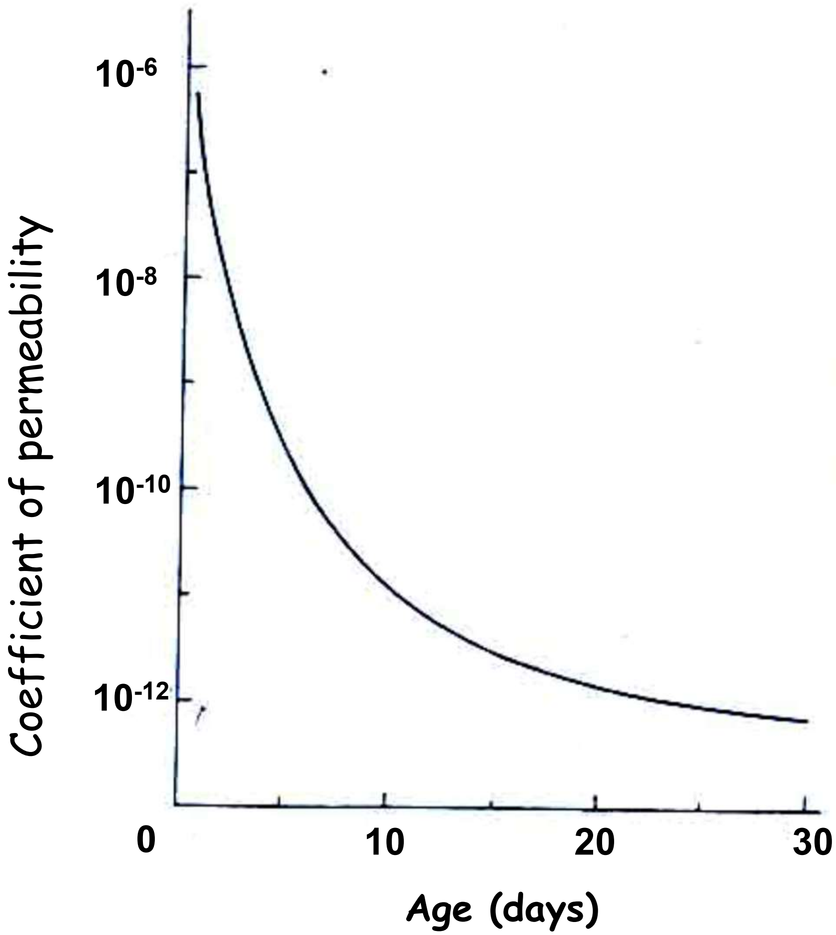
TRANSPORTATION of FLUIDS PLAY A CRUCIAL ROLE!

1. Water (pure or carrying aggresive ions)
2. Carbon dioxide
3. Oxygen

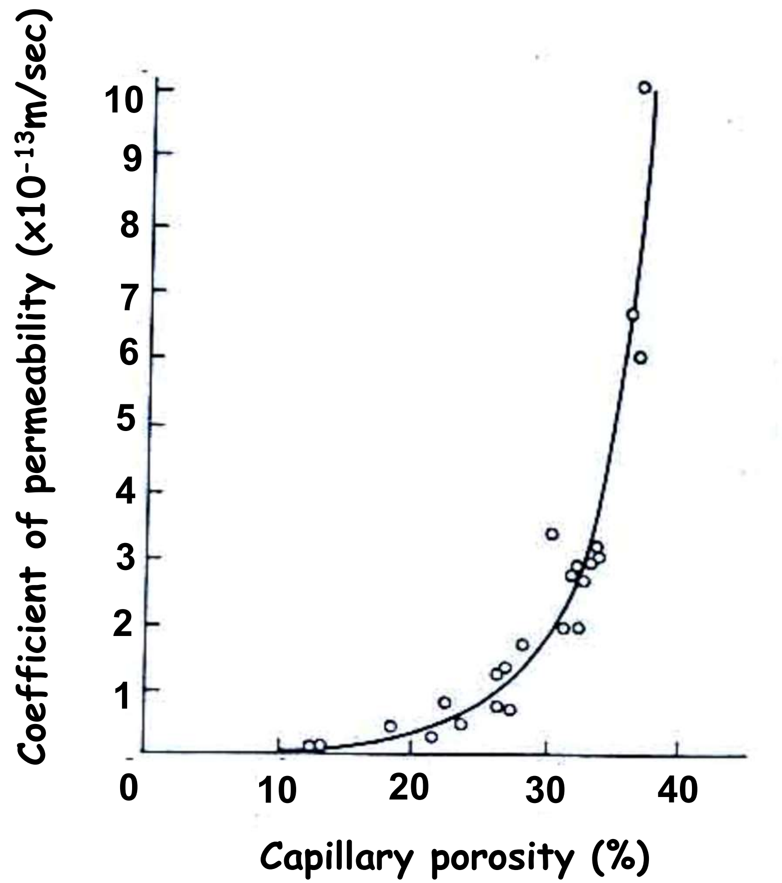
PERMEABILITY/PENETRABILITY of CONCRETE is very IMPORTANT.

2. Flow processes, cont'd

Permeability; measure of the ability of a material to transmit fluids

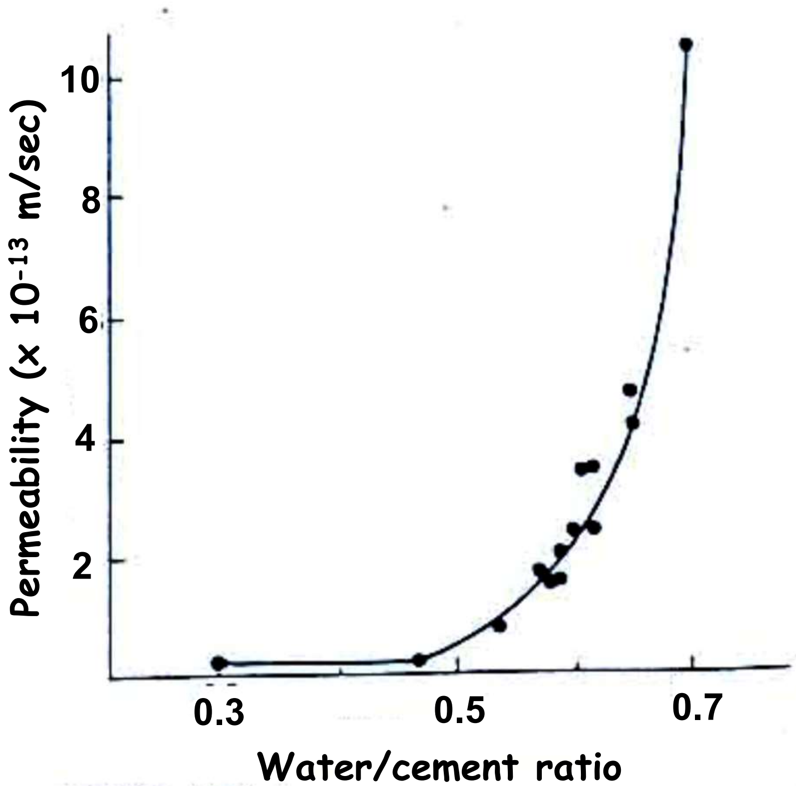


The effect of hydration on the permeability of cement paste (w/c =0.7)



The relationship between permeability and capillary porosity of hardened cement paste

2. Flow processes, cont'd



The relationship between permeability and water/cement ratio of mature cement paste (% 93 hydrated)

3. Degradation of concrete - Exposure classes (EN 206)

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: All exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows:		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity; Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact; Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity; External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3 Corrosion induced by chlorides other than from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water, the exposure shall be classified as follows:		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools; Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements, Car park slabs

3. Degradation of concrete - Exposure classes (EN 206), cont'd

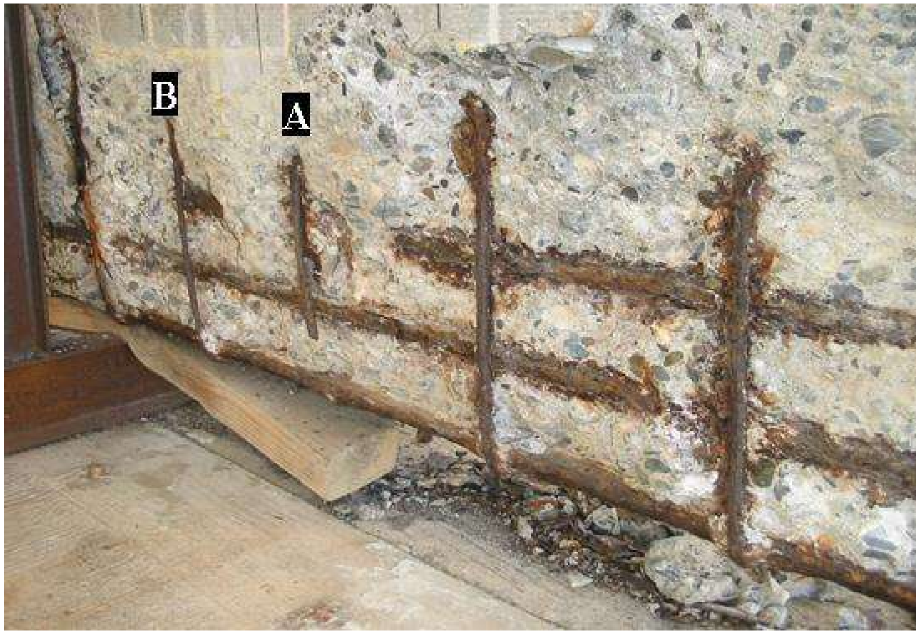
Class designation	Description of the environment	Informative examples where exposure classes may occur
4 Corrosion induced by chlorides from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing agents		
Where concrete is exposed to significant attack by freeze/thaw cycles whilst wet, the exposure shall be classified as follows:		
XF1	Moderate water saturation, without deicing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with deicing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents; Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zones of marine structures exposed to freezing
6 Chemical attack		
Where concrete is exposed to chemical attack from natural soils and ground water, the exposure shall be classified as follows:		
XA1	Slightly aggressive chemical environment	Concrete exposed to natural soil and ground water according to table 2
XA2	Moderately aggressive chemical environment	Concrete exposed to natural soil and ground water according to table 2
XA3	Highly aggressive chemical environment	Concrete exposed to natural soil and ground water according to table 2

3. Degradation of concrete - Exposure classes (EN 206), cont'd

1. No risk of corrosion or attack
2. Corrosion induced by carbonation
3. Corrosion induced by chlorides other than from sea water
4. Corrosion induced by chlorides from sea water
5. Freeze-thaw attack with or without de-icing agents
6. Chemical attack

3. Degradation of concrete – Corrosion of steel reinforcement

- Steel exist in concrete for reinforcing the concrete to compensate for weakness of concrete under tensile and shear stresses
- Sound concrete provides excellent protective medium for steel.
- If protection is broken, steel is left vulnerable to corrosion. Corrosion products, being expansive, caused cracking and/or spalling of concrete, exposing steel to more rapid corrosion



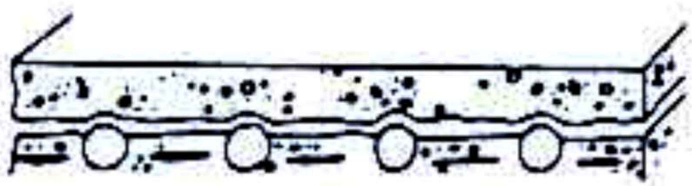
http://cce.oregonstate.edu/structural/images/corrosion_1.JPG

3. Degradation of concrete – Corrosion of steel reinforcement

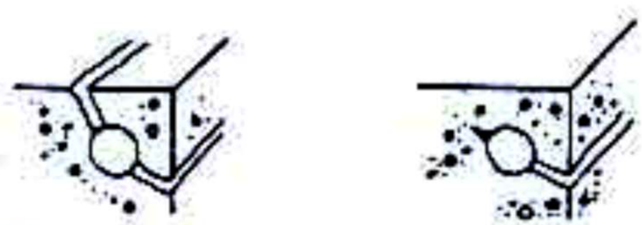
Different forms of damage from steel corrosion

(a) cracking

(b) spalling



(c) lamination



(d) corner effects

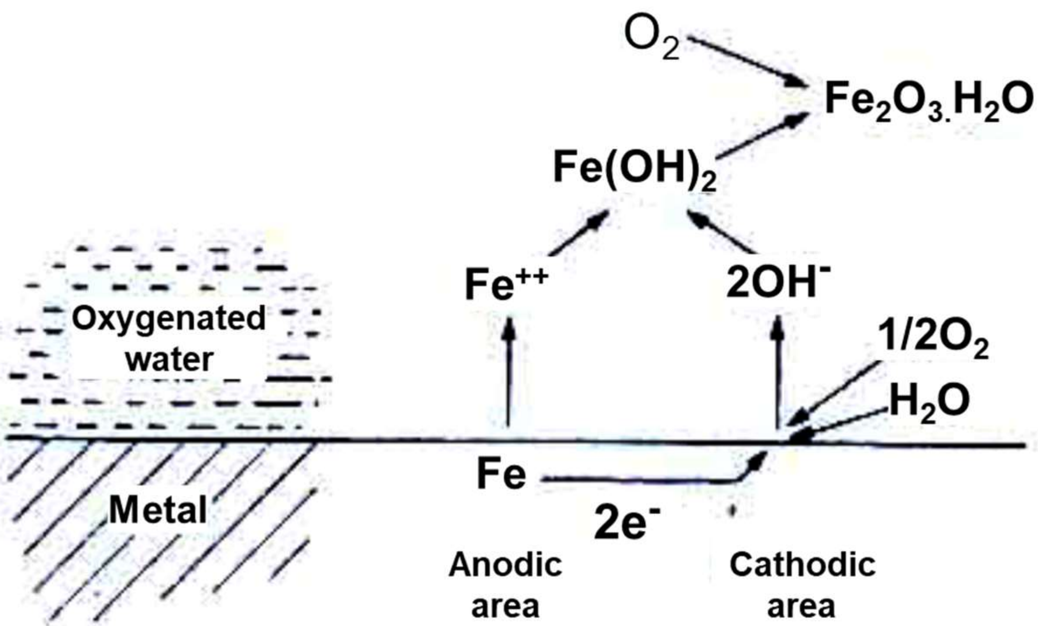
3. Degradation of concrete – Corrosion of steel reinforcement

Following is observed as a result of corrosion

- The volume of steel increases, spalling and cracking in concrete occur
- Aggressive agents readily permeate into concrete
- Cross section and load bearing capacity of steel rebars decrease
- Adherence between steel and concrete decreases

3. Degradation of concrete – Corrosion of steel reinforcement

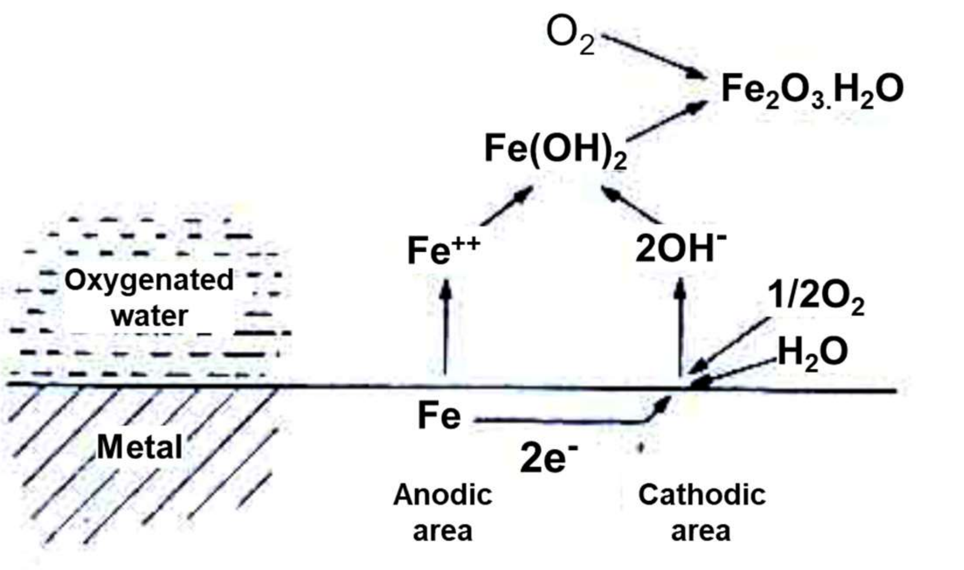
a) General principles of corrosion of steel



Spacial arrangement of corrosion reactions of iron in moist air or oxygenated water. Anodic and cathodic areas form due to potential differences on the metal.

3. Degradation of concrete – Corrosion of steel reinforcement

a) General principles of corrosion of steel



Anode reaction (oxidation) ; $2Fe \rightarrow 2Fe^{++} + 4e^-$
Cathode reaction (reduction) ; $4e + O_2 + 2H_2O \rightarrow 4OH^-$

at some distance from surface
$2Fe^{++} + 4OH^- \rightarrow 2Fe(OH)_2$ (Ferrous hydroxide (black rust))
Followed by
$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3H_2O + H_2O$ (Ferric hydroxide (red rust))

3. Degradation of concrete – Corrosion of steel reinforcement

a) General principles of corrosion of steel

- The water on or near the metal surface acts as the electrolyte of the corrosion cell, and the anode and the cathode are close together, (e.g. across a single crystal or grain).
- The oxide is formed and deposited near but not directly on the metal surface allowing the corrosion to be continuous.
- Volume of corrosion products are larger than the original steel, (2-3 times) hence they lead to bursting pressures in the concrete and eventually cracking.

3. Degradation of concrete – Corrosion of steel reinforcement

b) Principles of corrosion of steel in concrete

Electrolyte is the pore water of concrete in contact with steel. Normally highly alkaline (pH = 12-13) due to $Ca(OH)_2$ from the cement hydration and the small amounts of Na_2O and K_2O in cement.

In such a solution, anodic reaction gives out Fe_3O_4 instead of Fe^{++}. Fe_3O_4 is deposited at metal surface as tightly adherent thin film and stops any further corrosion (Steel is said to be passive)

Passivation is the spantaneous formation of a hard non-reactive surface film that inhibits further corrosion.

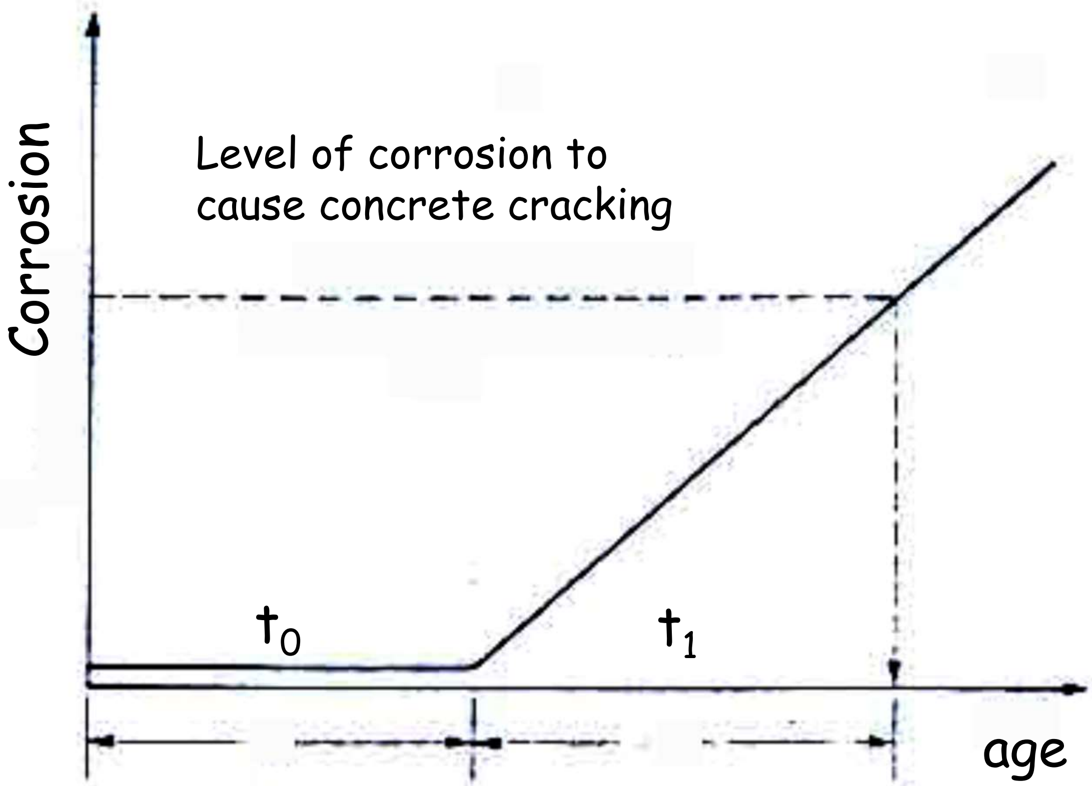
Concrete passivation may be broken by;

- A loss of alkalinity by carbonation
- Chloride ions (e.g. from seawater, road de-icing salts, etc.)

