Unit 7(Pt1)_Elasticity, Creep and Shrinkage

Presentations

By

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Unit 7

- **ELASTICITY, CREEP AND SHRINKAGE:** Modulus of elasticity – Dynamic modulus of elasticity – Poisson's ratio – Creep of concrete – Factors influencing creep – Relation between creep and time – Effects of creep – Shrinkage – Types of shrinkage.
- **MIX DESIGN:** Factors in the choice of mix proportions - BIS and ACI methods of mix design.

3 MAIN TYPES OF DEFORMATIONS IN CC

- **3 main types of *Deformations*** *take place in Hardened CC subjected to* → External Load and Environment
  - **Elastic Strains**. *These are the Instantaneous Deformations that occur when → an External Stress is applied* FIRST
  - **Shrinkage strains**. *These Deformations occur either*
    - *on LOSS of Moisture from the CC or*
    - *On Cooling of CC*
  - **Creep.** *It is the Time-dependent Deformation that occurs on → the Prolonged Application of Stress*
- Deformation Effect. *Any one or combinations of the above types of deformations in a hardened CC leads to → Cracking.*

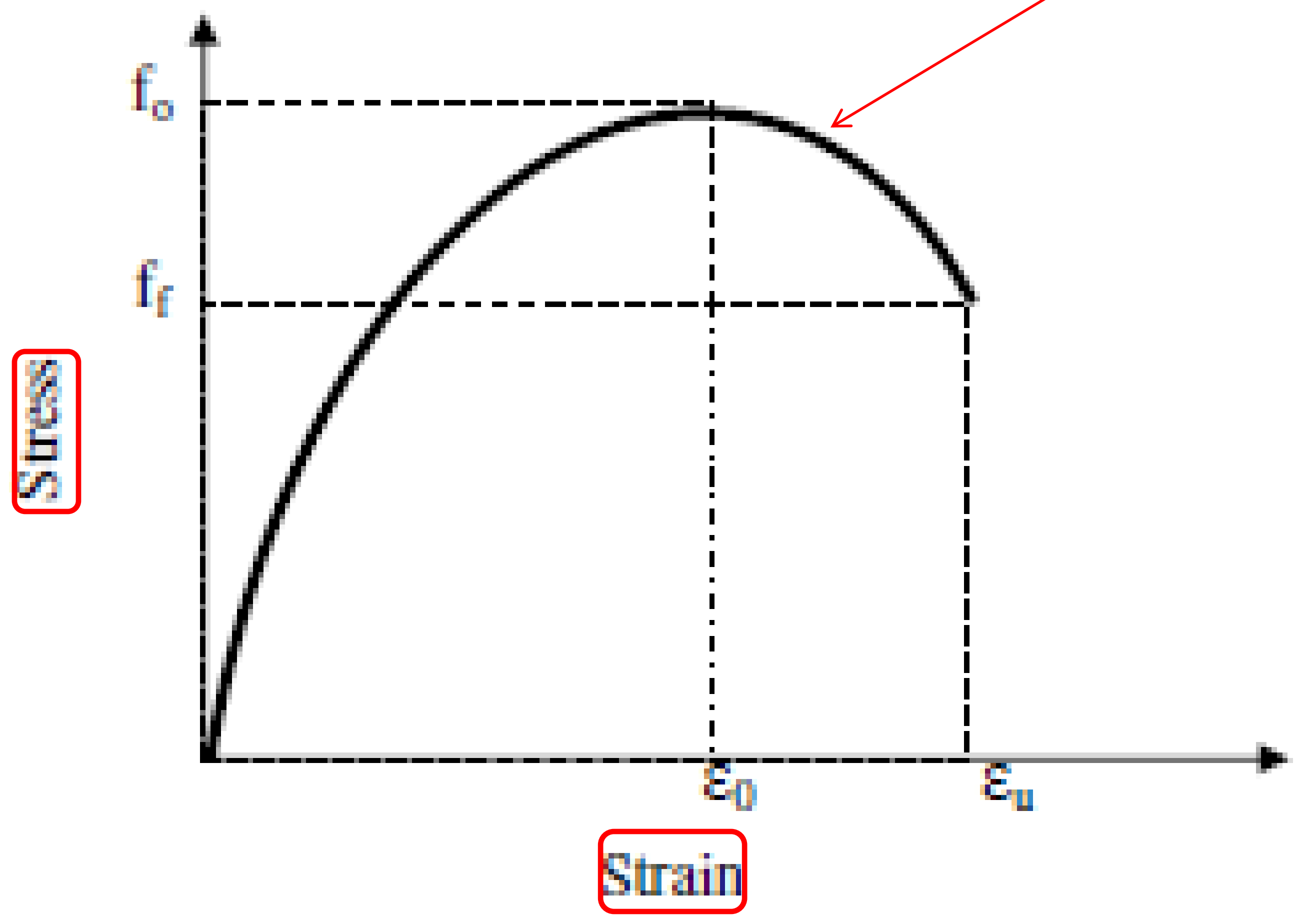
- 1. Elastic Strains. Elastic strain in CC, as defined above, depends on the Externally Applied Stress and the Modulus of Elasticity of CC:

