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**

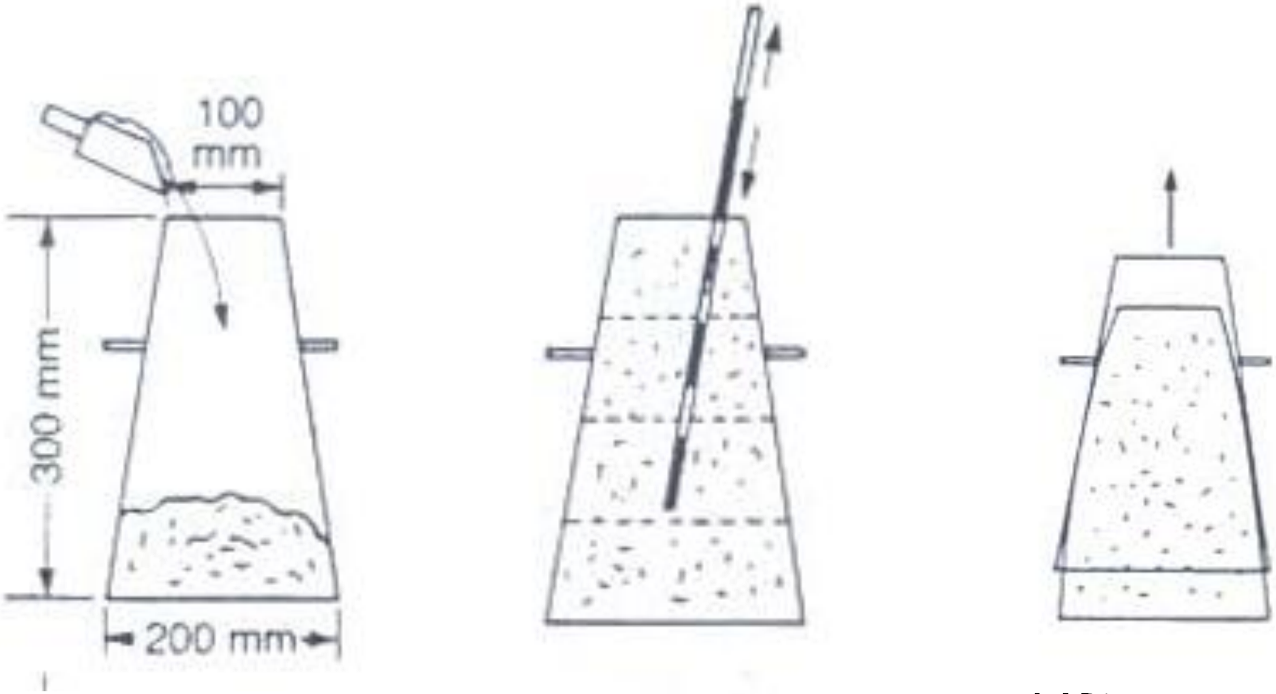
Fig ref : https://www.google.com/search?q=compaction+of+concrete&rlz=1C1EODB_enTR532TR534&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjR0qSv66HgAhXBTRUIHas7D_AQ_AUIDigB&biw=1920&bih=938#imgrc=9P7mTskScseoZM:

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

Lift cone up
Define slump as downward
Movement of the concrete

2. Workability measurement methods, cont'd

a) Slump test

Lift cone up

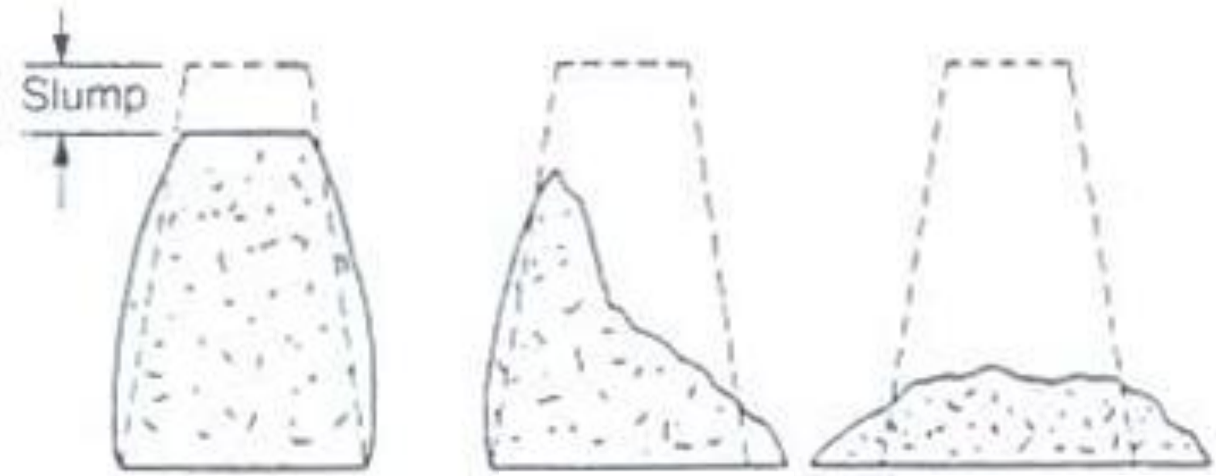
Define slump as downward movement of the concrete