4. Durability of steel in concrete, cont'd

c) Principles of corrosion of steel in concrete, cont'd

Two stages of corrosion damage



t_0 = time for depassivating agents to reach steel and initiate corrosion

t_1 = time for corrosion to reach critical levels, sufficient to crack concrete

3. Degradation of concrete - Exposure classes (EN 206), cont'd

1. No risk of corrosion or attack
2. Corrosion induced by carbonation
3. Corrosion induced by chlorides other than from sea water
4. Corrosion induced by chlorides from sea water
5. Freeze-thaw attack with or without de-icing agents
6. Chemical attack

3. Degradation of concrete – Corrosion of steel reinforcement

2) Corrosion induced by carbonation

Carbonation is the reaction of carbonic acid with hydrated cement in the presence of moisture.

$$CO_2 + H_2O \rightarrow H_2CO_3 \longrightarrow \text{Carbonic acid}$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$$

As a result;

H_2O is released *(shrinkage accompanies)*

Weight of paste increases

Strength increases

Permeability decreases

PH of concrete decreases (<7)

3. Degradation of concrete – Corrosion of steel reinforcement

2) Corrosion induced by carbonation

Max carbonation at 25-50 % RH!!!
If concrete is saturated, H_2CO_3 can not penetrate in concrete
If concrete is dry H_2CO_3 can not form

Carbonation first occurs on the surface and progresses inwards.

$$x = k\, t^{1/2}$$

k = constant
x = carbonation depth
t = time

High quality, well cured concrete is subjected to limited carbonation (only 20 – 30mm after years)

3. Degradation of concrete – Corrosion of steel reinforcement

2) Corrosion induced by carbonation - measurement

<u>A simple method for measuring carbonation depth;</u> applying solution of phenolphthalein in diluted alcohol to a freshly broken surface. Free $Ca(OH)_2$ is coloured pink while the carbonated portion is uncoloured.

Concrete surface

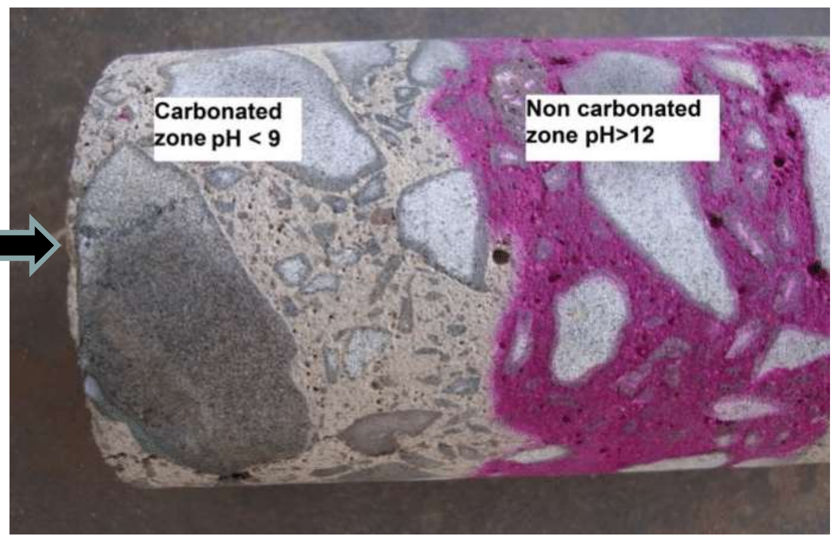


Figure reference http://www.iricen.gov.in/LAB/res/html/Test-35.html

3. Degradation of concrete – Corrosion of steel reinforcement

2) Corrosion induced by carbonation - measurement

Recommended limiting values for composition and properties of concrete

	Exposure classes																	
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion: Sea water			Chloride-induced corrosion: Chloride other than from sea water			Freeze/thaw attack				Aggressive chemical environments		
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum w/c[c]	–	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m^3)	–	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0[a]	4,0[a]	4,0[a]	–	–	–
Other requirements	–	–	–	–	–	–	–	–	–	–	–	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				–	Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement conforming to EN 197-1 or complementary national standards.

[c] Where the k-value concept is applied the maximum w/c ratio and the minimum cement content are modified in accordance with 5.2.5.2.

EN 206

3. Degradation of concrete - Exposure classes (EN 206), cont'd

1. No risk of corrosion or attack
2. Corrosion induced by carbonation
3. Corrosion induced by chlorides other than from sea water
4. Corrosion induced by chlorides from sea water
5. Freeze-thaw attack with or without de-icing agents
6. Chemical attack

3. Degradation of concrete – Corrosion of steel reinforcement

3-4) Corrosion induced by chlorides

Common sources of corrosion

- Calcium chloride (an accelerating admixture)
- Contamination in aggregates
- Sea water for coastal and marine structures
- Road deicing salts (on bridge decks)

First two enter into concrete during mixing and steel may never be passivated (t_0=0)
Last two have to penetrate the concrete cover sufficiently to depassivate the steel (t_0=finite)

3. Degradation of concrete – Corrosion of steel reinforcement

3-4) Corrosion induced by chlorides

Chloride ions destroy the passivation layer on steel reinforcement and in presence of water and oxygen corrosion occurs.

$Fe^{++} + 2Cl^{-} \rightarrow Fe(Cl)_2$
$Fe(Cl)_2 + 2H_2O \rightarrow Fe(OH)_2 + 2HCl$

Figure reference: http://www.ifb.ethz.ch/durability/research/ongoing-projects/initiation-of-chloride-induced-corrosion.html

3. Degradation of concrete – Corrosion of steel reinforcement

3-4) Corrosion induced by chlorides

Recommended limiting values for composition and properties of concrete

	Exposure classes																	
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion						Freeze/thaw attack				Aggressive chemical environments		
						Sea water			Chloride other than from sea water									
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum *w/c*[c]	–	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m^3)	–	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0[a]	4,0[a]	4,0[a]	–	–	–
Other requirements	–	–	–	–	–	–	–	–	–	–	–	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				–	Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement conforming to EN 197-1 or complementary national standards.

[c] Where the *k*-value concept is applied the maximum *w/c* ratio and the minimum cement content are modified in accordance with 5.2.5.2.

EN 206

3. Degradation of concrete – Corrosion of steel reinforcement

If protection against corrosion can not be guranteed, then

- Use corrosion inhibiting admixture (calcium nitrate)
- Use corrosion resistant stainless steel bars or epoxy coated bars
- Cover concrete surface by a protector
- Apply cathodic protection – method is based on preventing a metal surface from corroding by making it the cathode of an electrochemical cell. A simple method of protection connects protected metal to a more easily corroded "sacrificial metal" to act as the anode.

3. Degradation of concrete - Exposure classes (EN 206), cont'd

1. No risk of corrosion or attack
2. Corrosion induced by carbonation
3. Corrosion induced by chlorides other than from sea water
4. Corrosion induced by chlorides from sea water
5. Freeze-thaw attack with or without de-icing agents
6. Chemical attack

3. Degradation of concrete

5) Durability against freezing and thawing (important in cold climates)

- In winter time, water in capillary pores expands on freezing resulting in disruptive internal stresses. Successive cycles of freezing and thawing may lead to progressive deterioration.
- Water in the pores of aggregates may also freeze and affect the durability of concrete against frost action

Water – cement ratio is a controlling factor of durability of concrete against freezing and thawing cycles because its magnitude determines the amount and size of the capillary pores in the cement paste. For this reason, water-cement ratio is limited in specifications for durability of concrete against frost action.

3. Degradation of concrete

5) Durability against freezing and thawing, cont'd

Recommended limiting values for composition and properties of concrete

	Exposure classes																	
	No risk of corro-sion or attack	Carbonation-induced corrosion				Chloride-induced corrosion: Sea water			Chloride-induced corrosion: Chloride other than from sea water			Freeze/thaw attack				Aggressive chemical environments		
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum *w/c*[c]	–	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m³)	–	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0[a]	4,0[a]	4,0[a]	–	–	–
Other require-ments	–	–	–	–	–	–	–	–	–	–	–	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				–	Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement conforming to EN 197-1 or complementary national standards.

[c] Where the *k*-value concept is applied the maximum *w/c* ratio and the minimum cement content are modified in accordance with 5.2.5.2.

EN 206 – July 2014

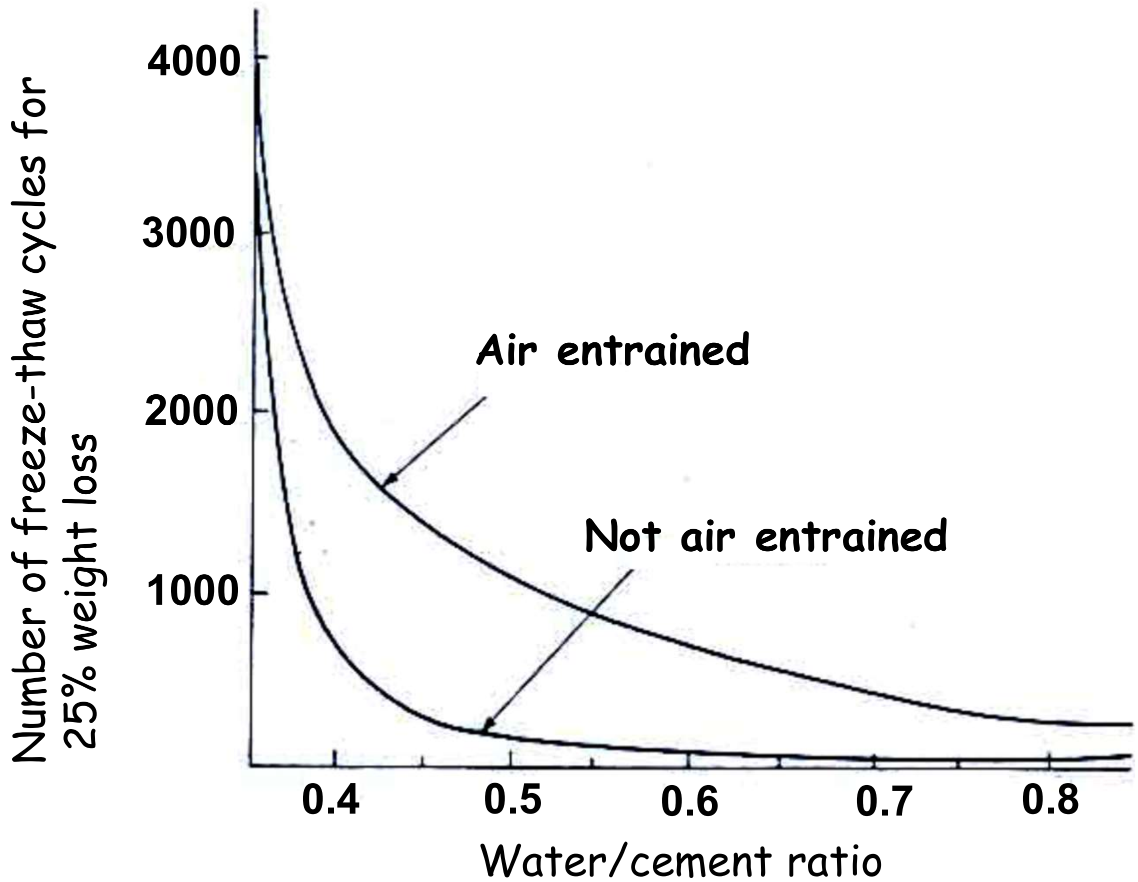
3. Degradation of concrete

5) Durability against freezing and thawing, cont'd

- Air-entrainment into concrete increases the durability of concrete against freezing and thawing.
- Optimum percentage of air-entrainment is about 4-6 % by volume.
- Air entrainment is achieved through some chemical admixtures
- Freezing of the water in the pores of the aggregates may also damage concrete via damaging aggregate particles.
- Durability of aggregate against frost action depends upon its pore characteristics and saturation degree. Indirect or direct tests of freezing and thawing are used to measure durability of aggregates

3. Degradation of concrete

5) Durability against freezing and thawing, cont'd



The effect of air entrainment and water/cement ratio on the frost resistance of concrete moist-cured for 28 days (US Bureau of Reclamation, 1955)

3. Degradation of concrete

5) Durability against freezing and thawing, cont'd

Therefore, to make concrete durable

1) Cement paste should be made durable
   (↓ w/c, air-entrain, use pozzolanic materials)
2) Use durable aggregates
3) Apply good curing to concrete

Concrete should be tested for durability against frost action

Prismatic specimens are subjected to 300 cycles of freezing at -17 °C and thawing at + 4 °C, a cycle completed in 4 hours (ASTM C 666).

Specimens are tested non-destructively from time to time by measuring dynamic modulus of elasticity through resonance frequency testing. Decrease in E_d with respect to control concrete indicates the degree of durability against frost action.

$$E_d = 4n^2 l^2 \rho$$

3. Degradation of concrete

5) Durability against freezing and thawing, cont'd

Freeze – thaw cabin

3. Degradation of concrete

6) Durability against chemical action

- Concrete in industrial buildings
- Concrete containing contaminated aggregates
- Concrete in contact with sulphate soils or ground water may be subjected to the harmful effects of some chemical compounds

Forms of chemical attack

Acid attack
Sulphate attack
Efflorescence
Chloride attack
Alkali – silica reaction
Alkali – carbonate reaction

3. Degradation of concrete

6) Durability against chemical action, cont'd

Table 2 — Limiting values for exposure classes for chemical attack from natural soil and ground water

Chemical characteristic	**Reference test method**	**XA1**	**XA2**	**XA3**
Ground water				
SO_4^{2-} mg/l	EN 196-2	≥ 200 and ≤ 600	> 600 and ≤ 3 000	> 3 000 and ≤ 6 000
pH	ISO 4316	≤ 6,5 and ≥ 5,5	< 5,5 and ≥ 4,5	< 4,5 and ≥ 4,0
CO_2 mg/l aggressive	EN 13577	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
NH_4^+ mg/l	ISO 7150-1 or ISO 7150-2	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg^{2+} mg/l	ISO 7980	≥ 300 and ≤ 1000	> 1 000 and ≤ 3 000	> 3 000 up to saturation
Soil				
SO_4^{2-} mg/kg[a] total	EN 196-2[b]	≥ 2 000 and ≤ 3 000[c]	> 3 000[c] and ≤ 12 000	> 12 000 and ≤ 24 000
Acidity ml/kg	DIN 4030-2	> 200 Baumann Gully	Not encountered in practice	

[a] Clay soils with a permeability below 10^{-5} m/s may be moved into a lower class.

[b] The test method prescribes the extraction of SO_4^{2-} by hydrochloric acid; alternatively, water extraction may be used, if experience is available in the place of use of the concrete.

[c] The 3 000 mg/kg limit shall be reduced to 2 000 mg/kg, where there is a risk of accumulation of sulfate ions in the concrete due to drying and wetting cycles or capillary suction.

EN 206 – July 2014

3. Degradation of concrete

6) Durability against chemical action, cont'd

Recommended limiting values for composition and properties of concrete

	Exposure classes																	
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion						Freeze/thaw attack				Aggressive chemical environments		
						Sea water			Chloride other than from sea water									
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum *w/c*[c]	–	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m^3)	–	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0[a]	4,0[a]	4,0[a]	–	–	–
Other requirements	–	–	–	–	–	–	–	–	–	–	–	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				–	Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement conforming to EN 197-1 or complementary national standards.

[c] Where the *k*-value concept is applied the maximum *w/c* ratio and the minimum cement content are modified in accordance with 5.2.5.2.

EN 206 – July 2014

3. Degradation of concrete

Durability against very high temperatures

Concrete maybe subjected to very high temperatures above 1000°C in the case of;

- Fire of buildings
- Pavements of air field
- Furnaces or chimneys of industrial buildings

Rate of degradation depends on;

- Maximum temperature
- Concrete constituents
- Size of element

3. Degradation of concrete

Durability against very high temperatures, cont'd

For the cement paste

a) at 105°C, capillary and gel water has been lost and shrinkage occurs
b) at 250-300°C, aluminous and ferrous constituents of cement loose crystal water
c) at 400-700°C, siliceous constituents loose crystal water and shrink meanwhile $Ca(OH)_2$ looses its water and converts to CaO.

3. Degradation of concrete

Durability against very high temperatures, cont'd

For the aggregates

a) Aggregates expand very mildly with increasing temperature
b) At 550°C, some siliceous aggregates may expand excessively due to a change in crystal structure
c) At 900°C, limestone aggregates may be calcined (separated from CO_2)
d) Basalt, blast furnace slag, crushed firebrick usually don't change their volume extensively up to and well above 1000°C

3. Degradation of concrete

Durability against very high temperatures, cont'd

To produce a concrete durable against medium temperatures (500-600°C)

- A proper design must be achieved
- Use limestone aggregates

To produce a concrete durable against higher temperatures (900-1100°C)

- A refractory concrete should be designed
- Stabilizing agent (shamotte earth, powdered silica, etc.) should be used in place of some fine aggregate
- Use basalt, blast furnace slag or crushed firebrick

On the other hand, aluminous cement is very profitable for refractory concrete

Chapter Outline

- CONCRETE
  - History of concrete
  - Constituents of concrete
  - Fresh state properties of concrete
  - Deformation and dimensional stability of concrete
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property composition relations for concrete and concrete mix design

Subchapter Outline

Statistical quality control in the production of concrete

1. Introduction
2. Related standards
3. TS 500
4. EN 206
    1. TS 13515 (complementary Turkish Standard for the implementation of TS EN 206)

Statistical quality control in the production of concrete

1. Introduction

Concrete quality will show variation due to factors such as;

variations in concrete making materials, production and measuring methods and human,

Compressive strength of concrete, which is an excellent measure of not only the mechanical strength, but also some other properties of concrete, is taken as a basis for investigating the quality of the concrete

When a concrete structure is designed, the designer will first decide about the compressive strength of the concrete. This strength shall be selected among the values given in the standards of that country, taking into account.

- Level of importance of structure
- Materials
- Equipment
- Production facilities

2. Related standards

TS 500: Requirements for design and construction of reinforced concrete structures (Feb 2000)→ revised on 2001, 2002, 2014

EN 206: Concrete, Specification, performance, production and conformity
→ obligatory standard
is adopted to accord with EU countries
(Last version July, 2014)

3. TS 500

TS 500 (2000) (Design principles for reinforced concrete buildings)

Presents concrete design strengths (f_{ck}) as;

C16, C18, C20, C25, C30, C35, C40, C45, C50

C16 → 28 day compressive strengths of concrete cylinder specimens in MPa (D=15cm, H=30cm).

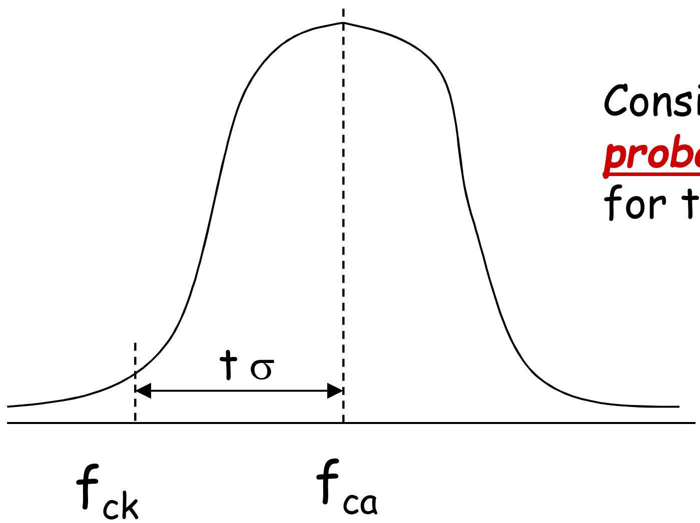
TS500 specifies that these strength values are lower limits with confidence degree of 90%.

That is, only 10% of the specimens taken from the produced concrete may have compressive strengths below these design strengths

3. TS 500, cont'd

Calculation of aim strength

(given by TS 500 (1984))
(not included in TS 500 (2000))



Considering test variation in conrete strength obeys ***normal probabilistic distribution*** law. The standard deviation (σ) for the concrete production plant should be known.

3. TS 500, cont'd

Given by TS 500 (1984) – not included in the new version TS 500 (2000)

Confidence limits in normal distribution		
Confidence parameter (t)	Degree of risk (r)	Degree of reliability (1-r)
0.00	0.50	0.50
0.67	0.25	0.75
1.00	0.16	0.84
1.28	0.10	0.90
1.65	0.05	0.95
1.96	0.025	0.975
2.33	0.01	0.99
3.00	0.001	0.999

Risk is (r) ($f_c \leq f_{ck}$)
Reliability is P ($f_c > f_{ck}$)

Then required average strength (aimed or targeted strength) to be used in mix design calculations is given for 90% confidence as:
$f_{ca} = f_{ck} + 1.28\,\sigma$

f_{ck} = design strength
f_{ca} = aim strength

3. TS 500, cont'd

If standard deviation (σ) is not known, then aimed strength is obtained by increasing the characteristic design strength by Δ_f as given

for C14 & C16 $\rightarrow$ Δ_f = 4MPa
for C18 - C30 $\rightarrow$ Δ_f = 6MPa
for C35 - C50 $\rightarrow$ Δ_f = 8MPa

Ex; for a design strength (f_{ck}) of C25, strength to be aimed in mix design is calculated as:
f_{ca} = 25+6 = 31MPa

3. TS 500, cont'd

Revision (T3) of TS 500 which was published in 2014 cites TS 13515 as follows for conformity control and conformity criteria;

TS 13515 – Addition B1 should be followed for conformity control and conformity criteria.

4. EN 206

EN 206 (July 2014)

Concrete design strengths C8-C100 (16 concrete classes are defined)
Strengths are given as C20/25

C 20 / 25

- 20 → 28 day compressive strengths of concrete cylinder specimens in MPa (D=15cm, H=30cm).
- 25 → 28 day compressive strengths of concrete cube specimens in MPa (a=15cm).

Lightweight concrete design strengths LC8 – LC80 (14 concrete classes are defined)

LC 8 / 9

- 8 → 28 day compressive strengths of concrete cylinder specimens in MPa (D=15cm, H=30cm).
- 9 → 28 day compressive strengths of concrete cube specimens in MPa (a=15cm).