Elastic Strain = Externally applied Stress/ Modulus of Elasticity of CC

Typical Stress-Strain Plot of Concrete

- (1) At Stress < 30% of Ultimate Str,
  - the Transition Zone Cracks → remain STABLE.
  - The Stress-Strain Plot → remains LINEAR.
- (2) At Stress 30% - 50% of Ultimate Str,
  - the Transition Zone Micro-Cracks begin to → INCREASE in length, width and numbers.
  - The Stress-Strain Plot becomes → NON-LINEAR.
- (3) At 50 - 60% of Ultimate Stress,
  - Cracks begin to form in the Matrix.
- (4) At about 75% of the Ultimate Stress,
  - the Cracks in the Transition become → UNSTABLE, and
  - Crack Propagation in the Matrix will → INCREASE.
  - The Stress-Strain Curve → bends towards the Horizontal.
- (5) At 75 - 80% of the Ultimate Stress,
  - the Stress reaches → a Critical Stress Level for Spontaneous Crack Growth under a Sustained Stress.
  - Cracks Propagate rapidly in → both the Matrix and the Transition Zone.
  - Failure occurs when → the Cracks Join together and become Continuous.

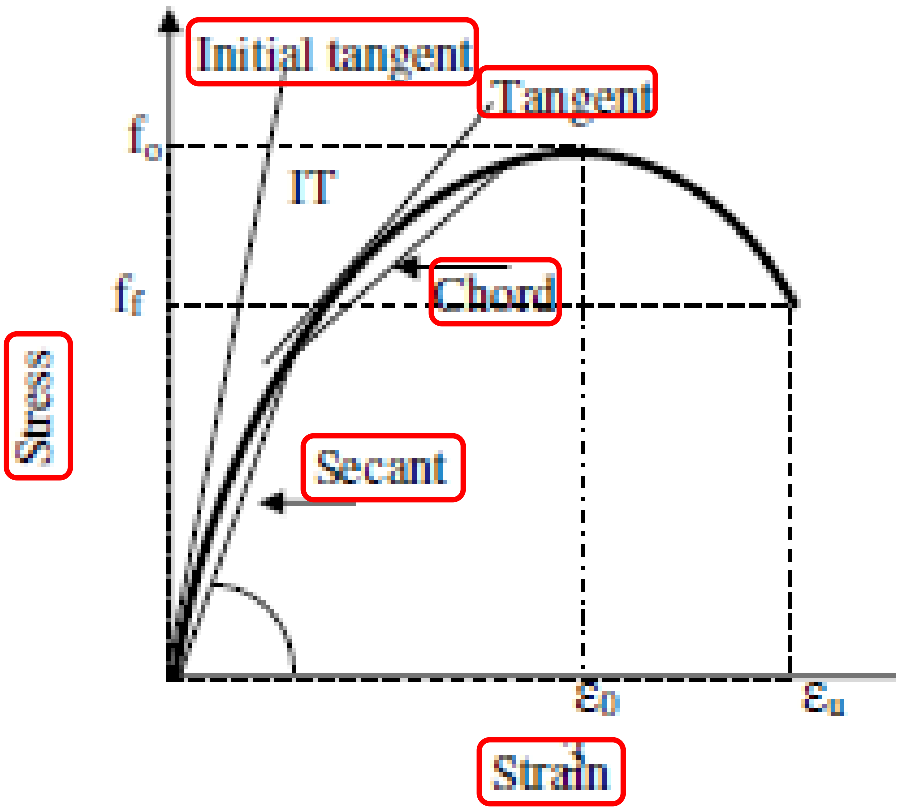
- CC is *NOT a truly Elastic Material*, as evident from → the *Nonlinear Stress-Strain Curve* for CC, shown in the following Fig.:



Methods of computing Modulus of Elasticity

- Since the Stress-Strain Curve for CC is Non-Linear, following methods for computing the modulus of elasticity of concrete are used yielding various types of Modulus of Elasticity for CC:
- *1. Initial Tangent Modulus. It is given by the Slope of a line drawn Tangent to the Stress-Strain Curve at the Origin*
- *2. Tangent Modulus. It is given by the Slope of a line drawn tangent to the stress-strain curve at Any Point on the curve*
- *3. Secant Modulus. It is given by the Slope of a line drawn from the Origin to a Point on the Curve corresponding to a 40% of Failure Stress*
- *4. Chord Modulus. It is given by the Slope of a line drawn between 2 Points on the Stress-Strain Curve*

- Calculation of the above 4 types of Moduli of Elasticity for CC has been explained below using a typical Stress-Strain Curve, as shown in the following Fig.:



1. Initial Tangent Modulus. *It is given by the Slope of a line drawn Tangent to the Stress-Strain Curve at the Origin*

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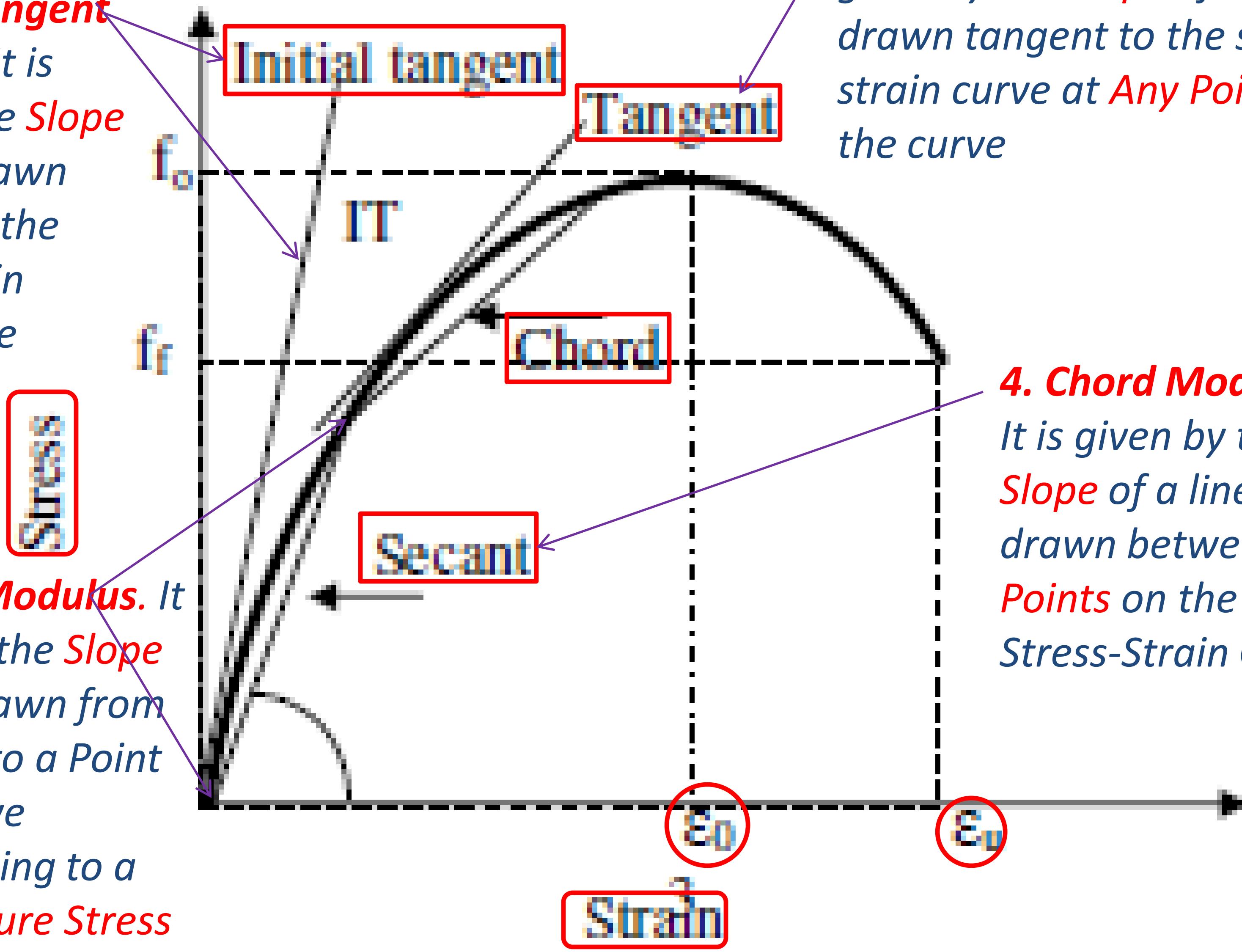