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

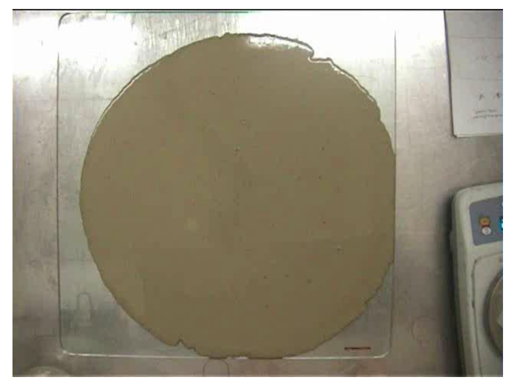
2. Workability measurement methods, cont'd

b) Mini slump test

- Used for workability testing of <u>cement pastes</u>
- 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

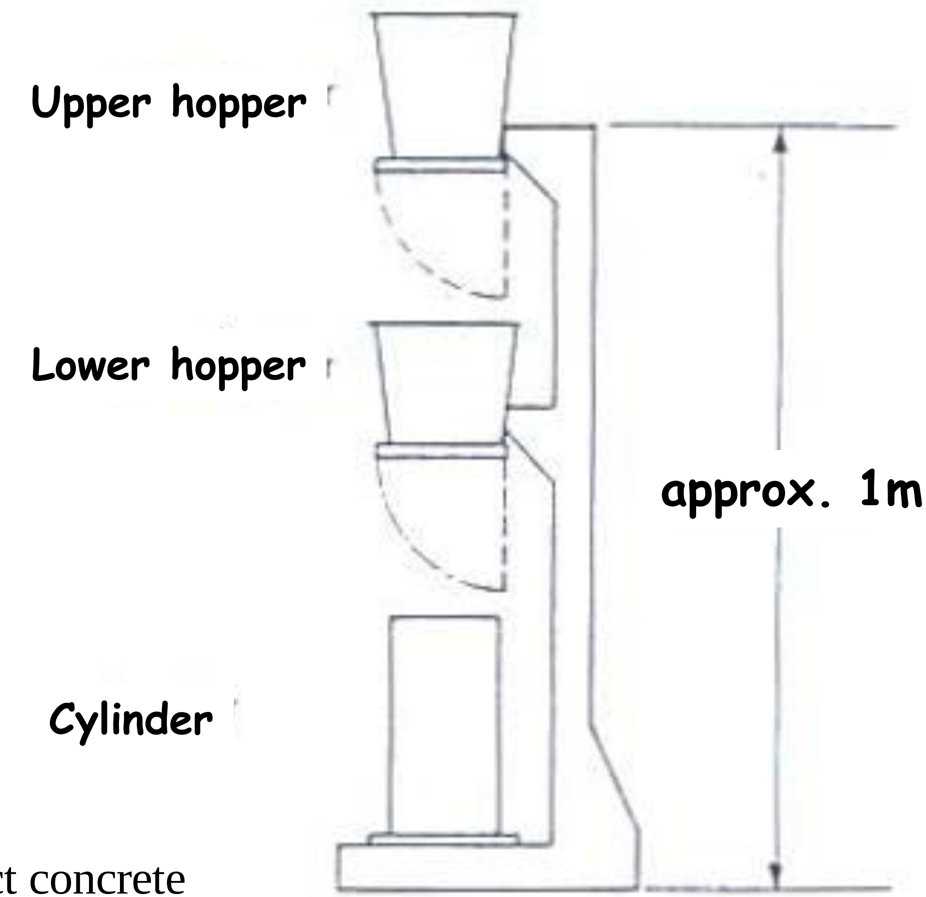


2. Workability measurement methods, cont'd

c. Compacting factor test

(to distinguish between low slump mixes)

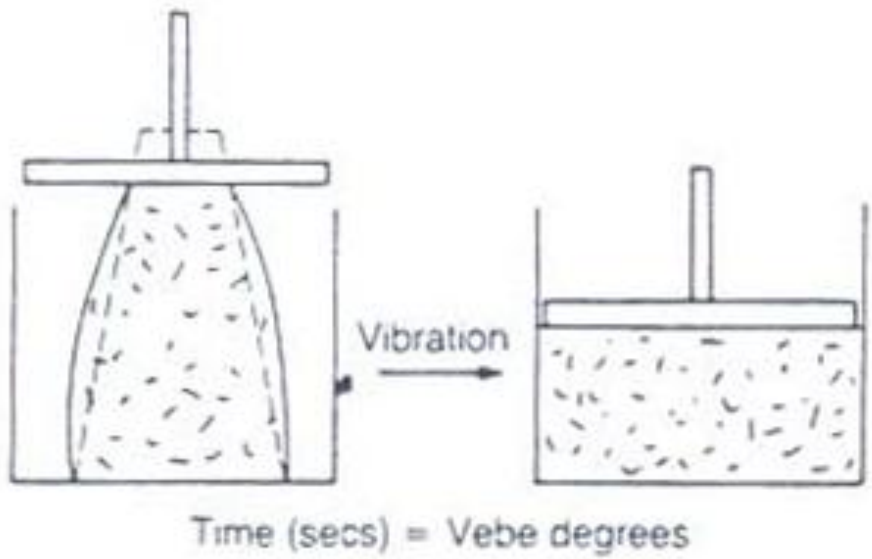
1. Concrete is placed in an upper hopper
2. Dropped into a lower hopper to bring it to a standard state and then allowed to fall into a standard cylinder.
3. The cylinder and concrete weighed (partially compacted weight)
5. The concrete is fully compacted, extra concrete added and then conrete and cylinder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