4. EN 206, cont'd

Minimum rate of sampling for assessing conformity

Table 17 — Minimum rate of sampling for assessing conformity

Production	**Minimum rate of sampling**		
	First 50 m^3 of production	Subsequent to first 50 m^3 of production[a], the highest rate given by:	
		Concrete with production control certification	Concrete without production control certification
Initial (until at least 35 test results are obtained)	3 samples	1 per 200 m^3 or 1 per 3 production days[d]	1 per 150 m^3 or 1 per production day[d]
Continuous[b] (when at least 35 test results are available)	---	1 per 400 m^3 or 1 per 5 production days[c, d] or 1 per calendar month	

[a] Sampling shall be distributed throughout the production and should not be more than 1 sample within each 25 m^3.

[b] Where the standard deviation of the last 15 or more test results exceeds the upper limits for s_n according to Table 19, the sampling rate shall be increased to that required for initial production for the next 35 test results.

[c] Or if there are more than 5 production days within 7 consecutive calendar days, once per calendar week.

[d] The definition of a ´production day´ shall be stated in provisions valid in the place of use.

4. EN 206 and modification done by TS 13515

Minimum rate of sampling for assessing conformity

<table>
<tr><th rowspan="3">Production</th><th colspan="3">Minimum rate of sampling [d]</th></tr>
<tr><td rowspan="2">First 50 m^3 of production</td><td colspan="2">Subsequent to first 50 m^3 of production[a], the highest rate given by:</td></tr>
<tr><td>Concrete with production control certification</td><td>Concrete without production control certification</td></tr>
<tr><td>Initial (until at least 35 test results are obtained)</td><td>3 samples</td><td>1 per 100 m^3 daily (2 per week for C16/C20 and lower classes)</td><td rowspan="2">1 per 50 m^3 daily (4 per week for C16/C20 and lower classes)</td></tr>
<tr><td>Continuous [b] (when at least 35 test results are available)</td><td>----</td><td>1 per 200 m^3 daily (1 per week[c] for C16/C20 and lower classes)</td></tr>
</table>

[a] Sampling shall be distributed throughout the production and should not be more than 1 sample within each 25 m^3.

[b] Where the standard deviation of the last 15 or more test results exceeds 1.37 σ, the sampling rate shall be increased to that required for initial production for the next 35 test results.

[c] Sampling rate may be reduced to half if more than 600m^3 concrete was transported to same delivery site.

[d] In conformity with the regulation that construction materials are subject to, sampling rates may be higher than this table for sites of firms that are obligated to inspect and observe within the scope of G conformity certificate.

Modified table given by TS 13515 must be used in Turkey.

Why is the table modified?

4. EN 206 is modified by TS 13515, cont'd

TS 13515 - Conformity criteria for compressive strength

1. Criteria for individual results

Each individual test result, f_{ci} shall satisfy: $f_{ci} \geq (f_{ck}-4)$ N/mm^2

If the batch fails the individual criterion, this batch is declared as non-conforming and this result is excluded from any further consideration of conformity of the remaining concrete.

Note: conformity is assessed on specimens tested on 28 days.

4. EN 206 is modified by TS 13515, cont'd

TS 13515 - Conformity criteria for compressive strength, cont'd

2. Criteria for mean results
The achievement of the specified characteristic strength shall be assessed by one of the following methods.

Method A – Initial production

Mean strength of groups of 3 consecutive results shall satisfy
$f_{cm} \geq (f_{ck} + 1.0)$ N/mm^2

Method B – Continuous production

The mean strength of groups of consecutive test results obtained from a single concrete or a concrete family in an assessment period shall satisfy
$f_{cm} \geq (f_{ck} + 1{,}48\sigma)$ N/mm^2

Evaluation of conformity (EN 206, TS 13515)

What if the concrete cast is not conformed and certified by the accredited inspection and certification bodies?

Concrete cast should be evaluated in situ by using specified in situ evaluation tests according to; TS EN 13791 and TS 13543. Concrete strength should be first evaluated by using non-destructive tests and core samples should be taken from the components yielding lowest strength values. If the core specimens confirm the following condition, strength is assumed to be satisfactory.

$f_{core} \geq 0,85\ (f_{ck} - 4)$

Evaluation procedure based on TS 13515

Step I

- Samples are taken during casting (in - situ)
- The specimens are sent to a lab. to be tested on 28th day and then evaluated based on the conformity criteria given in TS 13515.

Step II

- If the evaluated concrete does not satisfy the conformity criteria, then core specimens are taken from the structure and some other non-destructive tests are carried out to evaluate compressive strength of concrete.
- Core samples are tested in the lab. and the results are checked against the following criterion
- $f_{core} \geq 0{,}85\ (f_{ck} - 4)$.

Result

- If the samples satisfy the confirmity criteria for core specimens strength is assumed to be satisfactory.

Comparison of conformity criteria (TS 13515 vs. EN206)

		Conformity Criteria	
		TS 13515	**EN 206**
Individual test results		$f_{ci} \geq (f_{ck} - 4)$ MPa	$f_{ci} \geq (f_{ck} - 4)$ MPa
Mean results	**Initial production**	$f_{cm} \geq (f_{ck} + 1.0)$ MPa	$f_{cm} \geq (f_{ck} + 4)$ MPa
	Continuous production	$f_{cm} \geq (f_{ck} + 1.48\sigma)$ MPa	$f_{cm} \geq (f_{ck} + 1.48\sigma)$ MPa

***Initial production;** until at least 35 results are obtained.
** **Continuous production;** when at least 35 results are available.

4. EN 206, cont'd

Two definitons are given for concrete;

1) Designed concrete; concrete for which the required properties and additional characteristics are specified to the producer who is responsible for providing a concrete conforming to the required properties and additional characteristics
2) Prescribed concrete; concrete for which the composition of the concrete and the constituent materials to be used are specified to the producer who is responsible for providing a concrete with the specified composition

4. EN 206, cont'd

TS 500 vs. EN 206

EN 206 is more specific by means of durability regulations than TS 500. Limit values and conformity criterions are given for properties other than strength.

Ref; Selçuk Türkel, Kamile Tosun, The evaluation of TS EN 206-1, TS 500 and TS 11222 standards from the view point of concrete

Example

A series of specimens are obtained from a unit of concrete with design strength of C20. Specimens were stored under water for 28 days and tested. Compressive strength test results are given as follows for 6 groups. Evaluate the results obtained by using EN 206. State if this production should be rejected or accepted. Standard deviation for overall production is given as σ =1.31.
Hint: evaluate strength for specimen groups and for overall production.

28th day strength, (MPa) (cube specimens)
Group 1: 29.9; 28.7; 29.2
Group 2: 28.8; 28.5; 27.2
Group 3: 26.6; 28.0; 27.5
Group 4: 26.4; 27.3; 28.8
Group 5: 29.6; 30.2; 29.4
Group 6: 29.2; 29.8; 31.3

Chapter Outline

- CONCRETE
  - Cement
  - Admixtures
  - Aggregates
  - Strength and failure of concrete
  - Durability of concrete
  - Statistical quality control in the production of concrete
  - Property - composition relations for concrete and concrete mix design

Subchapter Outline

Property - composition relations for concrete and concrete mix design

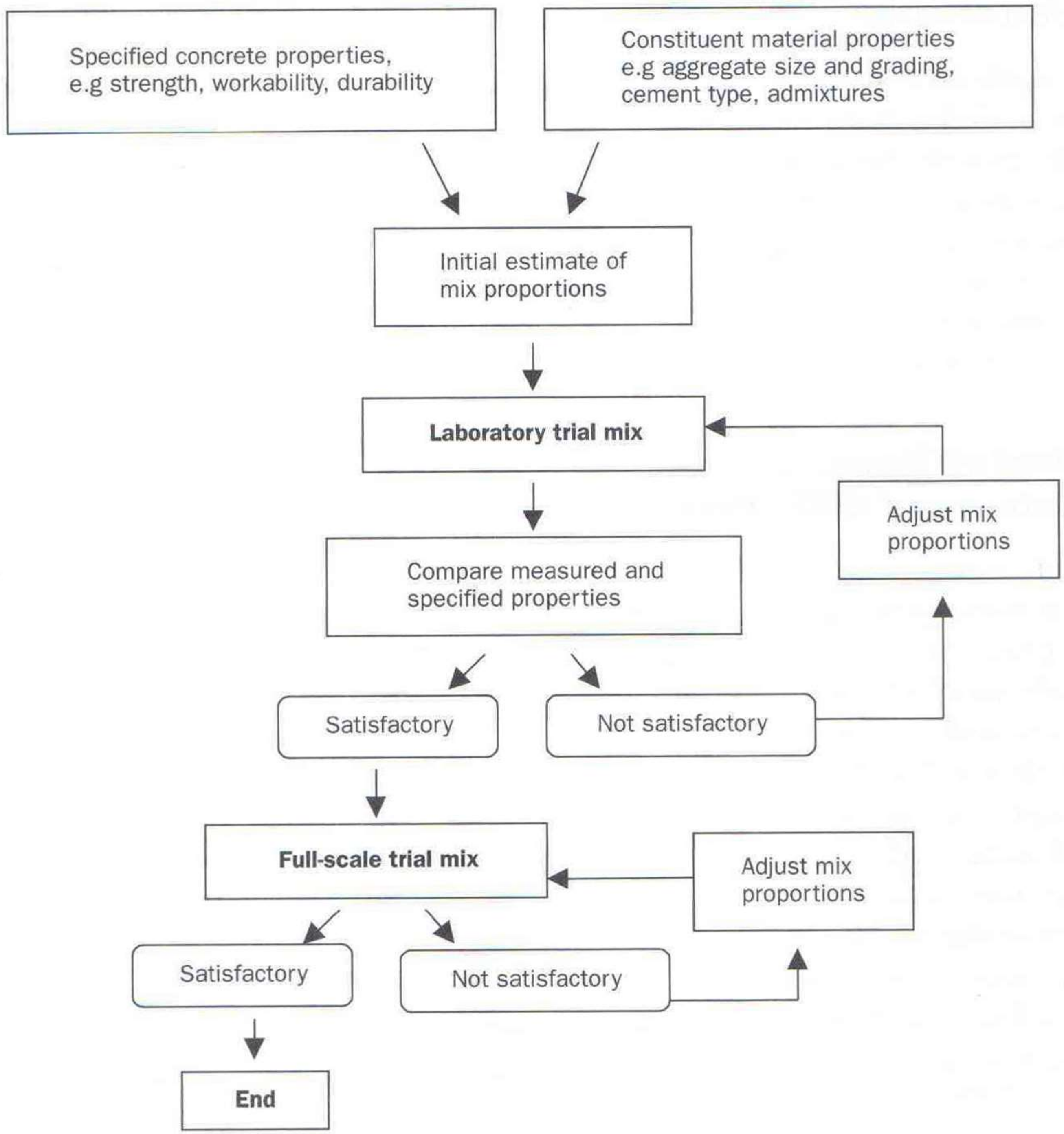
1. Specified and/or required properties
2. The mix design process
   a) Durability requirement
   b) Workability requirement
   c) Strength requirement
3. Mix design calculations
4. Examples

Property - composition relations for concrete and concrete mix design

1. Specified and/or required properties

- Durability
- Workability
- Compressive strength
- Deformation (elastic, creep, shrinkage, thermal)
- Permeability

2. The mix design process



2. The mix design process, cont'd

a) Durability requirement

Select maximum w/c, minimum strength class, minimum cement content and minimum air content (if applicable) for the defined/given exposure condition.

	Exposure classes																	
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion: Sea water			Chloride-induced corrosion: Chloride other than from sea water			Freeze/thaw attack				Aggressive chemical environments		
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum *w/c*[c]	–	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m^3)	–	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0[a]	4,0[a]	4,0[a]	–	–	–
Other requirements	–	–	–	–	–	–	–	–	–	–	–	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				–	Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement conforming to EN 197-1 or complementary national standards.

[c] Where the *k*-value concept is applied the maximum *w/c* ratio and the minimum cement content are modified in accordance with 5.2.5.2.

2. The mix design process, cont'd

b) Workability requirement

Empirical equation that relate the mix water to workability

$$W = \alpha(10 - m)$$

where, W = amount of mixing water, dm^3/m^3
α = coefficient depending on consistency & type of aggregate
m = fineness modulus of the aggregate mixture

	α_{ave}		
Consistency grade	**Natural sand & gravel**	**Natural sand & crushed stone**	**Sea sand & crushed stone**
Stiff	**29**	**33**	**37**
Plastic	**32**	**37**	**40**
Fluid	**38**	**43**	**47**

2. The mix design process, cont'd

c) Strength requirement

Abrams	$f_c = \dfrac{k_1}{k_2^{W/C}}$	(taken by weight)
Graf	$f_c = \dfrac{f_{cc}}{K_G (W/C)^2}$	(taken by weight)
Feret	$f_c = K_F \left(\dfrac{c}{c+w+v}\right)^2$	(taken by volume)
Bolomey	$f_c = K_B \left(\dfrac{C}{W+v} - k`\right)$	(taken by weight)

3) Mix design calculations

a) Preliminary design

Geometrical compatibility

$$a + c + w + v = \frac{A}{\delta_a} + \frac{C}{\delta_c} + \frac{W}{\delta_w} + v = 1m^3 = 1000dm^3$$

Constraint on air content;

Assumption for volume of entrapped air voids

~2-3 % for stiff consistency

~1-2 % for plastic consistency

~0-1 % for fluid consistency

Solve for C, A, W, v where C+A+W = Δ_{th}

3) Mix design calculations, cont'd

b) Trial batch production and measurement

Preliminary design → first approximation to actual values

- Trial batch produced based on proportions obtained from preliminary design.
- Only water requirement is adjusted till required workability is obtained. This is done by adding mix water incrementally to the mixture of dry ingredients (cement + aggregates) in the mixer.

- Workability is tested by slump test throughout incremental addition of mix water. Unit weight of the trial batch is measured (Δ_m).
- Specimens (cylinders or cubes) are cast from the trial batch with desired workability.
- Specimens are tested at 28 days to check whether strength requirement is satisfied or not. If not mix proportions are altered.

3) Mix design calculations, cont'd

Summary

- Determine w, c, a, v considering given requirements
- Calculate theoretical weight (Δ_{th})
- Cast trial batch
- Measure actual unit weight (Δ_{ac})
- Calculate actual proportions using Δ_{th}, Δ_{ac}

4. Examples

Example 1 (Concrete mix design)

Given:

Portland cement (f_{cc} = 41MPa, δ_c=3,15kg/dm^3)
Aggregate : mixture of sand & sandy gravel

Sieve size (mm)	0.25	0.50	1	2	4	8	16	δ
Sand	8	23	45	60	100	100	100	2.60
Sandy - gravel	1	3	7	12	20	55	100	2.65

Required properties:

Fresh concrete: plastic consistency
Hardened concrete: C16

Restrictions:

For the aggregate mixture, m=4.07
Assume v=1%
C_{min}=300kg/m^3

4. Examples

Example 2 (Concrete mix design)

Concrete conforming to EN 206 strength and durability requirements is to be produced by using PC52.5 cement, natural sand and crushed stone. The concrete produced is to be used for a bridge deck which will be exposed to de-icing agents. Air entraining concrete is used to provide resistance to freeze/thaw attack. It is known that each 0.5 % of air entraining admixture may cause 0.5 MPa decrease in 28 day compressive strength of the hardened concrete. Calculate the maximum amount of air entraining admixture that could be used without interfering the required strength. (Hint: find the exposure condition and limiting values (check for all of the limiting values) for the given concrete). Midterm II, 2013.

4. Examples

Example 3 (Concrete mix design)

1) Particle size distributions for 2 aggregates are given below. These aggregates will be used for producing concrete. Fineness modulus of the aggregate mixture is supposed to be equal to 3,4.

Material	0.25	1	2	4	8	16	mm	δ kg/dm^3
Sand	15	70	83	100	100	100	% passing	2,6
Gravel	0	0	0	0	20	100	% passing	2,7

Preliminary design values (for 1m^3 of concrete) for cement and water are given as follows:

Cement: 345 kg/m3 (δ: 3.15 kg/dm^3)
Water: 175 kg/m3 (δ: 1.00 kg/dm^3)

a) Find the theoretical amounts (preliminary design values) for sand and gravel by assuming 2 % air void volume in concrete.
b) Concrete specimens were produced by using the above calculated preliminary design and a cylindrical mould with a height of 200mm and a diameter of 100mm was used for calculating actual unit weight. The measured weight of the concrete in cylinder was found to be 3,75 kg. Calculate the actual amounts of the materials and the actual air content of this concrete.
c) Laboratory tests have shown that the aggregates were wet and surface moisture was measured as 1.5% for sand and 0.5% for gravel. Find the correct amounts for sand, gravel and water.

Final exam, 2013

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Concrete pavements
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter Outline

BITUMINOUS MATERIALS

1) Introduction
2) Sources of bitumen
3) Aggregates
4) Strength and Failure
    a) Modes of breakdown
    b) Evaluation of road condition
5) Viscosity of bitumen
6) Factors affecting deformation of bituminous mixes
7) Property composition relations for bituminous mixes
8) Test methods used to measure optimum bitumen content

Bituminous materials

1. Introduction

Bituminous materials include all materials consisting of aggregate bound with either bitumen or tar. Mineral dust called "filler" is also used. Bituminous materials are used in highway engineering to construct flexible pavements.

Asphalt : Bitumen + *Aggregate* OR Tar + *Aggregate*

Bitumen is a mixture of organic liquids that are highly viscous, black, sticky and composed primarily of hydrocarbons.
Tar is a viscous black liquid derived from the destructive distillation of organic matter. Most tar is produced from coal as a by product of fuel production.

picture: www.saocl.com

Bituminous materials

1. Introduction

Factors determining the type of bituminous mixtures

- Bitumen content
- Bitumen grade
- Aggregate grading
- Aggregate size

picture: www.saocl.com

2. Sources of bitumen

1) Natural deposits (types of deposit range from almost pure bitumen to bitumen-impregnated rocks and bituminous sands with only a few per cent bitumen)
   - Rock asphalt (Porous limestone or sandstone impregnated with bitumen with 10% content, “Val de Travers”, Switzerland, “Tar sands” of North America)
   - Lake asphalt (Bitumen lake with mineral matter dispersed throughout the bitumen, Trinidad lake (55 % bitumen, 35 % mineral matter, 10 % organic matter)

2) Refinery bitumen

2. Sources of bitumen, cont'd

2) Refinery bitumen: residual material left after the fractional distillation of crude oil

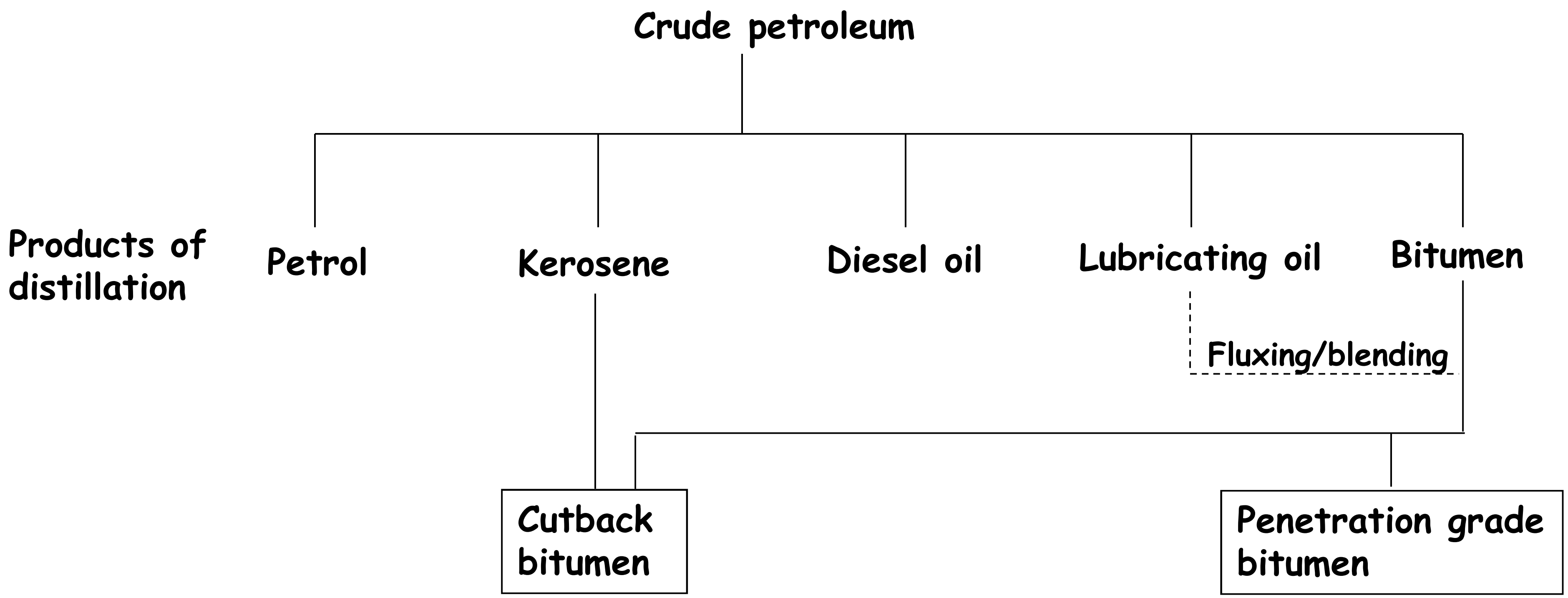


Fig. Preparation of refinery bitumens

3. Aggregates

Aggregates make up about 92 % of bituminous materials

Coarse aggregates → retained on 2.36mm sieve,

Fine aggregates → passes 2.36mm sieve but is retained on 75μm sieve.