3. Secant Modulus. *It is given by the Slope of a line drawn from the Origin to a Point on the Curve corresponding to a 40% of Failure Stress*

4. Chord Modulus. *It is given by the Slope of a line drawn between 2 Points on the Stress-Strain Curve*

Ec and Ed

- 1. *Static Modulus of Elasticity (Ec).* Modulus of Elasticity for CC determined from an Experimental Stress-Strain relation Curve

- *2. Dynamic Modulus of Elasticity (Ed). Modulus of Elasticity determined through the L*ongitudinal Vibration Test

Relationship : Modulus of Elasticity & Compr Str

BS 8110:Part 2:1985 has recommended the following expression for 28-day E_c in terms of 28-day cube compressive strength (f_{cu}), for normal weight concrete (*i.e. concrete with density, $\rho \approx 2400\ kg/m^3$*):

$$E_{c28} = 20 + 0.2\, f_{cu28}$$ *(where E_{c28} is in GPa and f_{cu28} is in MPa)*

Note: For lightweight concrete the above values of E_{c28} should be multiplied by the factors $(\rho/2400)^2$ and $(\rho/150)^2$ respectively.

Relationship between Modulus of Elasticity of CC & Compr Str

- ACI Building Code 318-89 recommends the following expression for (E_c) in terms of cylinder compressive strength (f_{cyl}), for normal weight concrete (*i.e. concrete with density, $\rho \approx 2400$ kg/m^3*):

$E_c = 4.7\,(f_{cyl})^{0.5}$ *(where E_c is in GPa and f_{cyl} is in MPa)*

$E_{c,28} = 9.1 f_{cu}^{\,0.33}$ - for normal weight concrete of density = 2400 kg/m^3,
and
$E_{c,28} = 1.7\rho^2 f_{cu}^{\,0.33} \times 10^{-6}$ for lightweight concrete - (ρ) =1400–2400 kg/m^3