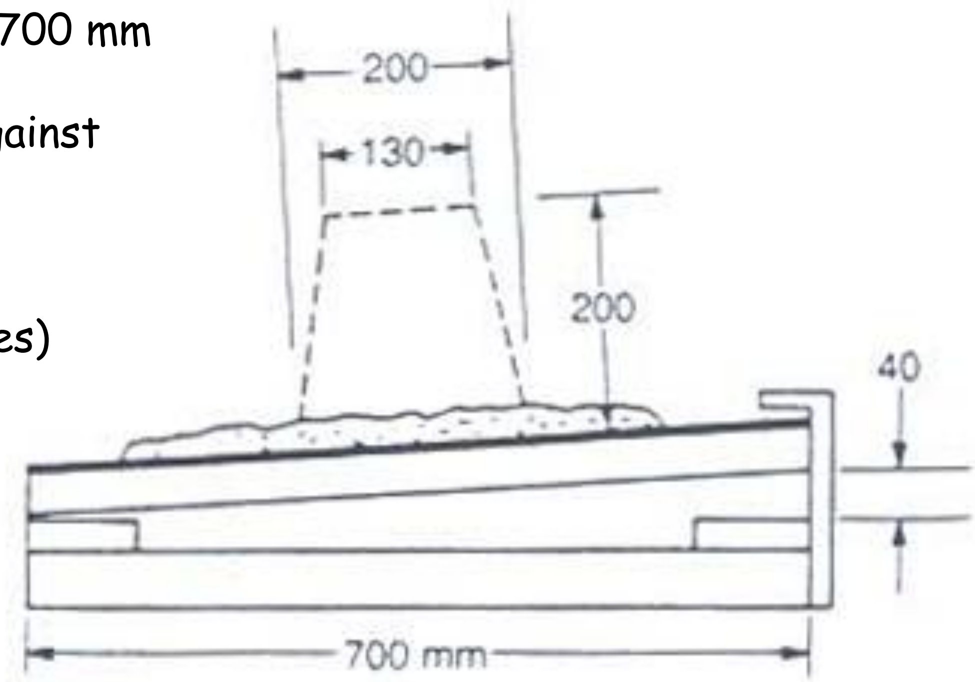
<u>Vebe time</u> is defined as the time taken to complete covering of the underside of the disc with concretecontainer

2. Workability measurement methods, cont'd

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

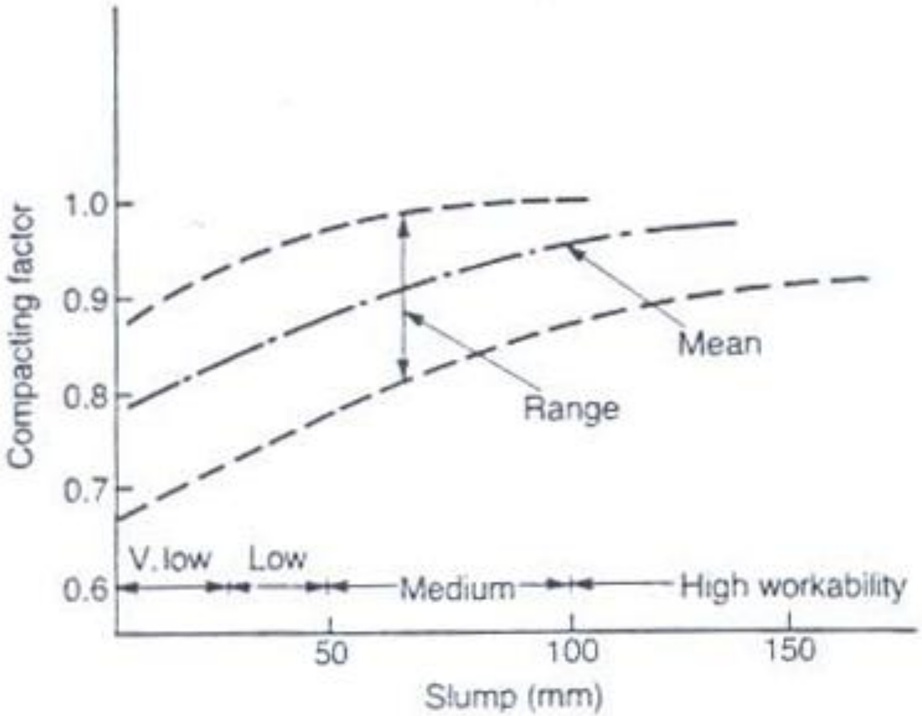
i. A conical mould is used to produce a sample of concrete in the centre of a 700 mm square board, hinged along one edge
ii. The free edge of the board is lifted against the stop and dropped 15 times