Filler → passes 75μm sieve

Open textured aggregate mixtures: Grading is continuous and provides a dense packing of particles. Strength and resistance to deformation are largely determined by aggregate grading with bitumen acting as adhesive

Dense graded aggregate mixtures: Aggregate grading is still important but properties are determined largely by the matrix of fines and bitumen

Aggregate particles must have sufficient strength for surfacing materials, they must be resistant to abrasion and polishing. Shape and surface texture are also important.

4. Strength and Failure

Purpose of the road is to distribute applied load from traffic to a level which the underlying subgrade can bear

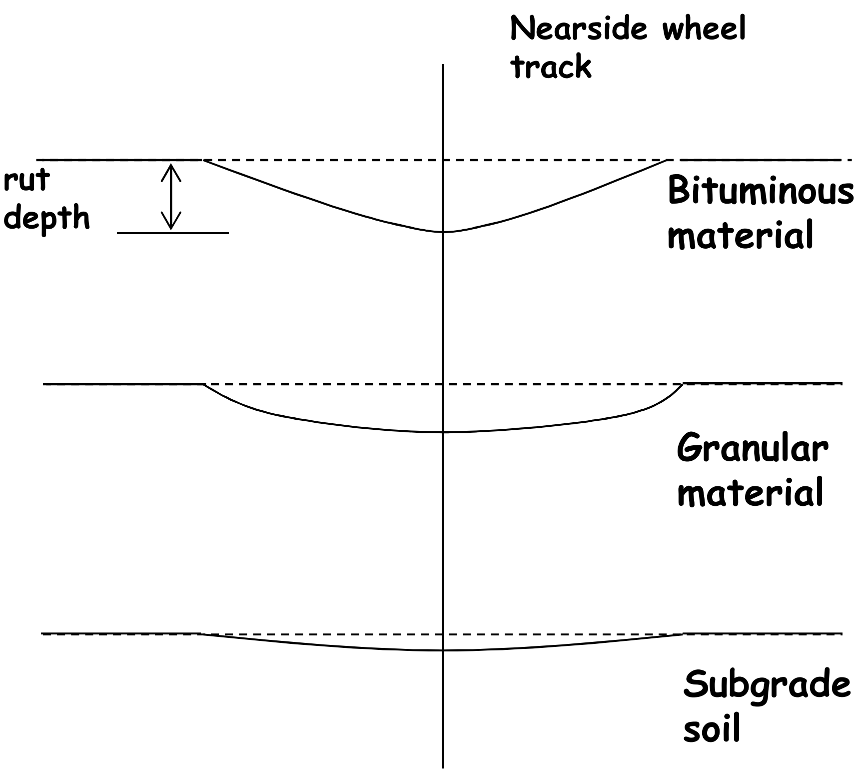
There are two forms of failure:

- Road surface may deteriorate through breakdown of surface material so that skidding resistance drops
- Road structure deteriorates – gradual and develops with the continued application of wheel loads

4. Strength and Failure, cont'd

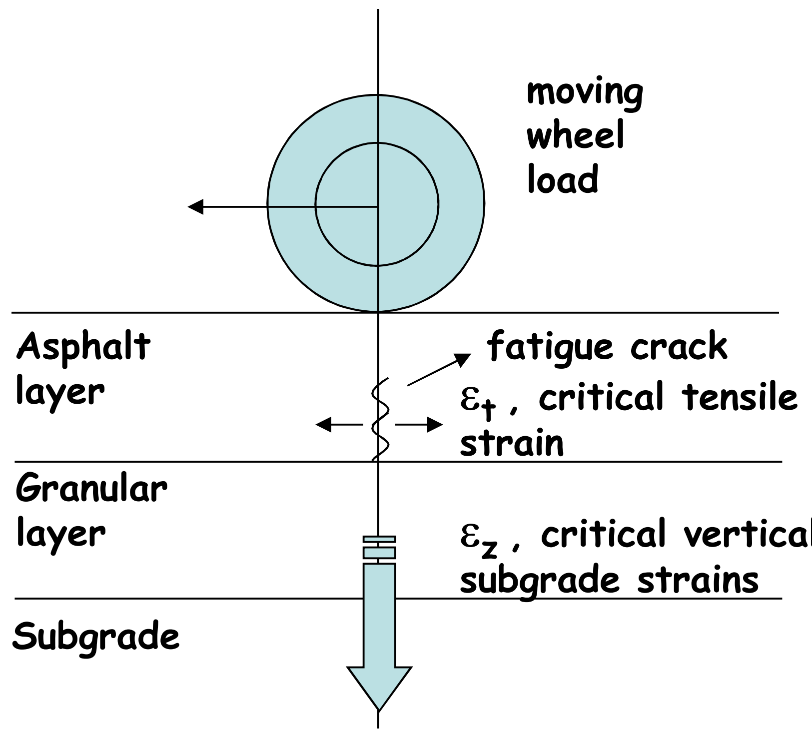
Modes of breakdown

Case I



Permanent deformation

Case II



Fatigue cracking and critical strains

4. Strength and Failure, cont'd

Modes of breakdown, cont'd

- Case I - Permanent deformation occurs in wheel tracks. Rutting is associated with deformations in all layers of pavement. It is linked to loss of support from subgrade soil.
- Case II - Cracking appears along wheel tracks, cracking is caused by tensile strain developed in bound layers as each wheel load passes. It is a fatigue failure.

4. Strength and Failure, cont'd

Evaluation of road condition

If failure can be defined, life of a road can be determined provided that loading can be assessed and performance of the materials evaluated. Complete collapse of roads are not encountered. *Therefore, failure of roads must be identified in terms of serviceability and/or repairability.*

- It is accepted that if cracking is visible at surface, road is regarded as being at critical condition or as having failed.
- For no visible cracking, if rut depth reaches 20mm, road is regarded as having failed

5. Viscosity of bitumen

Viscosity of a liquid is the property that retards flow so that when a force is applied to the liquid, the higher the viscosity, the slower will be the movement of the liquid. The viscosity of bitumen is dependent upon both its chemical composition and its structure.

There are two most common measures of viscosity

- Softening point: Temperature at which a bitumen reaches a specified level of viscosity
- Standard tar viscometer: (used to measure the viscosity of tars) time taken for 50ml of the tar to run out of a cup through a standard orifice

5. Viscosity of bitumen

Another test to evaluate viscosity

Penetration test: commonly applied to bitumen for material characterization. *The test measures the hardness of bitumen which is related to viscosity.* It measures depth to which a needle penetrates a sample of bitumen under a load of 100 gr over a period of 5 sec at a temperature of 25°C

Bitumen is viscoelastic; therefore, the penetration will depend on the elastic deformation and viscosity

Bitumens are thermoplastic materials so that they soften as the temperature rises but become hard again when the temperature drops. Susceptibility of bitumen to temperature is determined from the penetration value and softening point temperature

Viscoelasticity describes materials that exhibit both viscous and elastic characteristics when undergoing plastic deformation

6. Factors affecting deformation of bituminous mixes

1) Bituminous viscosity: when a stress is applied to a bituminous material, both the aggregate particles and the bitumen will be subjected to the stress. Aggregate particles, being hard and stiff, while undergo negligible strain, whereas the bitumen, being soft, will undergo considerable strain. Deformation is associated with movement in the bitumen and the extent of the movement will depend on its viscosity.

2) Aggregate: bituminous mixtures utilizing a continuously graded – aggregate rely mainly on aggregate particle interlock for their resistance to deformation. Thus, grading and particle shape of aggregate are major factors governing deformation. Characteristics of fine aggregate are important in gap-graded materials. WHY??

3) Temperature: permanent strain increases with temperature due to the reduction in viscosity and stiffness of bitumen.

7. Property composition relations for bituminous mixes

McKesson – Frickstad (California) formula

$$P = 0.015a + 0.03b + 0.17c$$

where, a = % of aggregate retained on No 10 (2mm) sieve

b = % of aggregate remaining between No 10 (2mm) and No 200 (0.075mm) sieves

c = % of aggregate passing No 200 (0.075mm) sieve

P = % of bitumen by weight of the bituminous mixture

In this equation, amount of bitumen is related to the surface area of the aggregate groups.

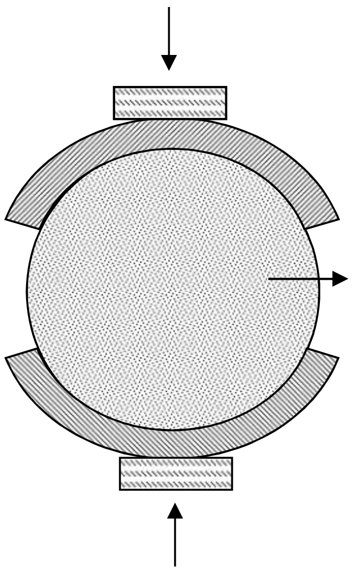
8. Test methods used to measure optimum bitumen content

In lab., some tests have been done to determine the optimum bitumen content

- Compression test
- Stability test (Marshall test, Hubbard-Field test, Hveem test)
- Triaxial test

8. Test methods used to measure optimum bitumen content

Marshall test (most common test method)



Objective

To determine an optimum binder content from a consideration of *mix strength (stability), mix density, mix deformability (flow)*

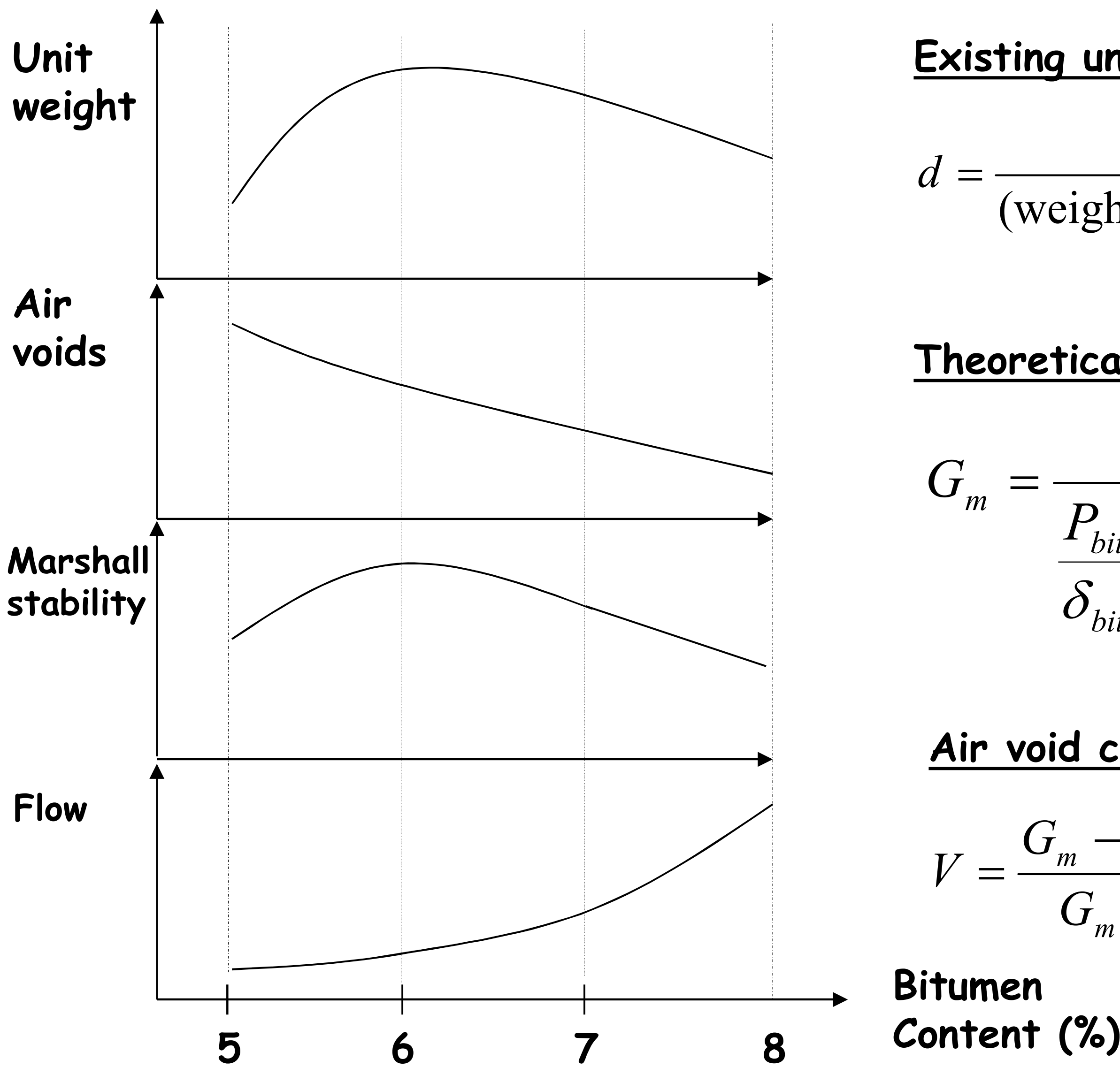
Cylindrical samples of 10cm diameter and 6.25cm height specimen is placed between the crescent shaped testing heads of testing machine and the force is applied from the side surfaces, subjecting the sample to an internal shearing towards the stress free plane surfaces. Loading speed is 5cm/min. Resultant maximum load and the corresponding deformations are measured

Required properties are 1) minimum stability of 225kg (2207N), 2)a maximum flow of 0.5cm, 3) air voids (3-5%) and 4) degree of saturation of aggregate voids with bitumen (75-85%).

Test is repeated with mixes of different bitumen contents and bitumen content fulfilling all requirements is determined as OPTIMUM BITUMEN CONTENT

Marshall test, cont'd

Analysis of mix design data from the Marshall test



In compacted bituminous mixture

Existing unit weight

$$d = \frac{\text{weight in air}}{(\text{weight in air}) - (\text{weight in water})}$$

Theoretical max, unit weight

$$G_m = \frac{100}{\frac{P_{bit}}{\delta_{bit}} + \sum_i \frac{(P_{agg})_i}{(\delta_{agg})_i}}$$

Air void content

$$V = \frac{G_m - d}{G_m} x100$$

Example

Properties and mix proportions of materials used for a bituminous mixture are as follows

Material	Density (δ)	Mix proportions (P)
Asphalt	1.04 kg/dm^3	10 % by wt
Crushed stone	2.70 kg/dm^3	90 % by wt

Following data are obtained from a lab. specimen made using this mix:
weight in air = 111.95 gr
weight in water = 61.16 gr

Example, cont'd

- Calculate unit weight of the lab. specimen
- Calculate the theoretical maximum unit wt. of the mix
- Calculate volume percentage of voids in the lab. specimen
- This mix is placed on the road and consolidated under a roller. After consolidation a core sample is taken and the unit wt. of this core sample is determined to be 2.13kg/dm^3. The specified degree of compaction for this pavement being at least 95% of the compaction of a laboratory specimen, indicate if this bituminous pavement is acceptable?

Example, cont'd

Solution:

a) $d =$

b) $G_m =$

c) $v =$

d) specified unit weight =

Example 2

Crushed limestone aggregate contains 10 % filler material (particles finer than 75μ) and 50 % of the aggregate particles are coarser than 2mm, both percentages by mass. This aggregate (δ = 2.73 kg/dm^3) is mixed with a cutback asphalt (δ = 1.15 kg/dm^3) at a proportion determined by McKesson-Frickstead formula to produce bituminous concrete for highway pavement construction. The unit weight of the specimen cut from the compacted pavement was measured as 2.40 kg/dm^3. Estimate the void content of this bituminous concrete.

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Concrete pavements
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Concrete pavements

- First concrete pavement – Ohio in 1891
- Increased use of concrete for pavements in the last century
- Service lives as much as 25-40 years
- Lower maintenance costs depending on the material costs and time of construction
- Increased sustainability

Ref: Norbert Delatte, Concrete pavement design, construction and performance

Types of concrete pavements

- Concrete pavements have two features in common
  - They resist traffic load through flexure of concrete. If reinforcement is used, it is used for crack control and not to carry load.
  - Concrete pavements contract due to drying shrinkage of concrete, and expand and contract due to thermal effects, all of these movements must be dealt with.

Ref: Norbert Delatte, Concrete pavement design, construction and performance

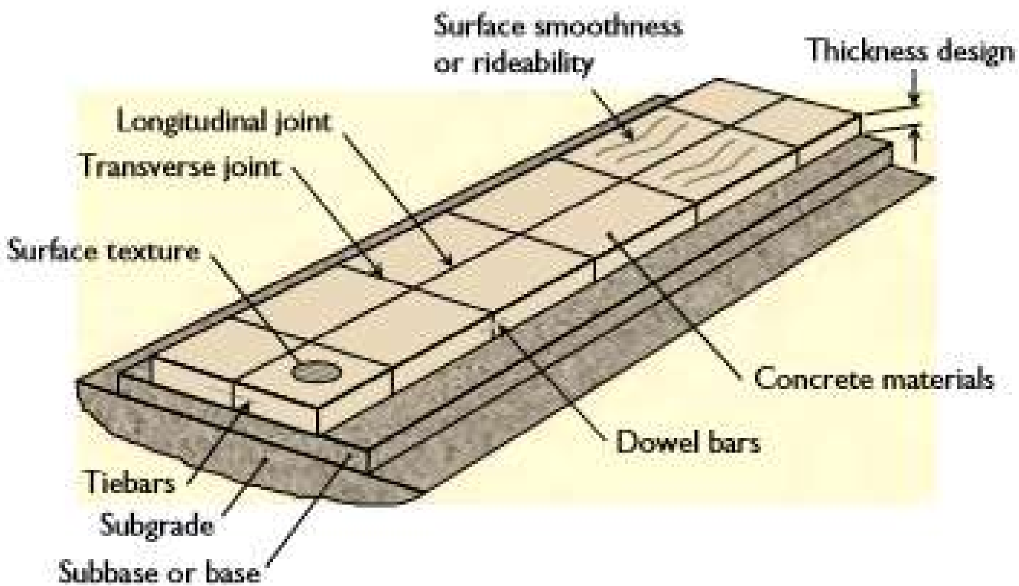
Types of concrete pavements, cont'd

1. Jointed plain concrete pavement (JPCP)
2. Jointed reinforced concrete pavement (JRCP)
3. Continuously reinforced concrete pavements
4. Roller compacted concrete (RCC)

Ref: Norbert Delatte, Concrete pavement design, construction and performance

1. Jointed plain concrete pavement

- Unreinforced concrete slabs from 3.6 to 6.0 m in length with transverse contraction joints between the slabs.
- Pavement expansions and contractions are addressed through joints.



Ref: Norbert Delatte, Concrete pavement design, construction and performance

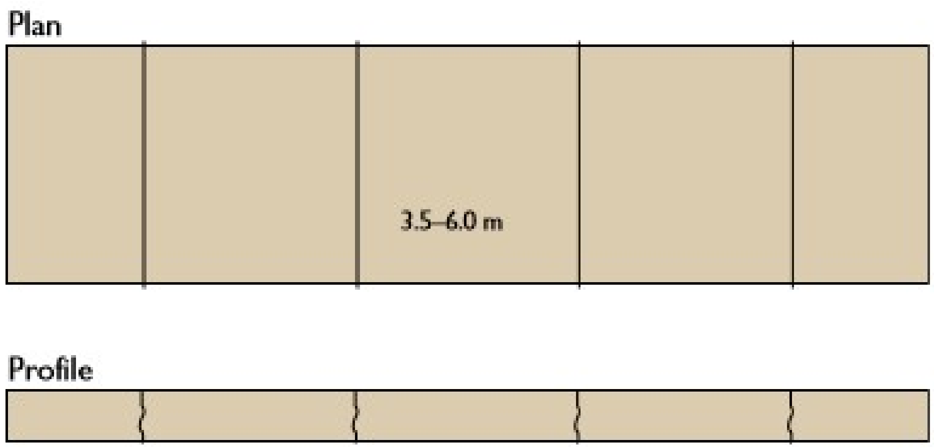
1. Jointed plain concrete pavement, cont'd

- Load transfer across the joints is important, since faulted joints may result in uncomfortable driving experience for the drivers.
  - Aggregate interlock joints
  - Dowels
- Most commonly used pavement type since it is the most economic.

Ref: Norbert Delatte, Concrete pavement design, construction and performance

1. Jointed plain concrete pavement, cont'd

- Aggregate interlock joints; formed by sawing 1/4 - 1/3 of the way through the pavement to create a plane of weakness. A crack then propagates through the remaining thickness as the concrete contracts.
- This crack has a rough surface because it propagates around the aggregates through the green cement paste, and as long as it remains narrow load transfer from one slab to another is possible. Load transfer is compromised if the joint opens too widely or if the aggregates wear away.



Aggregate interlock joints

Ref: Norbert Delatte, Concrete pavement design, construction and performance

1. Jointed plain concrete pavement, cont'd

- Dowels are preferred if the pavement carries heavy vehicle traffic since aggregate interlock will break down over time. Dowels are smooth rods, generally plain or epoxy coated steel, which are usually greased or oiled on side to allow the joints to open and close without resistance.

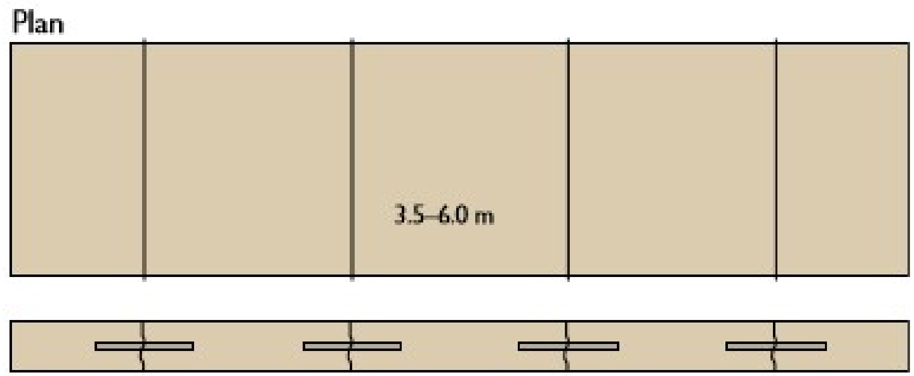


Figure 2.1 Jointed plain concrete pavement (JPCP) (courtesy: ACPA).