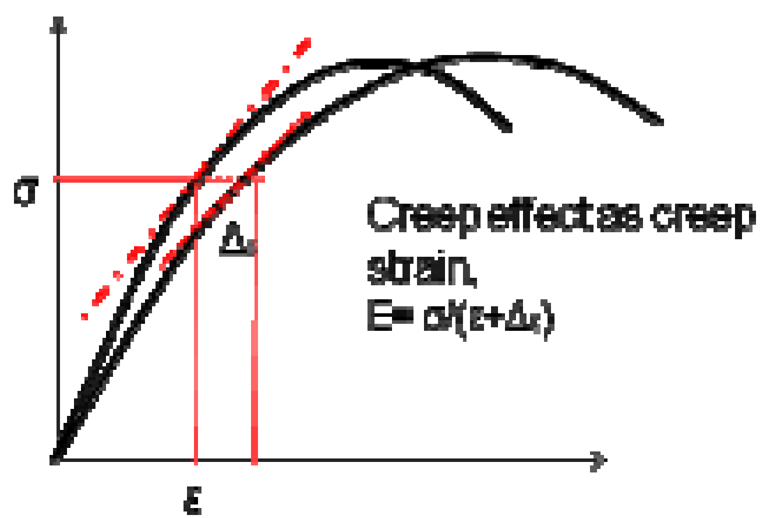
- CEB - FIP Model Code (Euro-International)
$E = 2.15 \times 10^4\,(f_{cm}/10)^{1/3}$ E in MPa and f_{cm} in MPa

Static Modulus of Elasticity (Ec) for CC

- Experimental stress-strain relation curve, as described above, is generally termed as static modulus of elasticity (E_c) and is short term modulus.
- If creep effect is considered at a given load, the modulus determined is referred to as long term modulus of elasticity.

Where θ is creep coefficient and Creep coefficient is the ratio of creep strain to elastic strain

$E_{Long} < E_{short}$



Dynamic Modulus of Elasticity (Ed) for CC

- Ed. Modulus of Elasticity determined through the Longitudinal Vibration Test by → Velocity of Sound or Frequency of Sound
  - Ed ≈ Initial Tangent Modulus of Elasticity of CC.
  - Ed is MORE as → Creep Effect is NOT considered.
- Ed for Normal and Light Wt CC in GN/m2 (GPa) is given by

  Ec = 1.25 Ed – 19 - for Normal Wt CC (NWC) and

  Ec = 1.04 Ed – 4.1 - for Light Wt CC (LWC)
- If M20 NWC is used,
  - Ec = 22.4 GPa, Ed = 33.12 GPa,
  - i.e. Ed = 1.48 Ec

- Conduct NDT on CC Prism.
  - Subject beam to Longitudinal Vibration at its Natural Frequency and measure
    - the Resonant Frequency (n, Hz) or
    - the UPV (km/s) through it.

$E_d = Kn^2L^2\rho$; If L in mm,
ρ in kg/m^3, then
$E_d = 4x10^{-15}n^2L^2\rho$, in GPa

- Appx. Ranges of Resonant Frequencies of CC Beam 100 x 100 x 500 mm
  - Transverse 900–1600 Hz,
  - Longitudinal 2500–4500 Hz.
- If n= 4000 Hz → Ed = 38.4 GPa

NDT for Ed

- Conduct NDT on Concrete Prism and measure the UPV (km/s) through it. UPV = Path length/Transit time