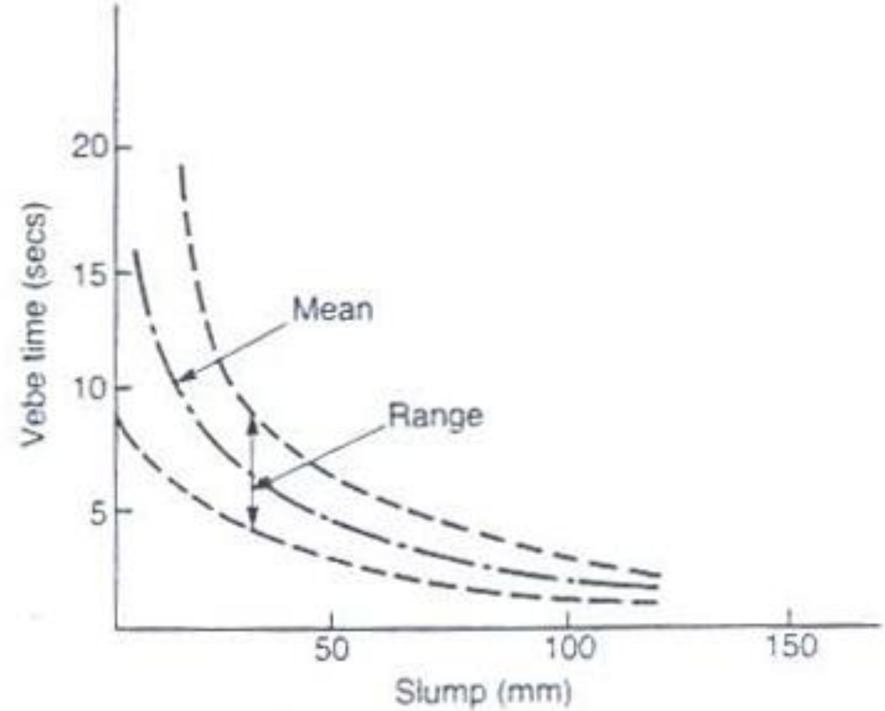
Flow = final diameter of the concrete
(mean of two measurements at right angles)



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

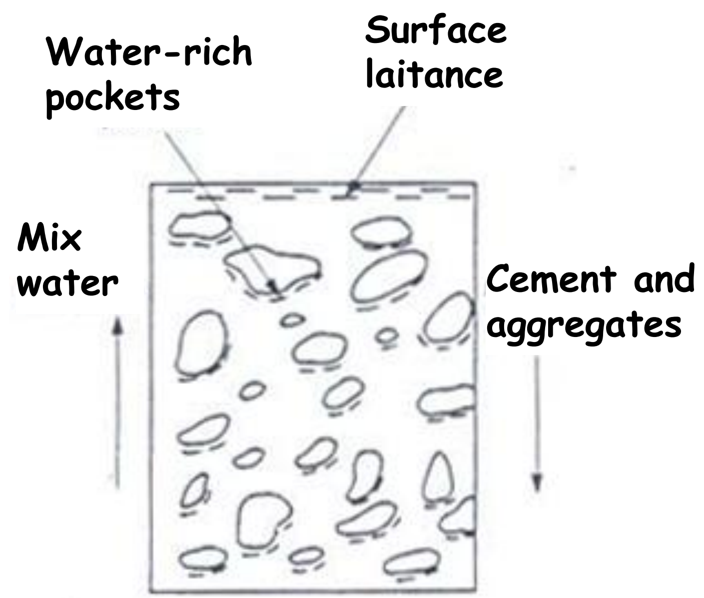
From placing to final set, concrete is in a plastic, semi-fluid state
Heavier particles (aggregates) have tendency to move down (SEGREGATION)
Mix water has a tendency to move up (BLEEDING)

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



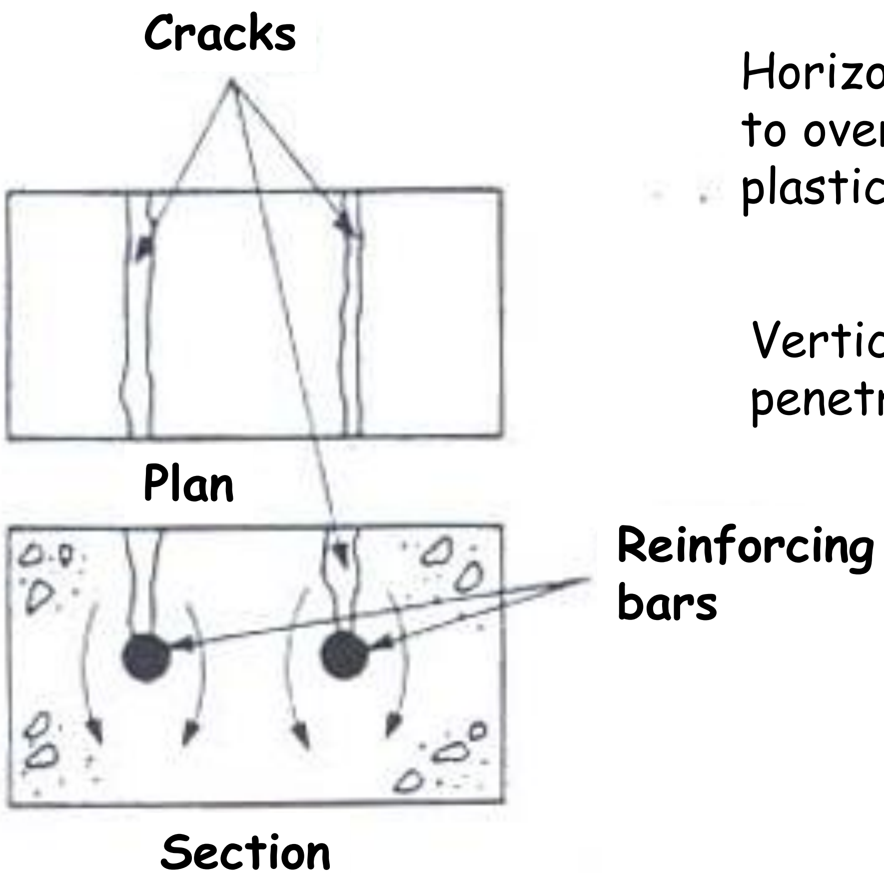
Other effects of bleeding;