Dowels

Ref: Norbert Delatte, Concrete pavement design, construction and performance

1. Jointed plain concrete pavement, cont'd

- JPCP often use tie bars (deformed reinforcing steel) to connect adjacent traffic lanes.
- Key performance issues of JPCP include;
  - Inital pavement smoothness, which is a function of construction practices;
  - Adequate pavement thickness to prevent mid-slab cracking
  - Limiting the joint spacing, also to prevent mid-slab cracking; and
  - Adequate joint design, detailing, and construction

Ref: Norbert Delatte, Concrete pavement design, construction and performance

2. Jointed reinforced concrete pavement (JRCP)

- slabs from 7.5 to 9 m with light reinforcement
- Slab reinforcement content is in the range of 0.1 – 0.25 % of the cross sectional area in the longitudinal direction with less reinforcement in the transverse direction.
- Reinforcement is placed at the mid-point of the slab it has no effect on the flexural performance of concrete and serves only to keep cracks together.
- JRCP is not used as common as JPCP since costs are higher and advantages over JPCP is limited.

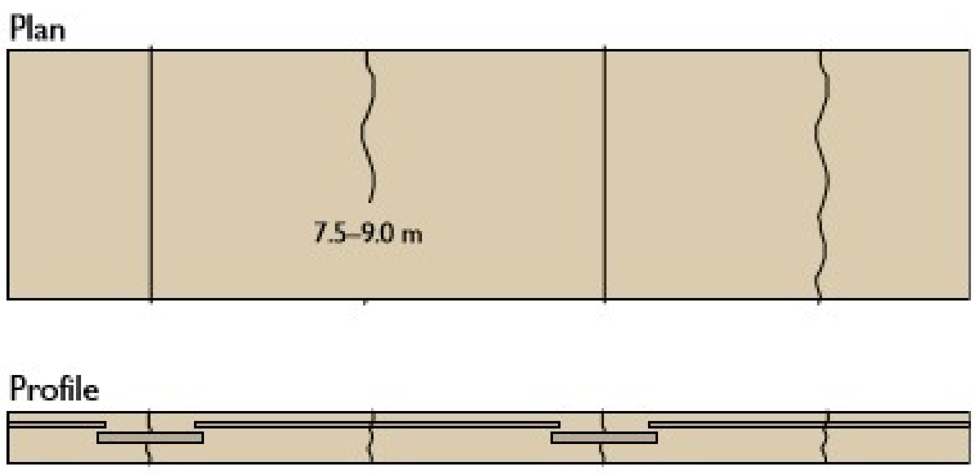


Figure 2.2 Jointed reinforced concrete pavement (JRCP) (courtesy: ACPA).

Ref: Norbert Delatte, Concrete pavement design, construction and performance

3. Continuously reinforced concrete pavement

- Characterized by heavy steel reinforcement (on the order of 0.4 – 0.8 by volume) and an absence of joints.
- Cracks form in CRCP approximately 0.6 – 2 m apart. The reinforcement holds the cracks tightly together and provides for aggregate interlock and shear transfer.
- CRCP costs more than JRCP because of the steel reinforcement, and is thus used less frequently. It provides a smoother ride and a longer life than any other type of pavement.
- Key performance considerations;
  - Initial pavement smoothness
  - Adequate pavement thickness to prevent excessive transverse cracking; and
  - Adequate reinforcing steel to hold cracks together and prevent punchouts. Punchouts are a distress mechanism distinct to CRCP.

Ref: Norbert Delatte, Concrete pavement design, construction and performance

4. Roller compacted concrete

- Very dry concrete mixture, delivered by dump trucks, placed into an asphalt paver and then rolled with steel rollers. The RCC is then cured. The pavement may be allowed to crack naturally, or joints may be cut. Because RCC shrinks less than conventional concrete, the joints or cracks are further apart than those for JPCP.
- Surface of concrete is rough due to construction process which are not suitable for high speed traffic.
- Very economical to construct. Compared to JPCP pavements, RCC pavements do not require forms, dowels or tie bars, or labor for texturing and finishing, so construction costs are lower. Maintenance costs also tend to be lower than other pavement types.

Ref: Norbert Delatte, Concrete pavement design, construction and performance

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Concrete pavements
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Brickwork and Blockwork (Masonry)

1. Introduction

Masonry;

- One of the oldest building material
- Used by mankind for more than 6000 years
- Ancient civilizations of Middle East, Greeks and Romans used masonry
- Many of mudbrick work has been lost. However, stone structures such as Egyptian pyramids, Greek temples and many structures from fired clay bricks have survived for thousands of years
- The Romans used both fired clay bricks and hydraulic mortar

2. Main techniques

There are four main techniques for achieving stable masonry

a) **Dry stone walls:** Irregularly shaped laminar pieces are placed by hand in an interlocking mass

b) **Ashlar:** Medium to large blocks are made to a few sizes and assembled to a basic grid pattern either without or with mortar having very thin joints

c) **Normal brickwork:** Small to medium units of different sizes are assembled to a basic grid pattern and mortar is used as a packing material

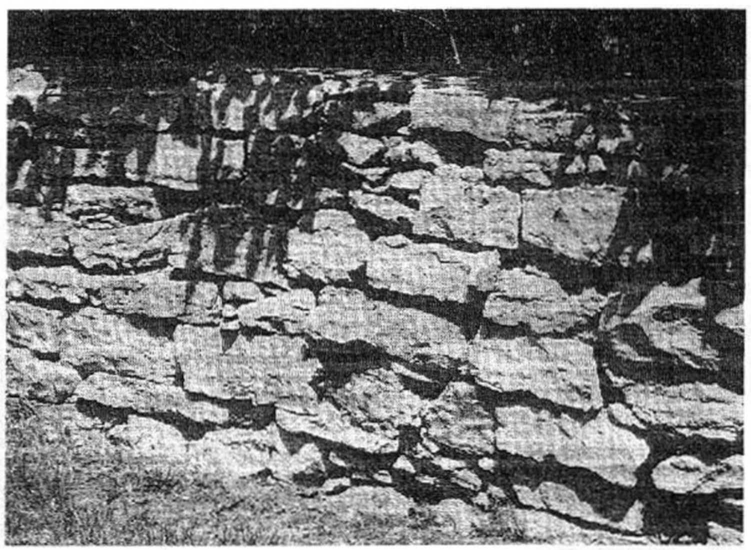
d) **Random rubble walls:** Irregularly shaped and sized pieces are bonded together with adherent mortar

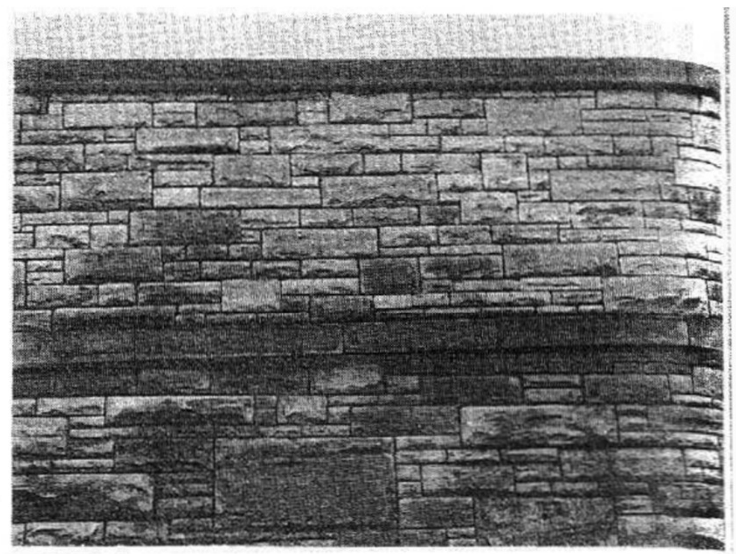
2. Main techniques, cont'd

There are four main techniques for achieving stable masonry

a) Dry stone walls:
Irregularly shaped laminar pieces are placed by hand in an interlocking mass

b) Ashlar: Medium to large blocks are made to a few sizes and assembled to a basic grid pattern either without or with mortar having very thin joints

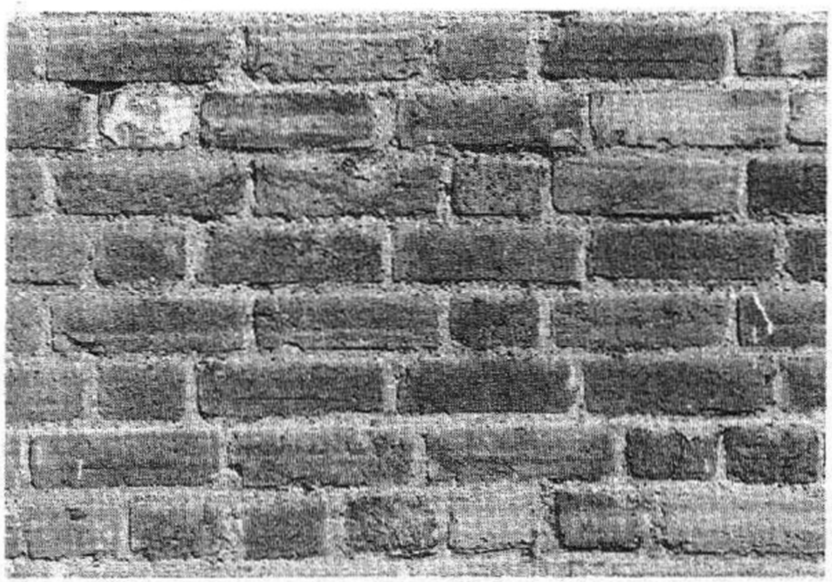


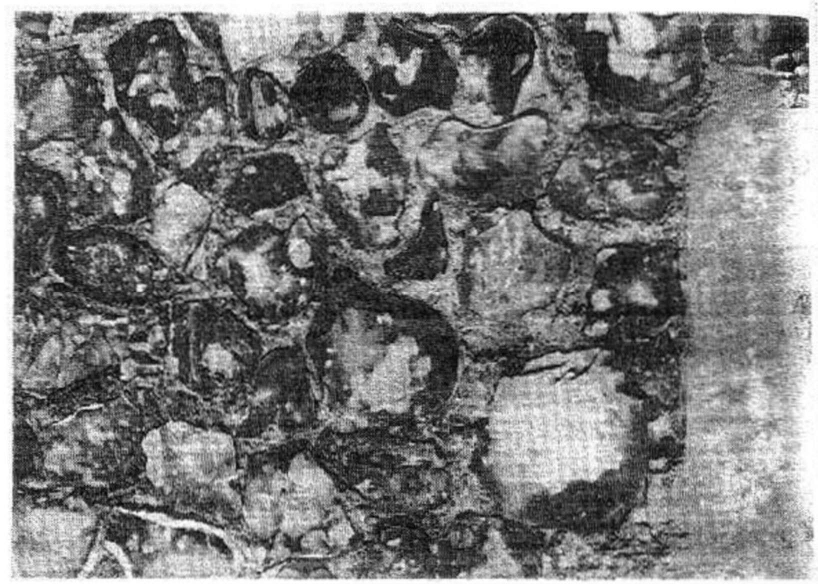


2. Main techniques, cont'd

c) Normal brickwork: Small to medium units of different sizes are assembled to a basic grid pattern and mortar is used as a packing material

d) Random rubble walls: Irregularly shaped and sized pieces are bonded together with adherent mortar





3. Materials

Sand: Particles with sizes from about 10mm diameter down to 75μm diameter. Sand should be free of clay particles.

Aggregates: Natural aggregates, sintered fly ash pellets, expanded clay and foamed slag

Binders: Binds mixtures of sands, aggregates, fillers to make mortar for masonry

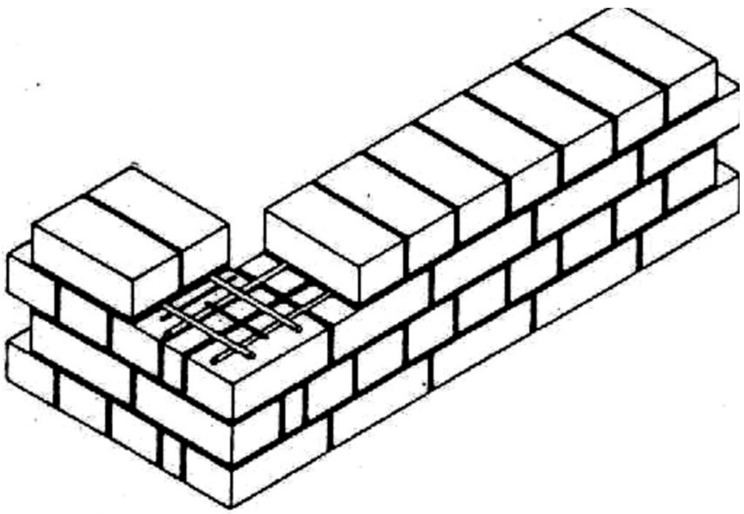
4. Masonry construction

Basic method of construction; units are laid one on top of another in such a way that they form an interlocking mass in at least the two horizontal dimensions

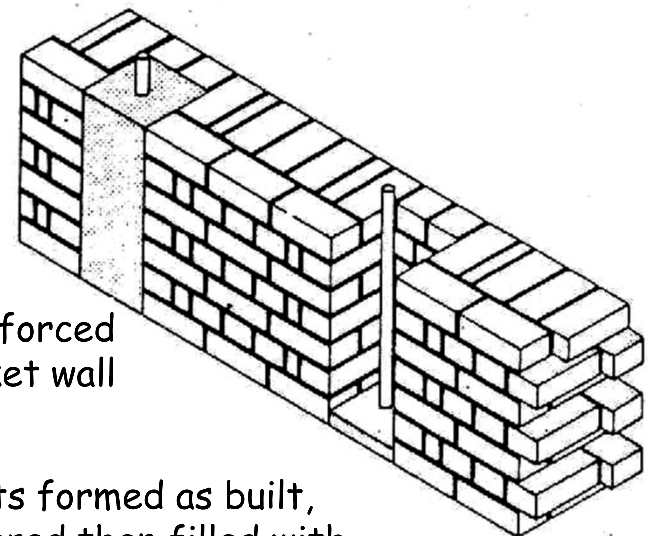
- Mortar needs to be firmly dry for dense low absorption units. While high absorption units need a sloppy wet mortar
- Walls and columns are built by laying out a plan at foundation level and masonry rises up layer by layer
- The foundation layers are horizontal
- It is essential to maintain the verticality
- Thickness of mortar joints must be kept constant
- Joint color and shape influence the appearance

4. Masonry construction, cont'd

Reinforced and post-stressed masonry forms



(a)

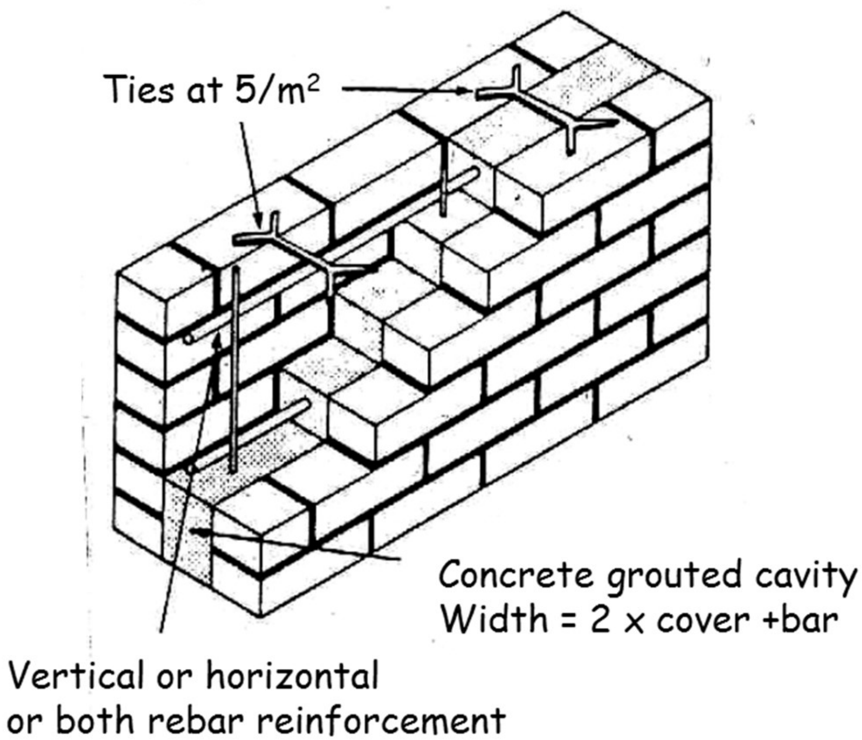


(b)

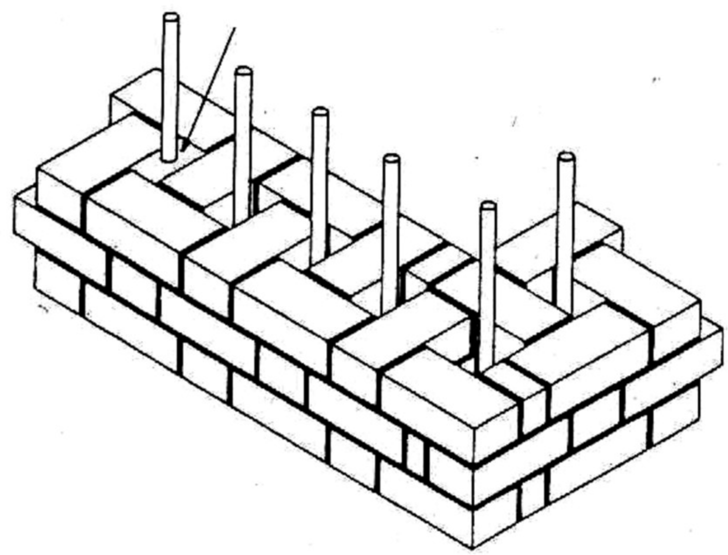
(a) Bed joint reinforced
(b) Reinforced pocket walls

4. Masonry construction, cont'd

Reinforced and post-stressed masonry forms



(c)



(d)

(c)Grouted cavity
(d)Quetta bond

5. Structural behavior, cont'd

Unreinforced masonry is;

- good at resisting compression forces,
- moderate to bad at resisting shear forces
- very poor when subjected to direct tension

However, reinforced masonry is good also at resisting tension forces

Any masonry under compressive stress also resists bending since the compressive prestress in the wall must be overcome before any tensile strain can occur

Most of small masonry structures are still designed using experience-based design rules. Strength of masonry elements are predicted from strength and/or other characteristics of materials used in masonry construction

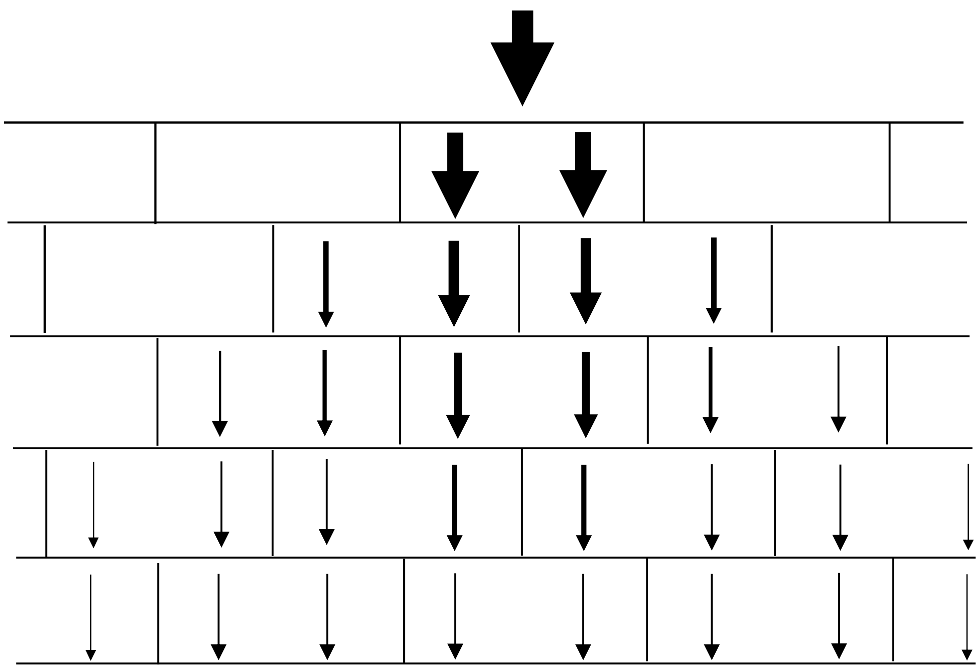
Then check is made against worst loading conditions obtained from past data. A factor of safety is applied to allow for statistical uncertainty in the material characteristics and loads. Relatively high (3-5) safety factors are used due to high variability and brittle failure mode

5. Structural behavior, cont'd

Compressive loading

Masonry is most effective under compressive load

If a load or force is put on a wall at a point, it would spread or toward from the point of application since each unit is supported by the two units below it.



Such a compressive force causes elastic shortening (strain) of the masonry. As a result of Poisson's ratio effects, a tension strain and hence a stress is generated normal to the applied stress.