$$E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

μ = Poisson's ratio, 0.2 - 0.24

If V in km/s, ρ in kg/m^3

Ed in MPa

Let V = 4km/s, μ = 0.2, ρ = 2400 kg/m^3

Ed = 34560 MPa = 34.6 GPa

Here Ed is more as there is no creep

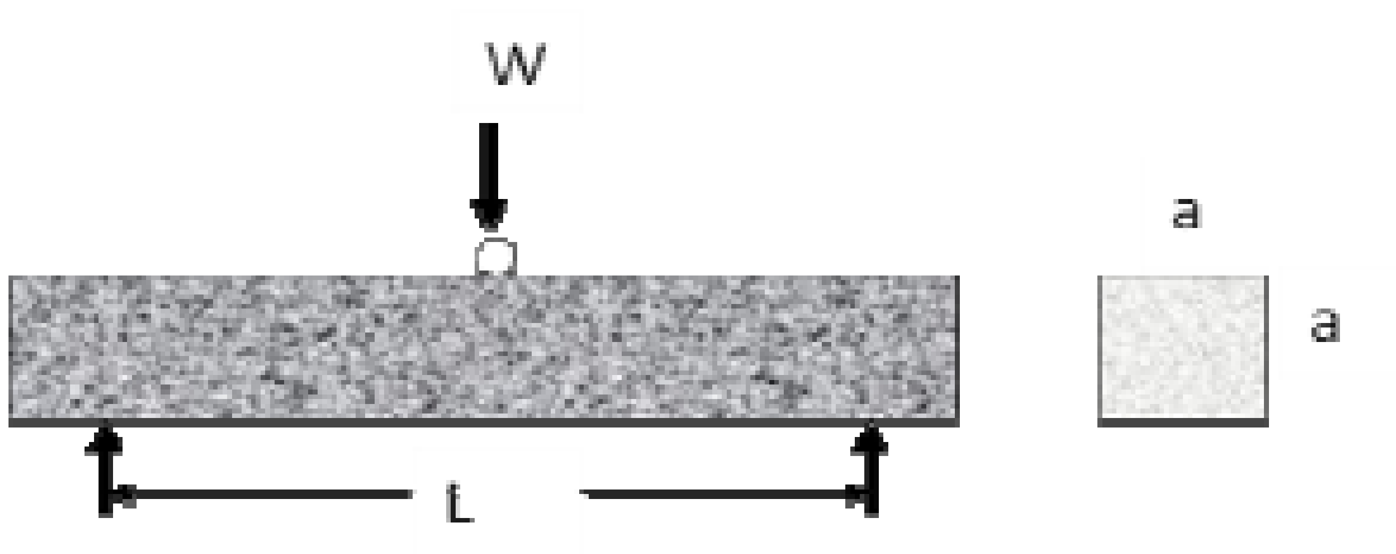
Determination of Modulus of Elasticity of CC

- Testing of Cube or Cylinder in uni-axial Compr test.
- Measure Load and the corresponding Deformation as the Load is increased. Draw the Stress-Strain Curve.
- Strain =Dial gauge reading/gauge length = dl/L
- Stress = Load/Cross sectional area= P/A
- Use Compressometer and Extensometer to measure → Deformations. Draw Stress Strain Diagram and determine → Modulus.
- Deflection: E can be determined from testing of Beam also.

‘E’ by Testing a Beam

For central point load

Max. deflection, $\delta = WL^3/48EI_{xx}$



Poisson Ratio

- Poisson effect. When a material is Compressed in one Direction, it usually tends to → Expand in the other 2 Directions perpendicular to the direction of Compression. This phenomenon is called the Poisson Effect.
- Poisson's Ratio μ. is a measure of the Poisson effect.
  - The Poisson Ratio is the ratio of the fraction (or %) of Expansion divided by the fraction (or %) of Compression
  - for small values of these changes. $\mu = 0.15 - 0.20$
  - Actual value to be found from Strain measurements on Concrete Cylinder using Extensometer.
- In Analysis and Design of some type of Structures, the knowledge of Poisson's Ratio is required.

Poisson Ratio – UPV Test

- An alternate method for finding Poisson's ratio is from → UPV Test and by finding → the Fundamental Natural Frequency of Longitudinal Vibration of CC Beam.
- The Poisson's Ratio is slightly HIGHER and it ranges from 0.2 - 0.24.
- The Poisson's ratio can be found from the following equation.

Where V = Pulse velocity mm/s
n = Resonant frequency in Hz and
L = Length of the beam in mm.
ρ = The density of concrete
E_d = Dynamic modulus of elasticity of concrete

$$\left(\frac{V^2}{2nL}\right)^2 = \frac{1-\mu}{(1+\mu)(1-2\mu)}$$

$$E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$$

Factors affecting Modulus of Elasticity

1. Cement and aggregate factors. Since CC is a composite material, consisting of Cement Paste and Agg, its Modulus of Elasticity depends on the Moduli of Elasticity and the Volume Fractions of Cement Paste and Agg, as follows:

$$E_c = [\ \{(1-V_a)E_p + (1+V_a)\ E_a\} / \ \{(1+V_a)E_p + (1-V_a)\ E_a\}]E_p$$

Where, E_c = modulus of elasticity of concrete

E_p = modulus of elasticity of cement paste

E_a = modulus of elasticity of aggregate

V_a = volume fraction of aggregate = $1-V_p$

V_p = volume fraction of cement paste = $1-V_a$

- E_p depends on the porosity of cement paste and the porosity of cement paste depends on the gel/space ratio (E_p is approximately proportional to the cube of the gel/space ratio) and gel/space ratio finally depends on the w/c ratio (gel/space ratio is inversely proportional to w/c ratio)

  Note: The reason behind relating E_p with compressive strength of concrete lies in the fact that the compressive strength is also affected in the same way as E_p

- E_a for lightweight aggregates is found to be much lower than that for the normal weight aggregate. This is why the elastic modulus of lightweight concrete is less than that of the normal-weight aggregate ($E_{c,\ light\ weight\ concrete} = 0.4$ to $0.8\ E_{c,\ normal\ weight\ concrete}$)

2. Moisture Condition Factor

- The Moisture Condition of the Specimen is a Factor: Modulus of Elasticity a Wet Specimen is > Dry Specimen, by 3 to 4 GPa
- Note: The Effect of Moisture Condition of Specimen is → REVERSE in case of the Compr Str

3. Condition of Curing

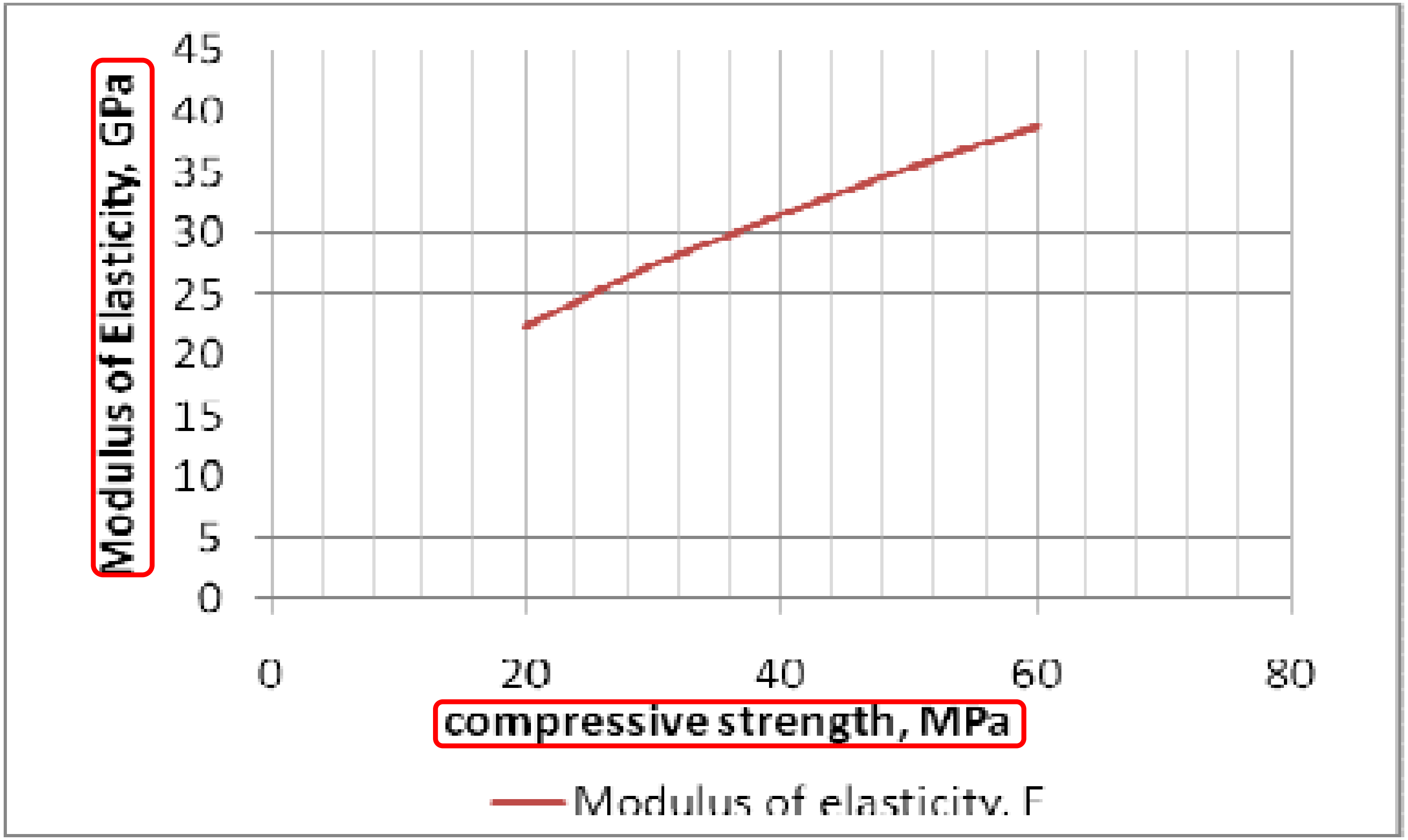
- Another factor affecting the Modulus of Elasticity of CC is the manner in which the Test Cylinders were Cured. In general, CC Specimens that were Cured in Moist Conditions resulted in → a Modulus value HIGHER than those Cured in Dry conditions.
  - This is due to the fact that → in Dry conditions CC is more likely to have → Drying Shrinkage.
  - Drying Shrinkage causes → Small Cracks. These Small Cracks thus will cause the CC to have → a REDUCED Modulus of Elasticity.