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

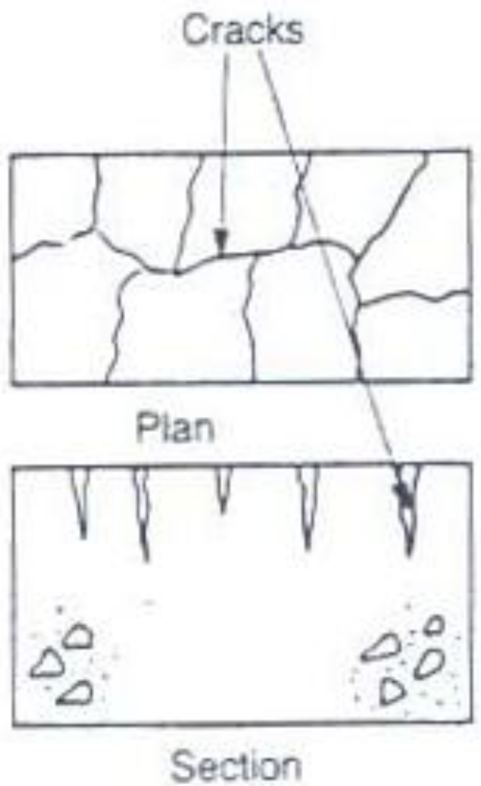


Horizontal reinforcing bars may put restraint to overall settlement of concrete. Then plastic settlement cracking can occur.

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

Poorly graded aggregate with a lack of fine material with particle size < 300μm

High workability mixes

REMEDIES

1. increase sand content
2. Air entrain concrete as substitute for fine materials

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

$Maturity = \Sigma\, t.(\mathrm{T}+10)$ $\rightarrow$ 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

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  - Deformation and dimensional stability of concrete
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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

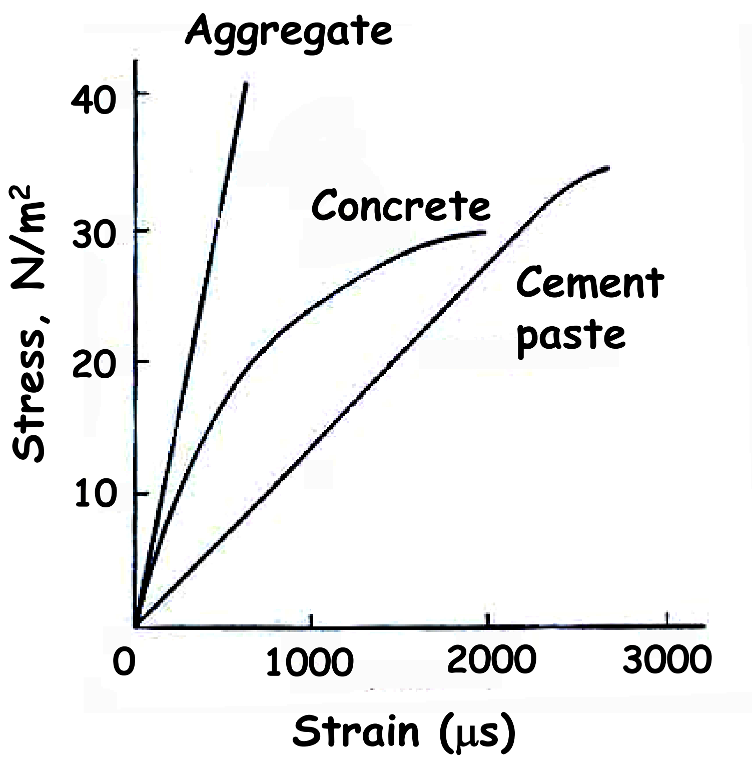
Concrete members are restricted in different ways (e.g. subgrade friction, end members, reinforcing steel).

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.