Regulatory framework in Türkiye

Masonry construction in Türkiye is governed by three interacting layers:

- Structural design codes (earthquake & structural safety) – Türkiye Bina Deprem Yönetmeliği (TBDY 2018)
- Material and workmanship standards (TS /TS EN)
- Implementation regulations (Ministry rules & specifications)

For new buildings, earthquake regulations are the primary consideration.
For existing masonry buildings, assessment and strengthening rules are critical.

Primary Structural & Earthquake Codes
Türkiye Bina Deprem Yönetmeliği (TBDY 2018)

- Includes:
  - Unreinforced masonry
  - Confined masonry
  - Reinforced masonry

Key masonry-related content

- Permitted masonry systems
- Wall thickness limits
- Height & storey limits
- Material strength requirements
- Seismic performance levels
- Assessment & retrofit of existing masonry buildings

TBDY 2018 is **the controlling document**.
Even if EN standards are used for materials, **design must comply with TBDY**.

TBDY 2018 – Chapter 11 (Masonry)

Scope:

- Load-bearing masonry walls
- In-plane and out-of-plane behavior
- Shear, compression, and tensile checks

Masonry Material Standards (TS / TS EN)

STANDARD		UNIT TYPE
TS EN 771-1		Clay masonry unit (bricks)
TS EN 771-2		Calcium silicate units
TS EN 771-3		Aggregate concrete blocks
TS EN 771-4		Autoclaved aerated concrete (AAC)
TS EN 771-5		Manufactured stone units
TS EN 771-6		Natural stone units

TS EN 772 Series – Methods of test for masonry units

1. Mechanical Properties	
TS EN Standard	Test
TS EN 772-1	Determination of compressive strength
TS EN 772-6	Determination of bending tensile strength of aggregate concrete units
TS EN 772-7	Determination of shear bond strength

TS EN 772 Series – Methods of test for masonry units

2. Physical Properties	
TS EN Standard	Test
TS EN 772-11	Water absorption of aggregate concrete, AAC, manufactured stone
TS EN 772-13	Dry density and apparent density
TS EN 772-14	Moisture movement (mainly clay units)
TS EN 772-16	Dimensions, shape and surface features
TS EN 772-18	Determination of shell and web thickness
TS EN 772-21	Water absorption by capillarity (clay units)

TS EN 772 Series – Methods of test for masonry units

3. Durability & Environmental Resistance	
TS EN Standard	Test
TS EN 772-22	Freeze–thaw resistance
TS EN 772-19	Moisture expansion (clay masonry units)
4. Geometrical & Structural Characteristics	
TS EN Standard	Test
TS EN 772-20	Flatness of faces
TS EN 772-25	Determination of shell and web geometry (advanced block characterization)
5. Special / Less Common Tests	
TS EN Standard	Test
TS EN 772-3	Net and gross volume and percentage of voids
TS EN 772-4	Real and bulk density (superseded in practice by 772-13 but still referenced)

Masonry mortars

Mortar for masonry – TS EN 998-2

Characteristics of fresh mortar

- Workable life
- Chloride content
- Air content

Masonry mortars

Mortar for masonry – TS EN 998-2

Characteristics of hardened mortar

- Compressive strength
- Bond strength
- Water absorption
- Water vapour permeability
- Density
- Thermal conductivity
- Durability
- Reaction to fire

Masonry mortars

5.4.1 Compressive strength

For designed mortars, the compressive strength of masonry mortar shall be declared by the manufacturer. The manufacturer may declare, alternatively or as supplement, the compressive strength class in accordance with Table 1, where the compressive strength is designated by an 'M' followed by the compressive strength class in N/mm^2, which it exceeds.

Table 1 — Mortar classes

Class	M 1	M 2,5	M 5	M 10	M 15	M 20	M d
Compressive strength N/mm^2	1	2,5	5	10	15	20	d
d is a compressive strength greater than 20 N/mm^2 as a multiple of 5 declared by the manufacturer.							

When the masonry mortar is sampled in accordance with EN 1015-2 and tested in accordance with EN 1015-11, the compressive strength shall not be less than the declared compressive strength or the declared compressive strength class. The declaration shall be followed by information on the test sample preparation used (with or without absorbent filter paper).

TS EN 1015 Series – Methods of tests for mortar masonry

1. Tests on Fresh Mortar	
TS EN Standard	Test
TS EN 1015-1	Determination of particle size distribution (by sieve analysis)
TS EN 1015-2	Bulk sampling of mortar
TS EN 1015-3	Determination of consistence (flow table method)
TS EN 1015-4	Determination of consistence (plunger penetration method)
TS EN 1015-5	Determination of bulk density of fresh mortar
TS EN 1015-6	Determination of bulk density of hardened mortar
TS EN 1015-7	Determination of air content of fresh mortar
TS EN 1015-8	Determination of retained water
TS EN 1015-9	Determination of workable life (pot life)

TS EN 1015 Series – Methods of tests for mortar masonry

2. Tests on Hardened Mortar	
TS EN Standard	Test
TS EN 1015-10	Determination of dry bulk density of hardened mortar
TS EN 1015-11	Determination of flexural and compressive strength
TS EN 1015-12	Determination of adhesive strength (bond to substrate)
TS EN 1015-18	Determination of water absorption by capillary action
TS EN 1015-19	Determination of water vapour permeability
TS EN 1015-21	Determination of compatibility with substrates

TS EN 1015 Series – Methods of tests for mortar masonry

3. Durability & Volume Stability	
TS EN Standard	Test
TS EN 1015-13	Determination of shrinkage and expansion
TS EN 1015-16	Determination of resistance to freeze–thaw cycles
TS EN 1015-17	Determination of water-soluble chloride content
TS EN 1015-20	Determination of water absorption due to capillary action (alternative method / specific applications)

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Concrete pavements
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter outline

Polymers and polymer composites

1) Introduction
2) Fibers for polymer composites
3) Mechanical properties
4) Fiber – reinforced polymer composites
5) Analysis of the behavior of fiber-reinforced polymer composites
6) Durability of polymer composites
7) Applications of polymers and polymer composites

Polymers and polymer composites
1. Introduction

Polymeric materials

produced by combining a large number of small molecular units (monomers) by polymerization to form long chain molecules

i. Thermoplastic polymers

Long chain molecules held together by weak Van der Waals forces. Cycle of softening by heating and hardening by cooling can be repeated almost indefinitely. However, with each cycle, the material tends to become more brittle

ii. Thermosetting polymers

Epoxies and phenolics are principle examples, cross linking exists between chains

iii. Elastomers

Long-chain polymer molecules made of coiled and twisted chains. Flexible material that undergoes very large deformations. Vulcanization provides rigidity and hardness.

2. Fibers for polymer composites

Load transfer from matrix to fibers results in high-strength, high-modulus material. Glass, carbon, boron fibers are examples of amorphous and crystalline fibers used in polymeric matrices.

a) Glass fibers
b) Carbon fibers
c) Aramid fibers

3. Mechanical properties, cont'd

Mechanical properties of common thermosetting and thermoplastic polymers

	Specific weight	Ultimate tensile strength (MPa)	Modulus of elasticity in tension, GPa	Coefficient of linear expansion $10^{-6}/^{o}C$
Thermosetting				
Polyester	1.28	45 – 90	2.5 – 4.0	100 – 110
Epoxy	1.30	90 – 110	3.0 – 7.0	45 – 65
Phenolic	1.35 - 1.75	45 – 59	5.5 – 8.3	30 – 45
Thermoplastics				
Polyvinylchloride (PVC)	1.37	58.0	2.4 – 2.8	50
Acrylonitrile butadiene styrene (ABS)	1.05	17 – 62	0.69 – 2.82	60 – 130
Nylon	1.13 – 1.15	48 – 83	1.03 – 2.76	80 – 150
Polyethylene (high-density)	0.96	30 - 35	1.10 – 1.30	120

3. Mechanical properties, cont'd

Fiber properties

Composite materials have high specific strength and high specific stiffness achieved by the use of low-density fibers with high strength and modulus values

	Specific weight	Ultimate tensile strength (GPa)	Modulus of elasticity in tension, (GPa)
Carbon fiber			
Type I	1.92	2.00	345
Type II	1.75	2.41	241
Type III	1.70	2.21	200
E – Glass	2.55	2.40	72.4
S2 – Glass fiber	2.47	4.6	88.0
Kevlar fibers			
29	1.44	2.65	64
49	1.45	2.65	127

4. Fiber-reinforced polymer composites

Mechanical properties of polymers can be greatly enhanced by incorporating fillers and/or fibers into resin formulations

For structural applications, such composites should

1) Consist of two or more phases
2) Be manufactured by combining separate phases such that dispersion of one material in the other achieves optimum properties of the resulting material
3) Have enhanced properties composed with those of individual components

5. Analysis of the behavior of fiber-reinforced polymer composites

i. In fiber-reinforced polymer materials, fiber uses plastic flow of the polymer to transfer load to fiber. This results in a high-strength, high-modulus composite.
ii. High strength and high modulus properties of fibers are associated with very fine fibers with diameters of 7-15μm.
iii. Fibers are usually brittle.
iv. Polymers may be ductile or brittle and generally have low strength and stiffness
v. By combining two components a bulk material is produced with a strength and stiffness dependent on fiber volume fraction and fiber orientation.
vi. Interface between fiber and matrix plays a major role in physical and mechanical properties of composite material
vii. Load is transferred from fiber to fiber through the interface and the matrix

5. Analysis of the behavior of fiber-reinforced polymer composites

Assumptions made

i. The matrix and the fiber behave as elastic materials
ii. Bond between fiber and matrix is perfect and consequently there will be no strain discontinuity across the interface
iii. Fibers are arranged in a regular or repeating array

Properties of interface region are very important for fracture toughness of the material

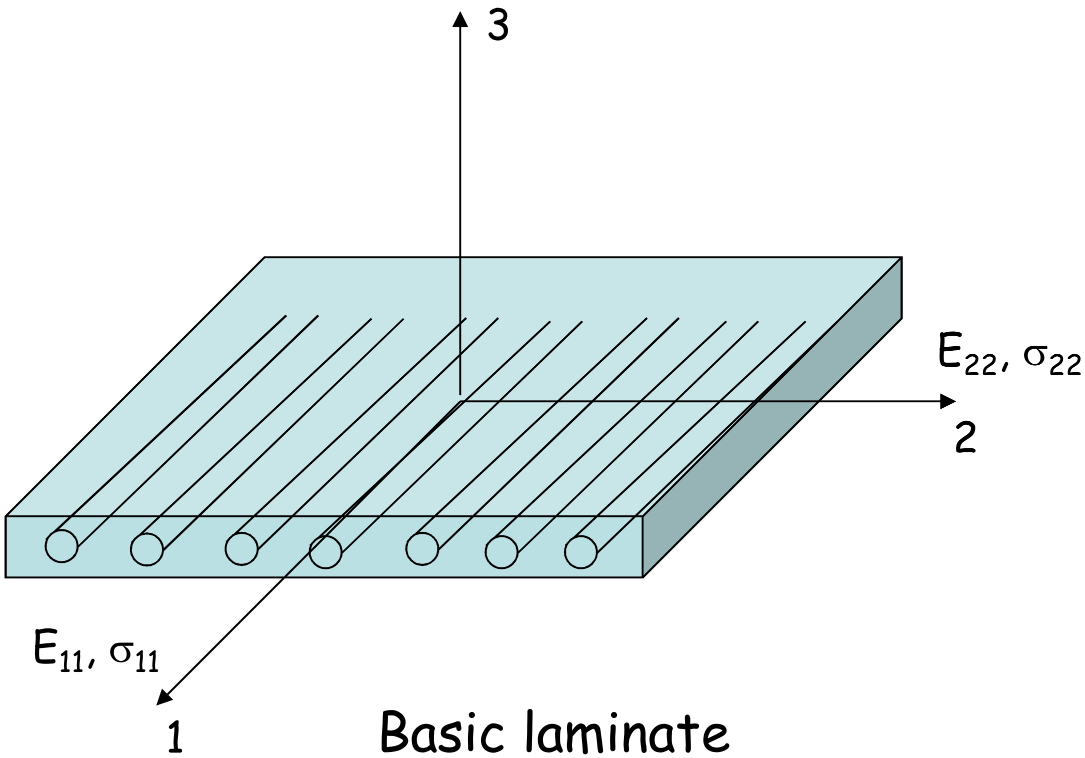
Weak interface → low strength and stiffness → high resistance to fracture (ductile)

Strong interface → high strength and stiffness → low fracture toughness (very brittle)

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Moduli of a continuous fiber reinforced lamina

i. Longitudinal stiffness
ii. Transverse stiffness



Basic laminate

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Moduli of a continuous fiber reinforced lamina

i) Longitudinal stiffness (longitudinal modulus)

The orthotropic layer has three mutually perpendicular plane of property symmetry, characterized elastically by four independent elastic constants.

$\mathbf{E_{11}}$= modulus of elasticity along fiber direction

$\mathbf{E_{22}}$= modulus of elasticity in the transverse direction

ν_{12} = Poisson's ratio i.e. strains produced in direction 2 when specimen is loaded in direction 1.

$\mathbf{G_{12}}$= longitudinal shear modulus

ν_{21} = Poisson's ratio, i.e. obtained from $E_{11}\,\nu_{21} = E_{22}\,\nu_{12}$

If line of action of a tensile or compressive force is applied parallel to fibers of a unidirectional lamina,

$\varepsilon_m = \varepsilon_f$ provided bond is perfect

As both fiber and matrix behave elastically then

$\sigma_f = E_f\,\varepsilon_f$ and $\sigma_m = E_m\,\varepsilon_m$ where $\varepsilon_f = \varepsilon_m$

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Moduli of a continuous fiber reinforced lamina

i) Longitudinal stiffness (longitudinal modulus)

Composite load $P_c = P_m + P_f$

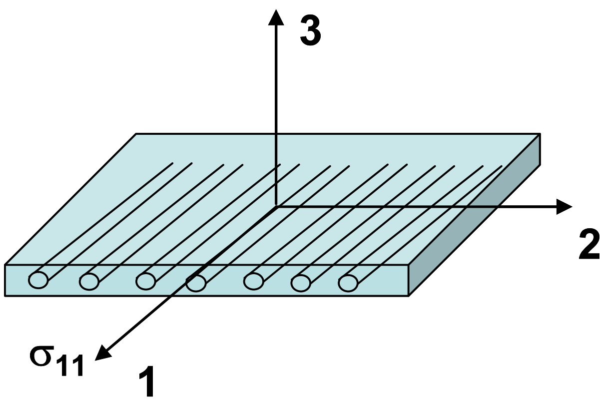
$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$

$\sigma_c = \sigma_m V_m + \sigma_f V_f$

where **A** = area of the phase

V = volume fraction of the phase

$\mathbf{V_c}$ = volume of composite = 1



for perfect bond

$\varepsilon_c = \varepsilon_m = \varepsilon_f$

From above equation

$E_c \varepsilon_c = E_m \varepsilon_c V_m + E_f \varepsilon_c V_f$

$E_c = E_m V_m + E_f V_f$

$E_c = E_{11} = E_m (1 - V_f) + E_f V_f$ (law of mixtures)

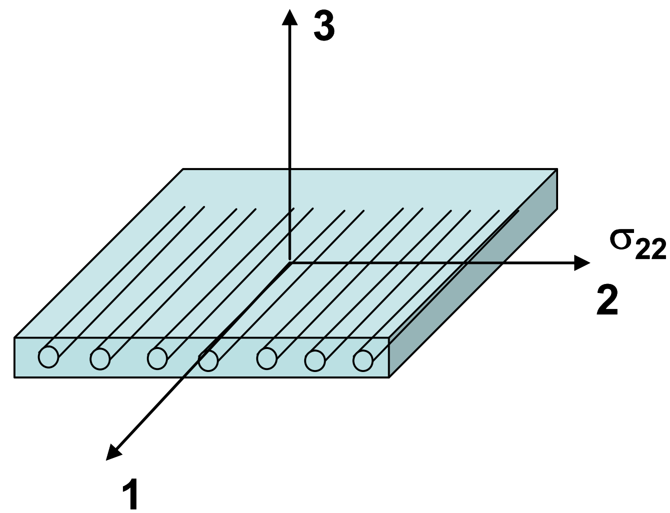
5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Moduli of a continuous fiber reinforced lamina

ii) Transverse stiffness (transverse modulus)

Applied load transverse to fibers acts equally on fiber and matrix; therefore,

$\sigma_f = \sigma_m$



$\varepsilon_f = \sigma_{22}/E_f$ and $\varepsilon_m = \sigma_{22}/E_m$

$\varepsilon_{22} = V_f\,\varepsilon_f + V_m\,\varepsilon_m$ or

$\varepsilon_{22} = V_f\,\sigma_{22}/E_f + V_m\,\sigma_{22}/E_m$

(substitute $\sigma_{22} = E_{22}\varepsilon_{22}$)

$E_{22} = E_f\,E_m / [\,E_f\,(1-V_f) + E_m V_f\,]$

to take into account of Poisson contraction effects

$$E_{22} = E_m`Ef / [\,E_f\,(1 - V_f) + E_m`V_f\,]$$

where $E_m` = Em / (1-\nu_m^2)$

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

<u>Assumptions made</u>

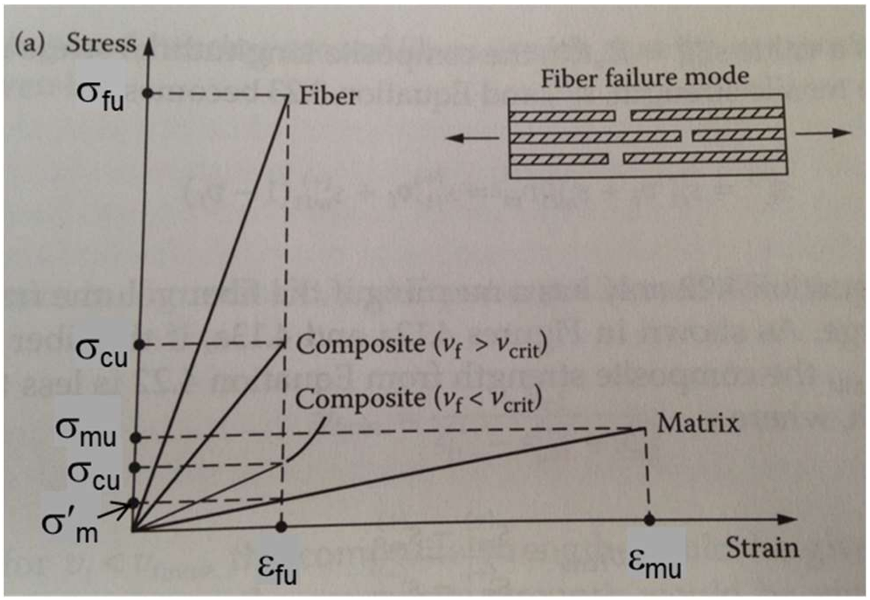
- Equal strengths in all fibers
- Linear elastic behavior up to failure
- Equal longitudinal strains in composite, fiber and matrix

Ref; Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

Case I – Matrix failure strain greater than fiber failure strain



σ_{fu} : strength of fiber
σ_{cu} : strength of composite
σ_{mu} : strength of matrix
σ'_{m} : stress in the matrix when fibers reach their strength

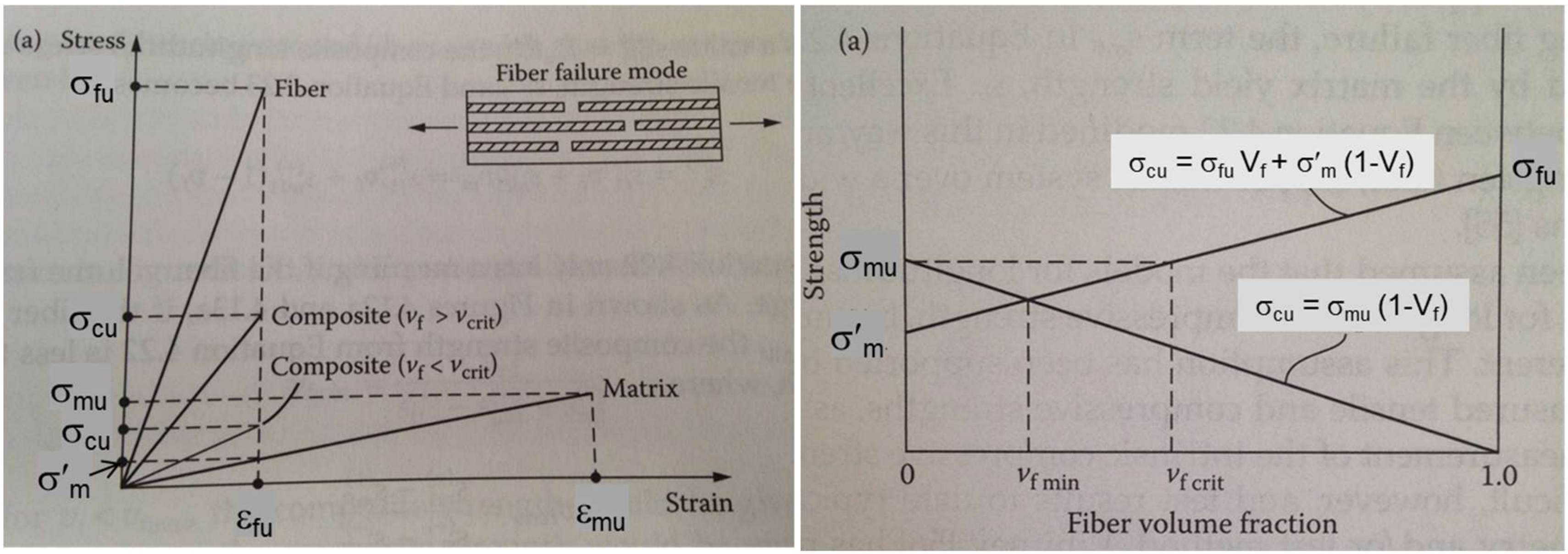
Composite must fail at a strain level corresponding to the fiber tensile failure strain;
$\varepsilon_{fu} = \sigma_{fu}/E_f$

Ref; Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

Case I – Matrix failure strain greater than fiber failure strain



Composite must fail at a strain level corresponding to the fiber tensile failure strain; $\varepsilon_{fu} = \sigma_{fu}/E_f$

Ref; Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

Case I – Matrix failure strain greater than fiber failure strain, cont'd

Fiber controlled failure

$\sigma_{cu} = \sigma_{fu} V_f + \sigma'_m (1 - V_f)$ - valid when $V_f > V_{min}$

Matrix controlled failure

$\sigma_{cu} = \sigma_{mu} (1 - V_f)$– valid when $V_f < V_{min}$

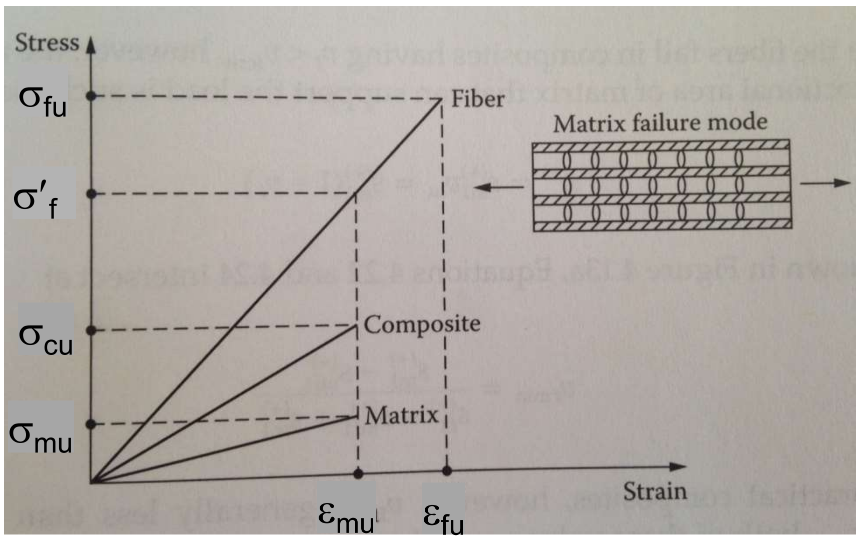
$$V_{crit} = \frac{\sigma_{mu} - \sigma'_m}{\sigma_{fu} - \sigma'_m} \qquad V_{\min} = \frac{\sigma_{mu} - \sigma'_m}{\sigma_{fu} + \sigma_{mu} - \sigma'_m}$$

Ref; Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

Case II – Fiber failure strain greater than matrix failure strain



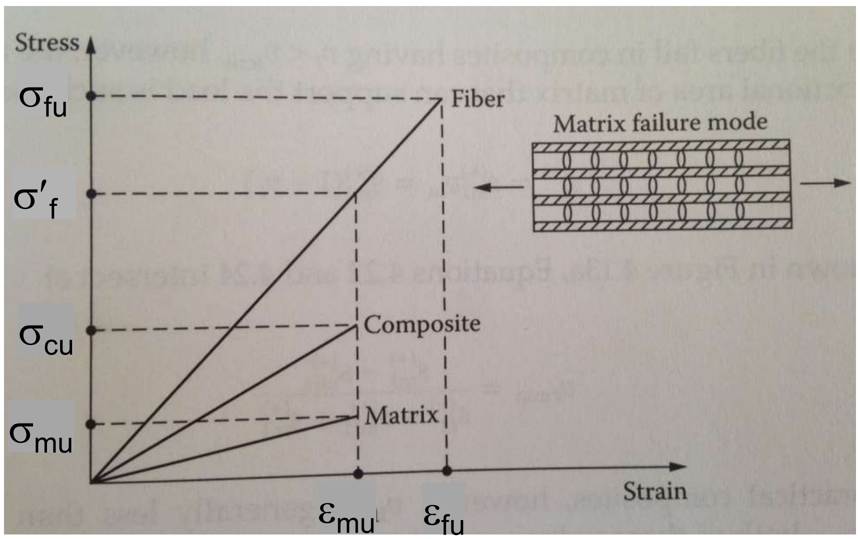
σ_{fu} : strength of fiber
σ_{cu} : strength of composite
σ_{mu} : strength of matrix
σ'_f : stress in the fiber when matrix reach its strength

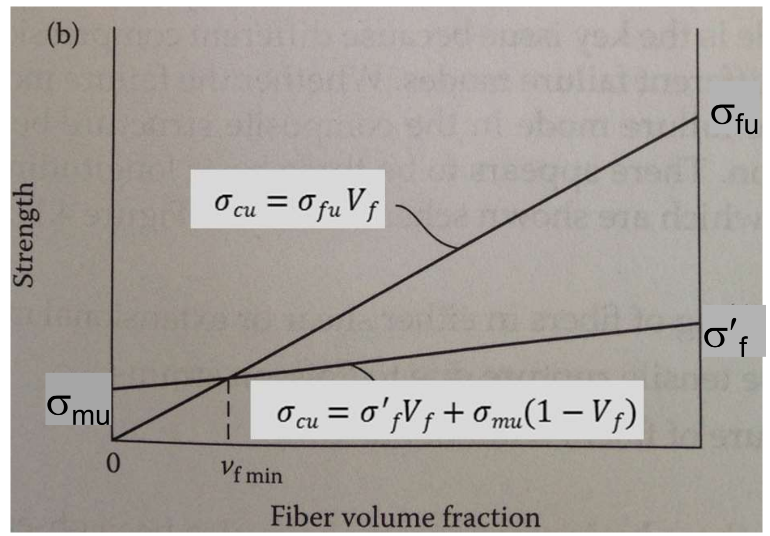
Ref; Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

Case II – Fiber failure strain greater than matrix failure strain





Ref; Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

5.1. Strength of a continuous fiber reinforced lamina (longitudinal tensile strength)

Case II – Fiber failure strain greater than matrix failure strain

$\sigma_{cu} = \sigma_{fu} V_f$ - valid when $V_f > V_{min}$

$\sigma_{cu} = \sigma'_f V_f + \sigma_m (1 - V_f)$ – valid when $V_f < V_{min}$

$$V_{\min} = \frac{\sigma_{mu}}{\sigma_{fu} + \sigma_{mu} - \sigma'_f}$$

Ref: Ronald F. Gibson, Principles of Composite Material Mechanics, 3rd Edition, 2012

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

5.2.1. Effect of fiber length

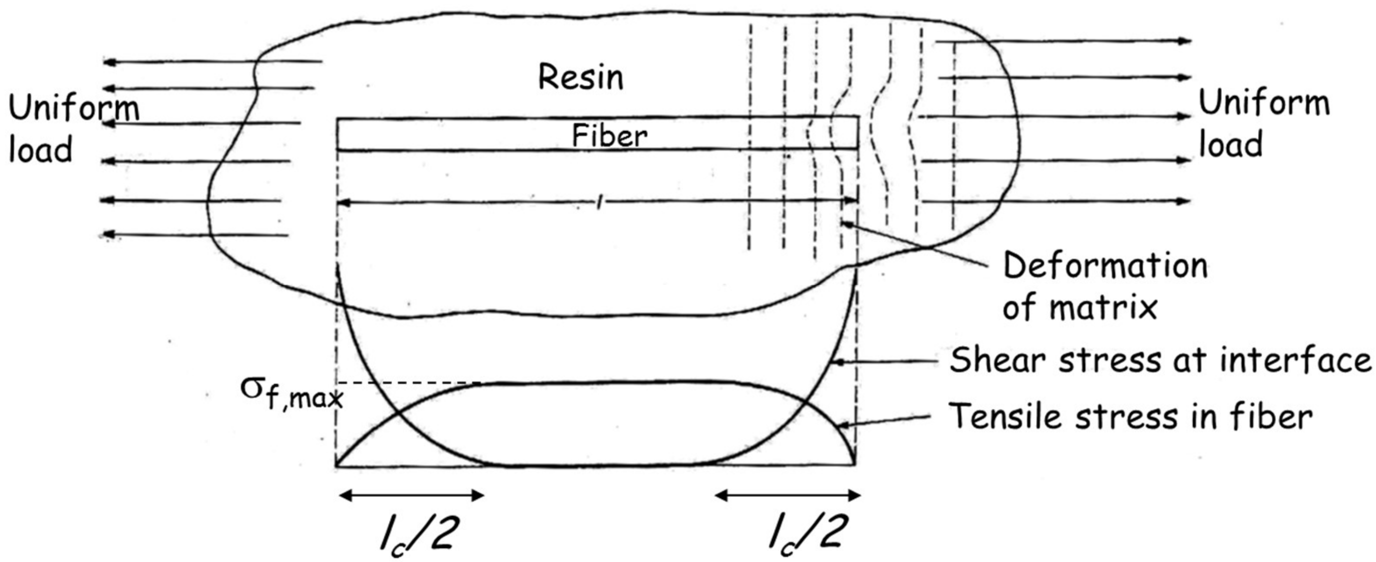
- As aspect ratio (l/d) decreases, effect of fiber length becomes more significant
- When a composite containing uniaxially aligned discontinuous fibers is stressed in tension parallel to the fiber direction there is a portion at the end of each finite fiber length and in surrounding matrix where stress and strain fields are modified by discontinuity
- Efficiency of the fiber to stiffen and to reinforce the matrix decreases as the fiber length decreases

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

5.2.1. Effect of fiber length

Diagrammatic representation of the deformation field around a discontinuous fiber embedded in a matrix



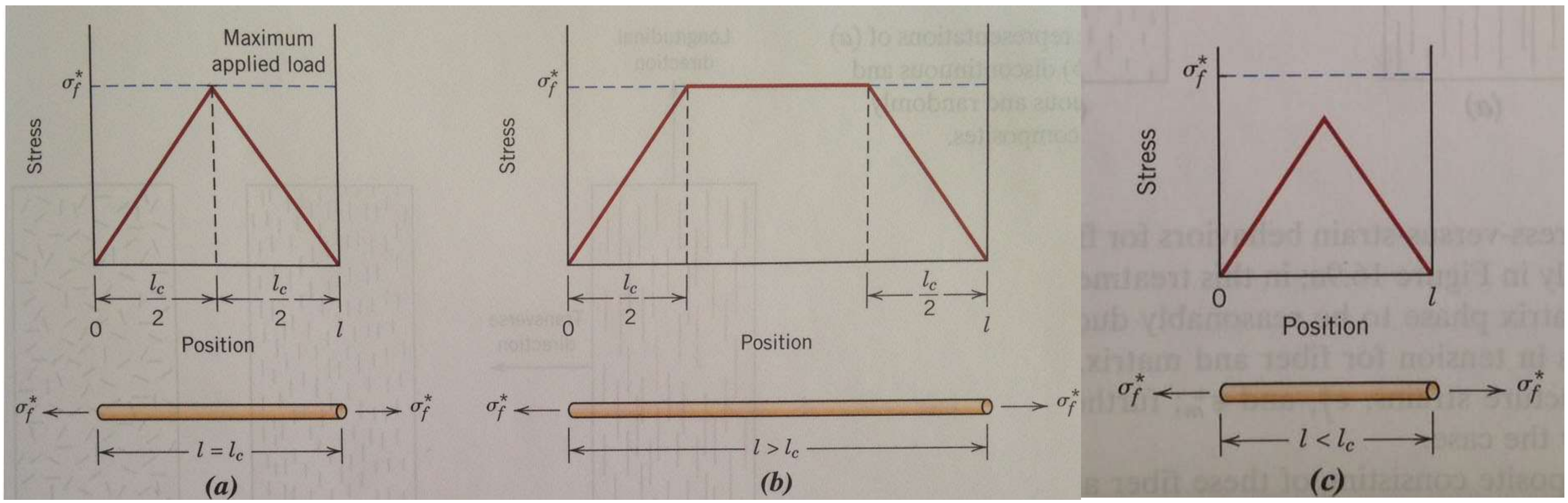
The critical transfer length over which fiber stress is decreased from maximum to zero at the end of fiber is referred to as half the critical length of fiber.

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

5.2.1. Effect of fiber length

Some critical fiber length is necessary for effective strengthening and stiffening of the composite material.



(Stress distributions for different values of fiber length, *l*)

$$l_c = \frac{r\sigma_{fu}}{\tau_{my}}$$

σ_{fu} or σ^*_f : ultimate fiber strength
r: radius of fiber
τ_{my}: shear stress at the interface

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

5.2.1. Effect of fiber length

- $l < l_c$ → maximum fiber load is not achieved
- $l = l_c$ → maximum fiber load is achieved only at the axial center of fiber
- $l > l_c$ → effectiveness of fiber reinforcement increases

If $l > 15l_c$ → fibers are termed to be continuous

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

5.2.2. Effects of fiber orientation and volume

- Reinforcing efficiency of short fibers is less than that for long fibers. Orientation of short fibers in a lamina is random and therefore lamina is assumed to be isotropic on a macro scale.
- Rule of mixture for long-parallel fiber case is modified by inclusion of a fiber orientation distribution factor n

$$E_c = E_{11} = \eta E_f V_f + E_m V_m$$

η = 0.375 for a randomly oriented fiber array

= 1.0 for unidirectional laminae when tested parallel to fiber

= 0 for unidirectional laminae when tested perpendicular to fiber

= 0.5 for a bidirectional fiber array

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

$$l_c = \frac{r\sigma_{fu}}{\tau_{my}} \quad \text{and} \quad \alpha = \frac{l}{l_c}$$

for which tensile strength in the fiber will be reached at the same force as the yield strength of matrix on the interface

If $\alpha > 1$, then matrix will yield first before fiber breaks in tension

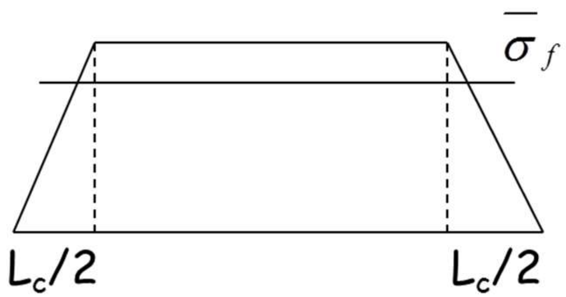
5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a <u>discontinuous</u> fiber reinforced lamina (longitudinal tensile strength)

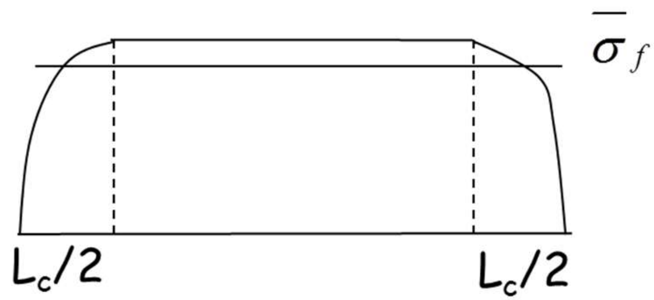
Average value of tensile stress in the fiber is found as

$$\bar{\sigma}_f = \sigma_f \left(1 - \frac{1-\beta}{\alpha}\right) \qquad \frac{\bar{\sigma}_f}{\sigma_f} = \eta = \text{fiber efficiency factor}$$

where β is related to stress distribution on fiber.
β= 0.5 for fully plastic stress distribution
β = 1.0 for fully elastic distribution



For elastic fibers in fully plastic matrix β = 0.5



For elastic fibers in an ideal elastic matrix $\beta \cong 1$

β = ratio of the area under the stress distribution curve over the length Lc/2 to the area of a rectangle represented by the product of σ_{fu} and Lc/2.

5. Analysis of the behavior of fiber-reinforced polymer composites

5.2. Strength of a discontinuous fiber reinforced lamina (longitudinal tensile strength)

$$\sigma_{cu_d} = \sigma_{fu} V_f \left(1 - \frac{1-\beta}{\alpha}\right) + \sigma'_m (1 - V_f) \quad \text{for } V_f > V_{min}$$

If $\alpha > 5$ and $\beta = 0.5$ then $\dfrac{\sigma_{cu_d}}{\sigma_{cu}} \geq 0.9$

If fibers are not too short, their discontinuity may be neglected

Example 1

Properties of matrix and fiber materials for a glass fiber reinforced composite with continuous fibers of 30% volume fraction are as follows

	E (GPa)	σ_{fu} (MPa)	ε_u
Polymer matrix	**2**	**200**	**0.10 (yield)**
Glass fibers	**140**	**2800**	**0.02**

a) Determine the modulus of elasticity of the composite for tension parallel to fibers
b) Assuming linear elastic behavior both for fibers and the matrix, determine ultimate tensile strength of composite
c) What minimum fiber volume ratio should be used to obtain a reinforcing effect

Example 2

A glass fiber reinforced polymer composite is to be produced **(Final 2013)**.

Fibers: continuous and parallel, σ_{fu}=3000 MPa,

Matrix: σ_{mu} =176 MPa, $\sigma_{m'}$ = 66 MPa, ε_{my} = 0,08

a. Draw stress-strain diagram for fibers, polyester and resulting composite material (Show σ_{fu}, σ_{mu}, $\sigma_{m'}$, ε_{fu}, σ_{cu} on diagram).

b. Calculate the volume of fibers and matrix if the modulus of elasticity parallel to fibers is 31,5 GPa.

c. Based on the fiber volume ratio calculated in part b, state if the composite behaves in a fiber-controlled or matrix controlled manner. Find ultimate strength that can be achieved by using this composite material.

Important note: show **units** of all parameters used in calculations.

Example 3

Fiber reinforced composite will be used to make thin roof elements. short cut discontinuous fibers with a volume ratio of 15% is going to be used in design. Fiber efficiency factor is calculated to be 0.85. Both fibers and matrix show elastic behavior.

(Final, 2012).

σ_{fu} = 60 MPa, σ_{mu} = 8 MPa, E_f = 60 GPa, ε_{my} = $1.3*10^{-3}$

a) Draw stress-strain diagrams for fiber, matrix and the composite
b) Calculate the minimum and critical fiber volume ratios and indicate their respective roles on the mechanical behavior of the composite
c) Determine the mode of failure and calculate strength of the composite

6. Durability of polymer composites

Polymer composites change with time and most significant factors are

- Elevated temperatures
- Fire
- Moisture
- Adverse chemical environments
- Natural weathering when exposed to sun's ultra-violet radiation

6. Durability of polymer composites, cont'd

Temperature

- Fluctuating temperatures have a greater deterioration effect on GRP. Difference in coefficients of thermal expansion of glass and resin may cause debonding.
- Exposed to high temperatures a discoloration of the resin may occur composite becoming yellow. Both polyester and epoxy show this effect. As a result of exposure to high temperatures, the composite becomes brittle.

Fire

- A composite material must meet appropriate standards of fire performance
- Some mineral filler, calcium carbonate can improve mechanical properties.

6. Durability of polymer composites, cont'd

Moisture

- Cross-linked polymers absorb water which may cause a decrease in strength and modulus of elasticity. Absorption of water by polyesters and epoxies leads to swelling of the laminate.
- Water will also cause some surface flaws on fibers and reduce strength, long-term water absorption may cause weakening of the bond between fiber and polymer

6. Durability of polymer composites, cont'd

Weather

- Natural weathering causes some deterioration of GRP composites. Sunlight degrades both polyester and epoxy resins. As a result of discoloration, loss of light transmission occur.
- UV absorbers and stabilizers are added to resin formulations. A rise of temperature accelerates chemical reaction and hence degradation.
- Weathering can affect mechanical properties of GRP composites through surface debonding.
- Because weathering is a surface effect, thickness of laminate becomes important. 3mm thick laminate shows 12-20% reduction in flexural strength after 15 years exposure, while 10mm laminate shows only ~ 3% reduction after 50 years exposure

7. Applications of polymers and polymer composites

- Use of polymers and polymer composites in construction industry falls into three categories;
  - Non - load - bearing
  - Semi - load – bearing
  - Load - bearing

Non - load - bearing and Semi - load – bearing → Unreinforced polymers

Load - bearing → Fiber – reinforced polymers

7. Applications of polymers and polymer composites, cont'd

Selection of most appropriate resin should be done considering particular end use since every material does not possess all the following characteristics

- High light transmission
- Infinite texture possibilities
- Minimum maintenance requirements
- Infinite design possibilities
- Resistance to water and corrosion
- High specific strength
- High impact resistance

7. Applications of polymers and polymer composites, cont'd

Disadvantages of polymers in construction are

- High cost of materials. However, low density and reduced foundation size make them competitive
- Low stiffness and strength (use in composites)
- Poor scratch resistance
- Degradation under UV light (stabilizers used)
- Low resistance to fire and high temperatures (additives used)

- *Non-load bearing thermoplastic polymers such as polyethylene have been used to manufacture pipes for transportation of water, oil and gas*

7. Applications of polymers and polymer composites, cont'd

- *Geosynthethics*
- *Marine applications*
- *Truck and automobile systems*
- *Aircraft and space applications*
- *Pipes and tanks for chemicals*
- *Civil engineering structures*

7. Applications of polymers and polymer composites, cont'd

Civil engineering structures

Applications have started with GRP structures

- A dome structure erected in 1968 in Benghazi, Libya
- Roof structure in Dubai Airport built in 1972
- 1970-1980 prestigious buildings in UK
  (Morpeth School, Mondial House, Covent Garden Flower Market etc.)

These buildings are built as a composite system, with either steel or reinforced concrete structural system and GRP composite as load-bearing infill panels.