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

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

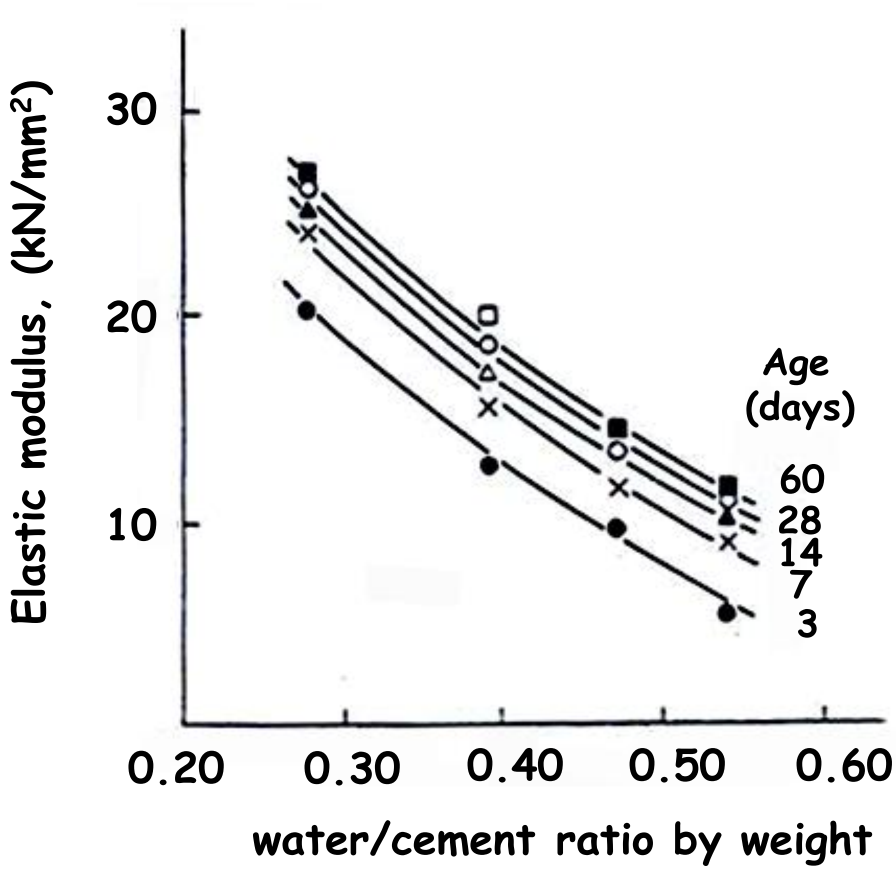
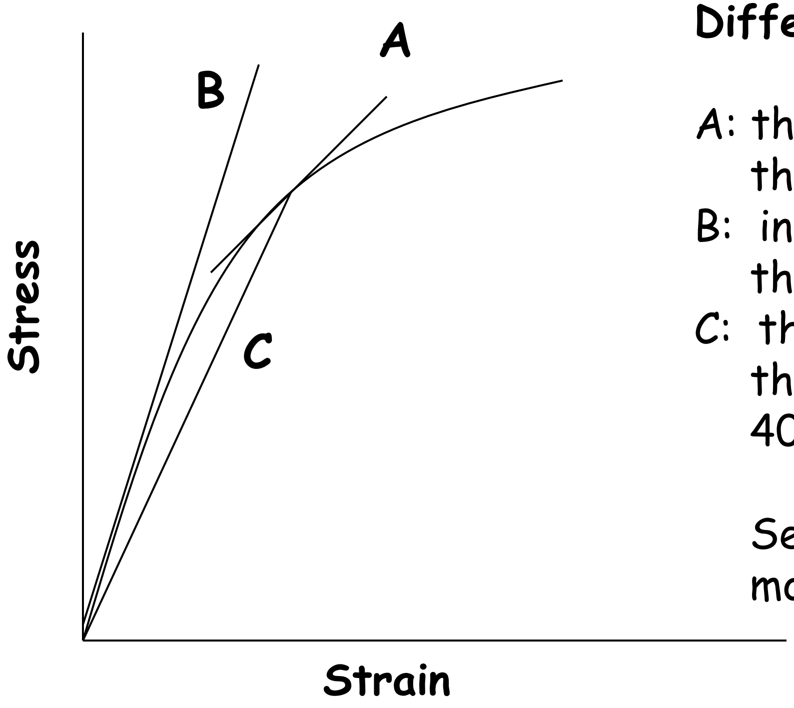


Fig. Effect of w/c and age on the elastic modulus of hcp

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

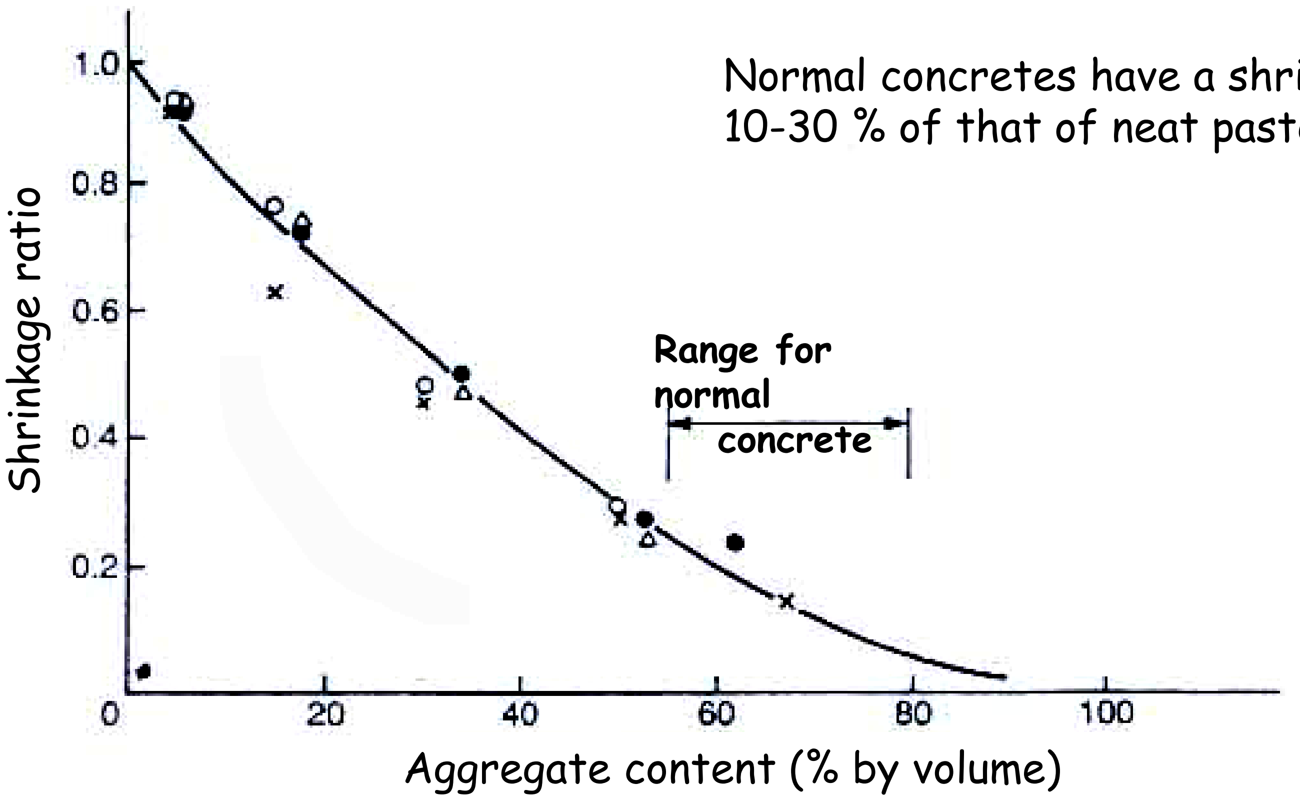
In hcp; unhydrated cement grains also act as a restraint

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

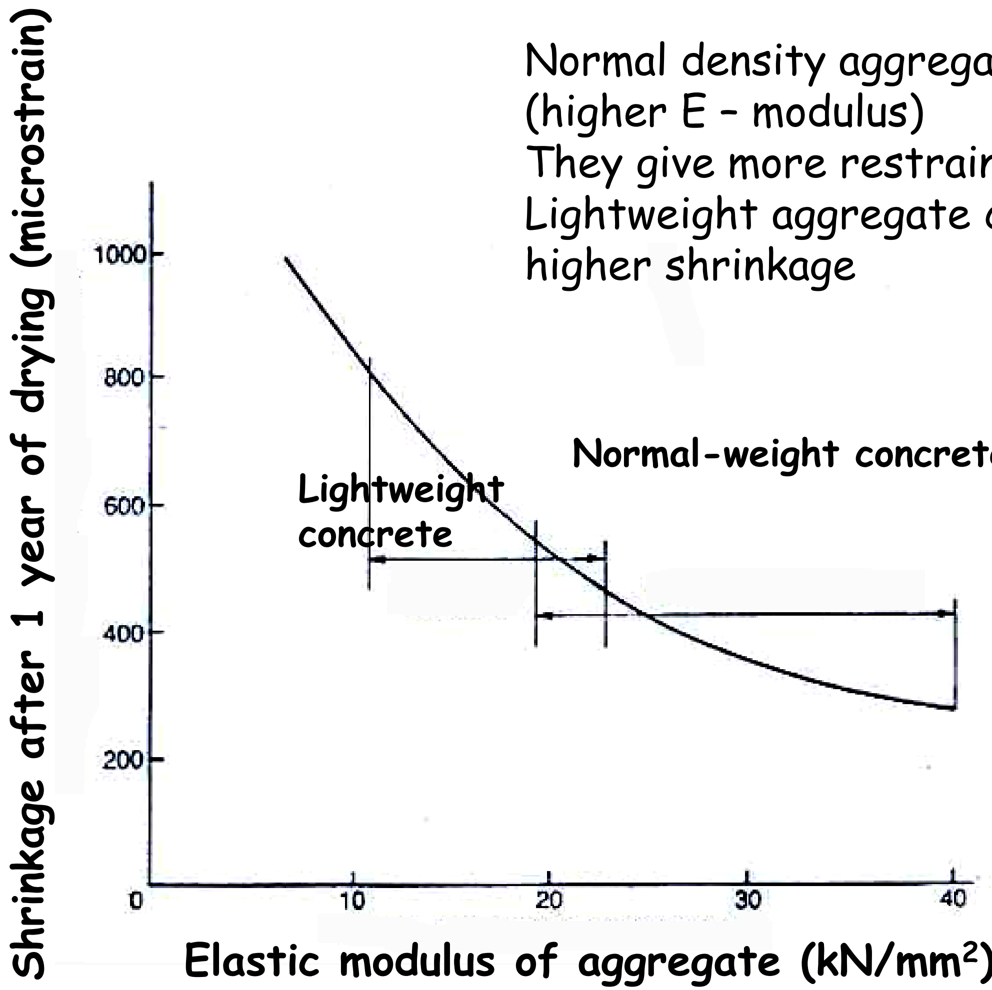


i) Drying shrinkage, cont'd

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

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

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.