In 1970, a classroom system, using only GRP, by folding flat plates into a folded plate system so that stiffness is provided by the structural shape.

In 1980's more ambitious structural elements were produced

7. Applications of polymers and polymer composites, cont'd

Mondial house (clad with FRP panels)

FRP radar dome (25m diameter, factory made FRP sandwich panels are bolted together on site)

FRP modular classroom

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Masonry
- Polymers and polymer composites
- Fiber – reinforced cement-based composites
- Metals
- Timber

Chapter outline

Fiber – reinforced cement-based composites

1) Introduction
2) Properties of the materials
3) Structure of fiber - matrix interface
4) Structure and post – cracking composite theory

Fiber – reinforced cement - based composites

1. Introduction

- Matrix : cement-based material (cement paste, mortar or concrete)
- Distributed phase : fibers

Brittle matrix + ductile fibers.

2. Properties of the materials

MATERİAL	Relative density	Diameter thickness ratio (microns)	Length (mm)	E (GPa)	Tens. Str. (MPa)	Failure strain (%)	Volume in composite (%)
Mortar matrix	1.8-2.0	300-5000	-	10-30	1-10	0.01-0.05	85-97
Concrete matrix	1.8-2.4	10000-20000	-	20-40	1-4	0.01-0.02	97-99.5
Asbestos	2.55	0.02-30	5-40	164	200-1800	2-3	5-15
Carbon	1.16-1.95	7-18	3-cont.	30-390	600-2700	0.5-2.4	3-5
Glass	2.7	12.5	10-50	70	600-2500	3.6	3-7
Polyethylene							
HDPE filament	0.96	900	3-5	5	200	-	2-4
High modulus	0.96	20-50	Cont.	10-30	> 400	> 4	5-10
Polypropylene (Monofilament)	0.91	20-100	5-20	4	-	-	0.1-0.2
Polyvinyl alcohol (PVA)	1-3	3-8	2-6	12-40	700-1500	-	2-3
Steel	7.86	100-600	10-60	200	700-2000	3-5	0.3-2.0

Performance is controlled by

- vol. fraction of fibers
- properties of fibers and matrix
- bond between the two

2. Properties of the materials, cont'd

- Table shows that elongations at break of all fibers are two or three orders of magnitude greater than strain at failure of matrix. Hence matrix cracks before fiber strength is approached.
- Most organic fibers have modulus of elasticity less than five times that of the matrix. Low modulus fibers are used in situations where matrix is expected to be uncracked. Large Poisson's ratio of these fibers may cause debonding and pull-out, woven meshes or networks of fibers are necessary for efficient composites.
- Steel fibers of varying cross-sections or bond ends provide anchorage; glass fiber bundles may be penetrated with cement hydration products to give effective bonding.

D_{max} of mortars or concrete affect efficient fiber distribution

Concrete with a D_{max} = 10mm is preferred.

D_{max} > 20mm is never allowed.

To avoid shrinkage, at least 50% by volume of inert filler (aggregate, fly ash, or limestone dust) should be used

3. Structure of fiber – matrix interface

Properties of fiber reinforced cementitious materials depends on microstructure of interface

Interface is initially water-filled zone which develops to a microstructure different than bulk matrix

There are 3 layers in interface;

a) Very thin (less than one micron) $Ca(OH)_2$ rich rather discontinuous, directly in contact with fiber
b) Massive $Ca(OH)_2$ layer
c) Porous zone (up to 40 microns) consisting of CSH and some ettringite

4. Structure and post-cracking composite theory

In hardened cement-based composites, fibers bridging the cracks contribute to the increase in strength, failure strain and toughness. Limited volume fraction of low modulus fibers do not contribute to the modulus of elasticity of the composite.

4. Structure and post-cracking composite theory

Composite materials approach – the rule of mixtures – properties of the composite are the weighted average of the properties of its individual components. This is only valid if the 2 components behave linear-elastic and the bond between them is perfect. Therefore the rule of mixtures can only be applied for the elastic, pre-cracked zone of fiber reinforced cement based materials.

For the pre-cracked zone where the matrix and fibers behave elastically use composite materials approach;

$$E_c = E_f V_f + E_m (1-V_f)$$

$$\sigma_{cu} = \sigma_{mu} (1-V_f) + \sigma'_f V_f$$

Please note that the main influence of fibers is in the post-cracking zone!

4. Structure and post-cracking composite theory, cont'd

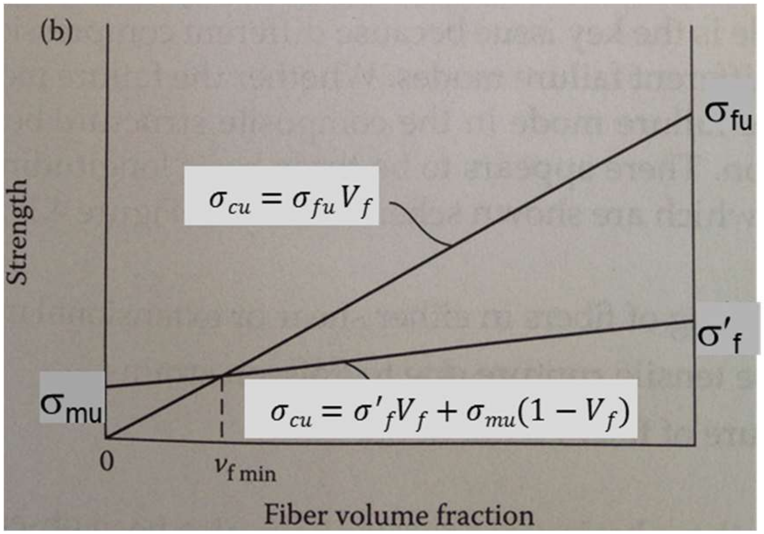
For the post-cracking zone; equations should be modified to neglect the contribution of the matrix

$$E_c = \left(\frac{d\sigma_f}{d\varepsilon_f} \right) . V_f$$

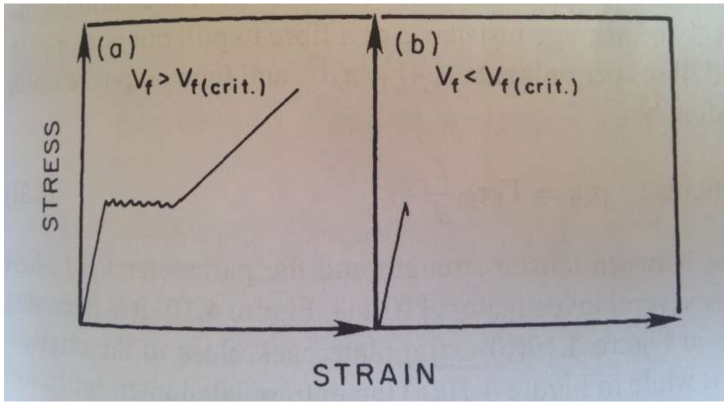
$\sigma_{cu} = \sigma_{fu} V_f$ - (V_f must be greater than V_{crit})

4. Structure and post-cracking composite theory, cont'd

Remember the case for continuous and aligned fibers when fiber failure strain is greater than matrix failure strain



Relations between composite strength and fiber volume content (Kelly, 1973)



Stress strain curves for composites with a) $V_f > V_{crit}$ b) $V_f < V_{crit}$ (Bentur and Mindess, 2007)

$$V_{cr} = \frac{E_c}{E_m} \frac{\sigma_{mu}}{\sigma_{fu}}$$

Ref; A. Kelly, Strong Solids, Oxford University Press, Oxford, 1973
A. Bentur, S. Mindess, Fiber reinforced cementitious composites, 2nd edition, 2007

4. Structure and post-cracking composite theory, cont'd

After 1st cracking, the load carried by the matrix is transferred to the fibers, which due to their sufficiently large volume can support this load without failure. Additional loading leads to more matrix cracking, which is still not accompanied by failure of the composite. In contrast, at $V_f < V_{crit}$ the mode of failure will be by the propagation of a single crack, since there is insufficient volume of fibers to support the load that was carried by the matrix as it cracked.

Ref; A. Bentur, S. Mindess, Fiber reinforced cementitious composites, 2nd edition, 2007

4. Structure and post-cracking composite theory, cont'd

When short fibers are under consideration previous eqs. must be modified as follows;

$\sigma_{cu} = \sigma_{mu} (1-V_f) + \eta\, \sigma'_f V_f (l/d)$ when $V_f < V_{crit}$

$$\sigma_{cu} = \eta V_f \tau_{my} \frac{l}{d}$$ when $V_f > V_{crit}$

Example

Steel fiber reinforced concrete is to be produced by using 5 % of steel fibers. Tensile strength and ultimate strain of fibers are given to be 1100 MPa and 0,005, while the yield strength and ultimate strain of the concrete matrix are 35 MPa and 0,001 respectively. Both fibers and matrix are assumed to show linear elastic behavior.

- Draw stress – strain diagram for concrete matrix and fiber.
- Find the expected failure mode for this fiber – reinforced composite.
- Calculate the ultimate strength of the composite material and show the expected curve on the figure you have drawn for the 1st part of the question.
- Calculate modulus of elasticity of this composite material.

Overall Outline

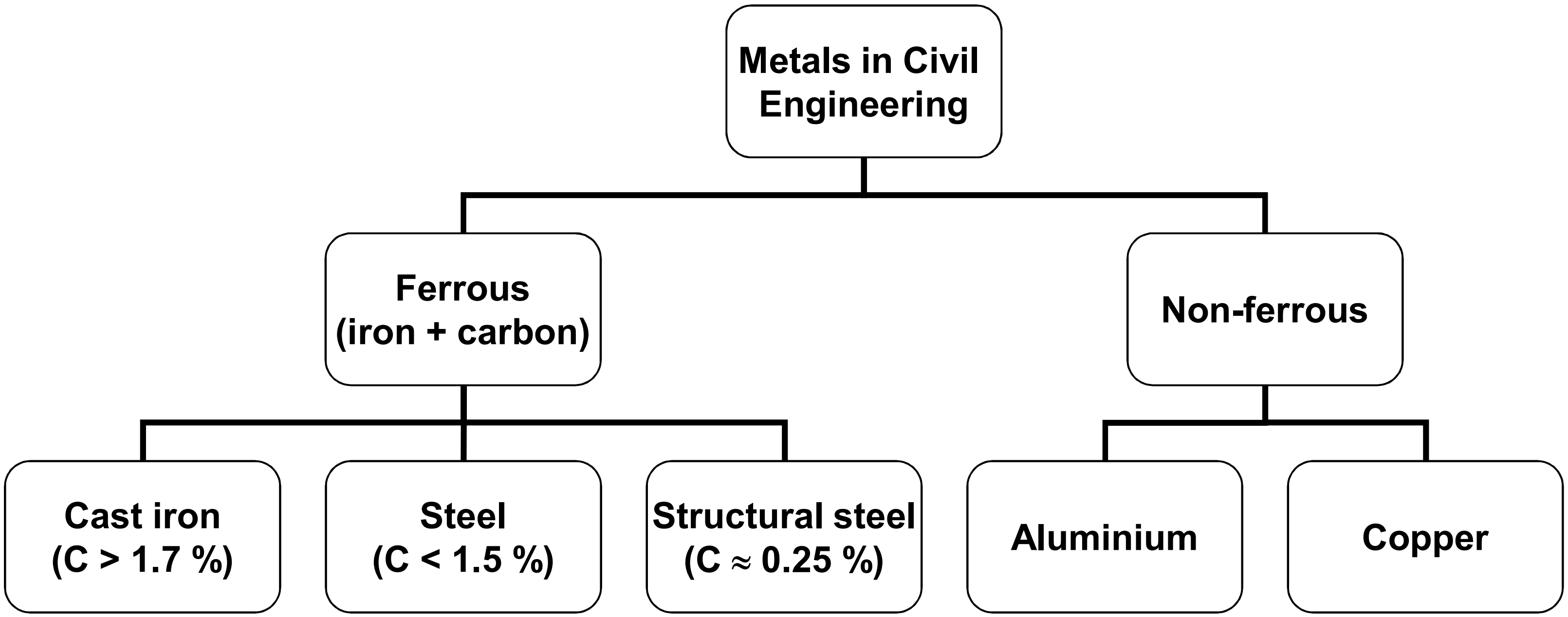
- Introduction
- Concrete
- Bituminous materials
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter outline

Metals

1) Introduction
2) Ferrous metals
3) Non – ferrous metals
4) Standard for reinforcing steels

Metals, their differences and uses
1. Introduction



2. Ferrous metals

1) Cast irons

- Major consumption in pipes and fittings
- In civil engineering for tunnel segments and mine shaft tubing
- Carbon content is greater than 2 %.
- Hard and brittle.

2) Steel

Steel is obtained through carbon reducing operations. Carbon steel is an alloy of iron and carbon. Amount of carbon within the lattice determines the properties of the steel. Alloys containing less than 0.008 % carbon are classed as irons. Steel has a carbon content less than 2.0 %

$C \leq 0.25\ \%$ $\Rightarrow$ mild steel, low carbon steel (structural steel is in this category)

$0.3\ \% \leq C \leq 0.6\ \%$ $\Rightarrow$ medium carbon steel, carbon steel

$C > 0.6\ \%$ $\Rightarrow$ high carbon steel

Normally, Mn and S are added to steel during production

If elements other than Mn and Si are added $\Rightarrow$ alloy steels

If elements like Cr and Ni are added $\Rightarrow$ stainless steels

2. Ferrous metals, cont'd

3. Structural steel

Four grades of structural steels

Grade	Min.ten.st.(MPa)
40	400
43	430
50	500
55	550

All structural steels are readily weldable. For higher grades care is needed in welding

2. Ferrous metals, cont'd

Heat treated steels

Properties of steel ($C > 0.3$ %) can be varied by heat treatment

- Heating to high temperature
- Fast cooling by quenching in oil or water
- Followed by reheating to about 650°C (tempering)

Fast cooling produces ⇒ hard, brittle microstructure (known as martensite)

Used only for cutting tools, no use in structural engineering

Stainless steels

Ferrous alloys containing at least 12% Cr and some Ni and Mo. Chromium produces a stable passive oxide film.

3. Non - ferrous metals

4. Aluminium and alloys

- Used both structurally and decoratively in cladding, roofing, window frames, window and door furniture.
- Lightness of aluminium is an advantage in structures with high self-weight / live load. Such as roofs, footbridges and long span structures
- High durability of aluminium makes it usable in polluted and coastal areas
- High cost limits its use
- High initial cost maybe offset by reduced maintenance
- Structural sections are produced by extrusion

E_{al} = 70GPa & E_{st} = 210 GPa $\Rightarrow$ Aluminium deflects more under same load

However, specific moduli (E/ρ) is comparable

$(E/\rho)_{al} = 20$, $(E/\rho)_{st} = 29$

3. Non - ferrous metals, cont'd

5. Copper and alloys

Used in applications where high thermal and electrical conductivity needed such as domestic water services, heating, sanitation

5.1 Brasses; copper – zinc alloys ⇒ enhanced strength and corrosion resistance

2.2 Bronzes; copper – tin alloys ⇒ high corrosion resistance

4. Standard for reinforcing steels – TS 708

Mechanical properties of reinforcing bars as given in TS 708 and TS 500

ÇİZELGE 3.1 - Donatı Çeliklerinin Mekanik Özellikleri (TS 708 den)

Mekanik Özellikler	Donatı Çubukları				Hasır Donatı	
	Doğal Sertlikte			Soğukta İşlem Görmüş		
	S220a	S420a	S500a	S420b	S500bs	S500bk
Minimum akma dayanımı f_{yk} (MPa)	220	420	500	420	500	500
Minimum kopma dayanımı f_{su} (MPa)	340	500	550	550	550	550
$\phi \leq 32$ Minimum kopma uzaması ε_{su} (%)	18	12	12	10	8	5
$32 < \phi \leq 50$ Minimum kopma uzaması ε_{su} (%)	18	10	10	10	8	5

Overall Outline

- Introduction
- Concrete
- Bituminous materials
- Masonry
- Polymers and polymer composites
- Cement-based fiber composites
- Metals
- Timber

Chapter Outline

TIMBER

1. Introduction
2. Types of trees
3. Properties of timber
4. Timber specification

TIMBER

1. Introduction

Timber has been one of the basic materials of construction since the earliest days of human kind. Today it has been largely superseded by concrete and steel. However, the use of timber remains extensive.

Wood – A Nature Made Composite

Wood contains; 60 % cellulose
28 % lignine
12 % pectine & some others

3. Properties of timber

Table 1. Mechanical properties of trees in Turkey in air-dried condition and parallel to grains

Type of tree	Unit weight (kg/dm^3)	Compressive str. (MPa)	Flexural str. (MPa)
Poplar (kavak)	0,398	41	69
Fir (köknar)	0,431	36	71
Spruce (ladin)	0,436	31	69
Yellow pine (sarıçam)	0,515	38	65
Cedar (sedir)	0,523	45	77
Black pine (karaçam)	0,568	48	110
Red pine (kızılçam)	0,577	38	73
Oak (meşe)	0,690	55	94
Beech (kayın)	0,720	53	105

Even though chemical composition is the same, differences in internal structure result in differences of properties.

3. Properties of timber, cont'd

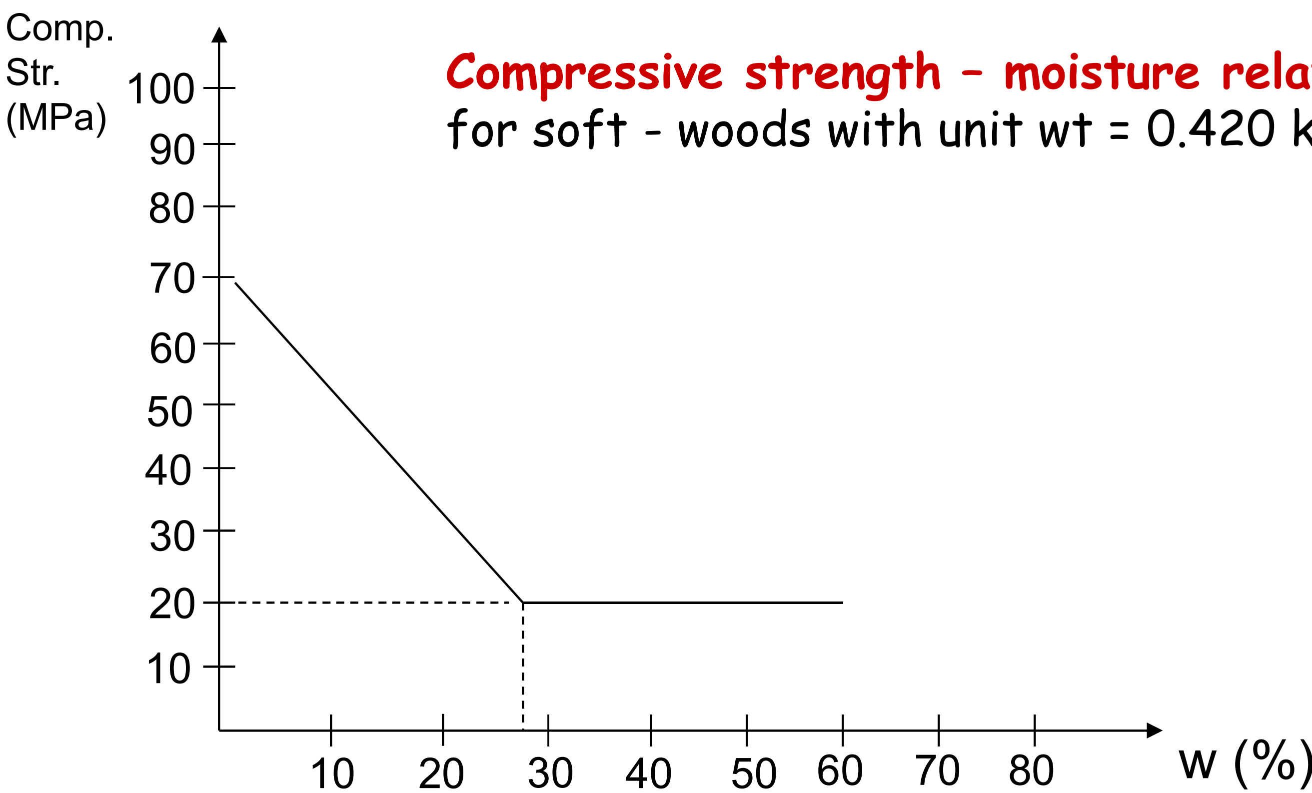
Properties of timber change with
- direction
- moisture content

- Largest properties are obtained in the direction parallel to grain and in dry condition which is the condition in which wood is usually utilized
- Being an organic material, wood is affected by the moisture in the atmosphere, by the ultraviolet rays of sun and deteriorated by parasites such as fungus or worms. Wood has to be protected by coatings and poisonous preservatives
- Its anisotropical nature and the limitations of size make its use difficult. To correct those deficiencies, artificial wood products like plywood, fiberboard, etc. are manufactured and used to a great extend

3. Properties of timber, cont'd

Compressive strength - moisture relation

for soft - woods with unit wt = 0.420 kg/dm^3



4. Timber specification (TS 647)
Allowable stresses

	3rd class		2nd class		1st class	
Strength (MPa)	Pine	Oak	Pine	Oak	Pine	Oak
Tensile //	-	-	8.5	10.0	10.5	11.0
Compressive //	6.0	7.0	8.5	10.0	11.0	12.0
Compressive ⊥	2.0	3.0	2.0	3.0	2.0	3.0

Modulus of elasticity
Pine: // 10 GPa
⊥ 0.3 GPa
Oak: // 12.5 GPa
⊥ 0.6 GPa

The End ☺