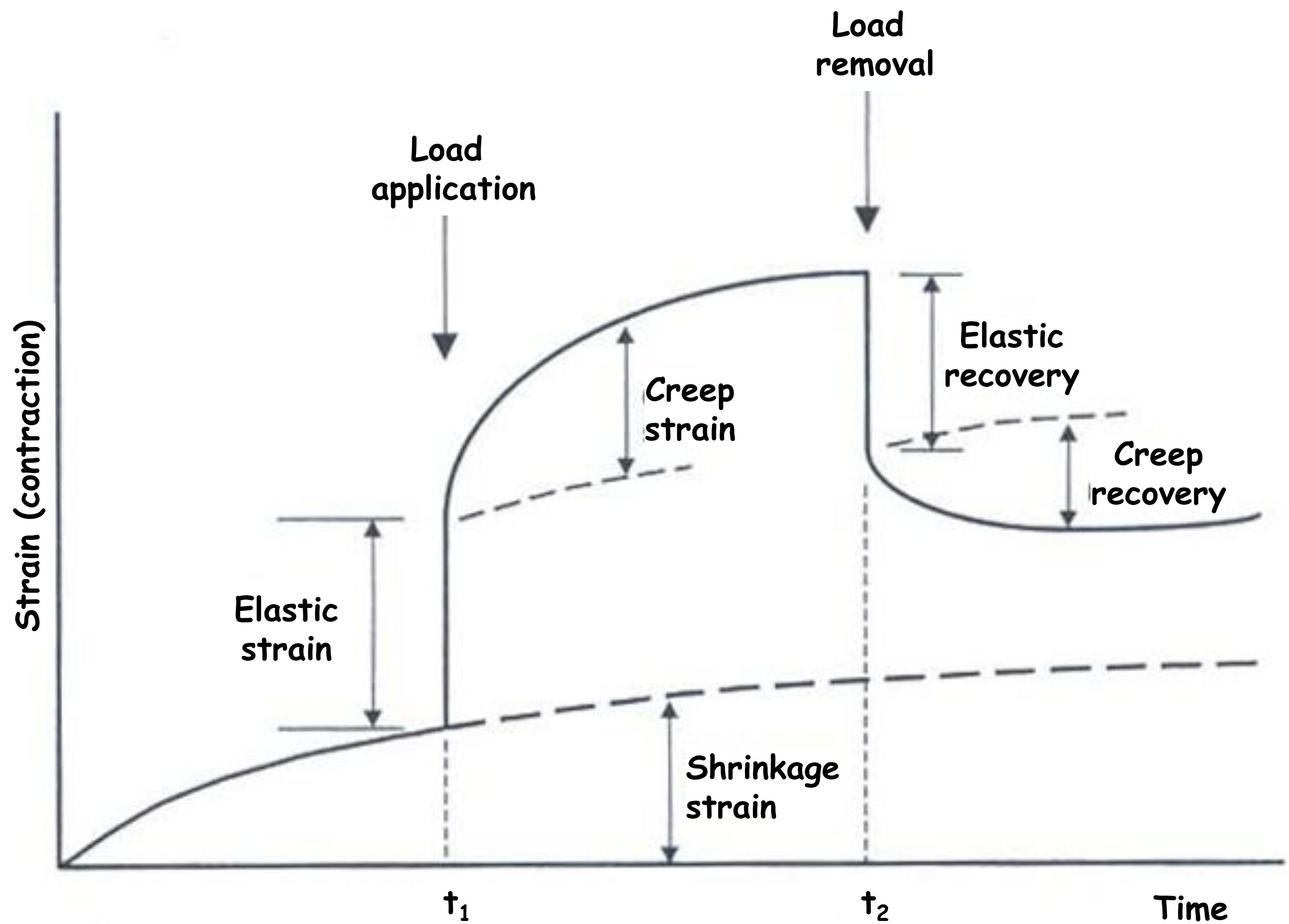
4. Creep

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

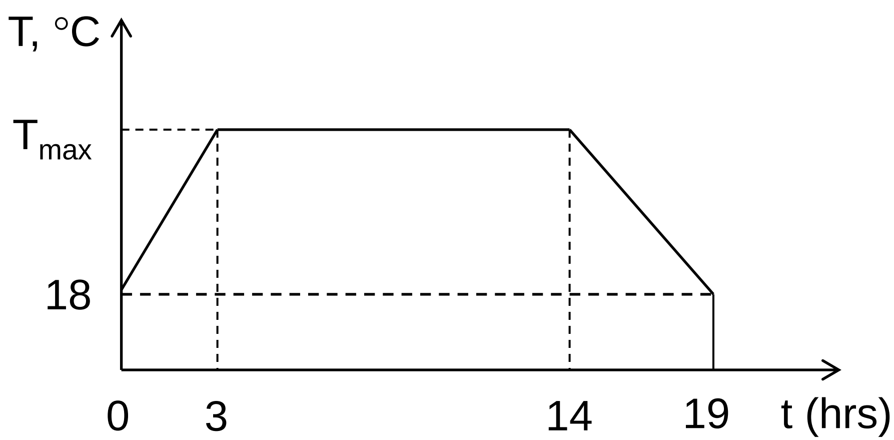
- Coefficient of thermal expansion of most rocks = 6 - 10 x 10^{-6} / °C
- Therefore, coefficient of thermal expansion of concrete is less than that of hcp
- Since aggregate occupies 70- 80 % of concrete volume, effect of humidity is very much reduced, therefore, we assume a constant coefficient of thermal 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: $\mu = 0.20$ $\varepsilon_{sh} = 0.003$

Aggregate: $\mu = 0.22$ $E = 60$ 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.