4. Age of concrete: As Age increases → E increases

5. Mix Proportion (C + A + W): All ingredients will have its own effect. For a given mix, the effect of one variable should be considered → keeping all other variables constant.

6. Strength of CC: As Str increases → E increases as shown in Table

Variation of modulus of elasticity (GPa) with compressive strength (MPa) for concrete	
Compressive strength, fck, MPa	Modulus of elasticity, E, GPa
20	22.4
30	27.4
40	31.6
50	35.4
60	38.7


45
40
35
30
25
20
15
10
5
0
Modulus of Elasticity, GPa
0
20
40
60
80
compressive strength, MPa
Modulus of elasticity, E

7. Rate of Loading. As the rate of loading increases → E also increases as → the Creep effect is LESS.

8. Size and Shape of Specimen - Cube vs Cylinder, Small vs Large

9. Effect of Transition Zone

- The Void Spaces and the Micro-Cracks in the Transition Zone play a major role in affecting the Stress-Strain behavior of CC.
- The Transition Zone characteristics affect the Elastic Modulus more than it affects the Compr Str of CC.
- Silica fume, meta-kaolin, RHA in CC have significant effect on E

SHRINKAGE

SHRINKAGE

- Shrinkage is the REDUCTION in the Volume of a Freshly Hardened CC → exposed to the ambient Temp and Humidity
- Reduction in the Volume due to Shrinkage causes → Volumetric Strain.
- Volumetric Strain = 3 * Linear Strain
- In practice, *Shrinkage is measured simply as a Linear Strain*

TYPES of SHRINKAGE

- Shrinkage in CC is caused *mainly by → Loss of Water by*
  - *Evaporation*
  - *Hydration of Cement.*
- However, Cooling and Carbonation *may also* cause the Shrinkage
- Following are the various Cl of Shrinkage, depending upon the cause of Shrinkage:
  - 1. Types of Shrinkages, *caused due to → Loss of Water*
    - *Plastic Shrinkage*
    - *Drying Shrinkage*
    - *Autogenous Shrinkage*
  - 2. Types of Shrinkages, *caused due to → Cooling and Carbonation*
    - *Thermal Shrinkage*
    - *Carbonation Shrinkage*

Types of SHRINKAGES, caused *due to* LOSS OF WATER

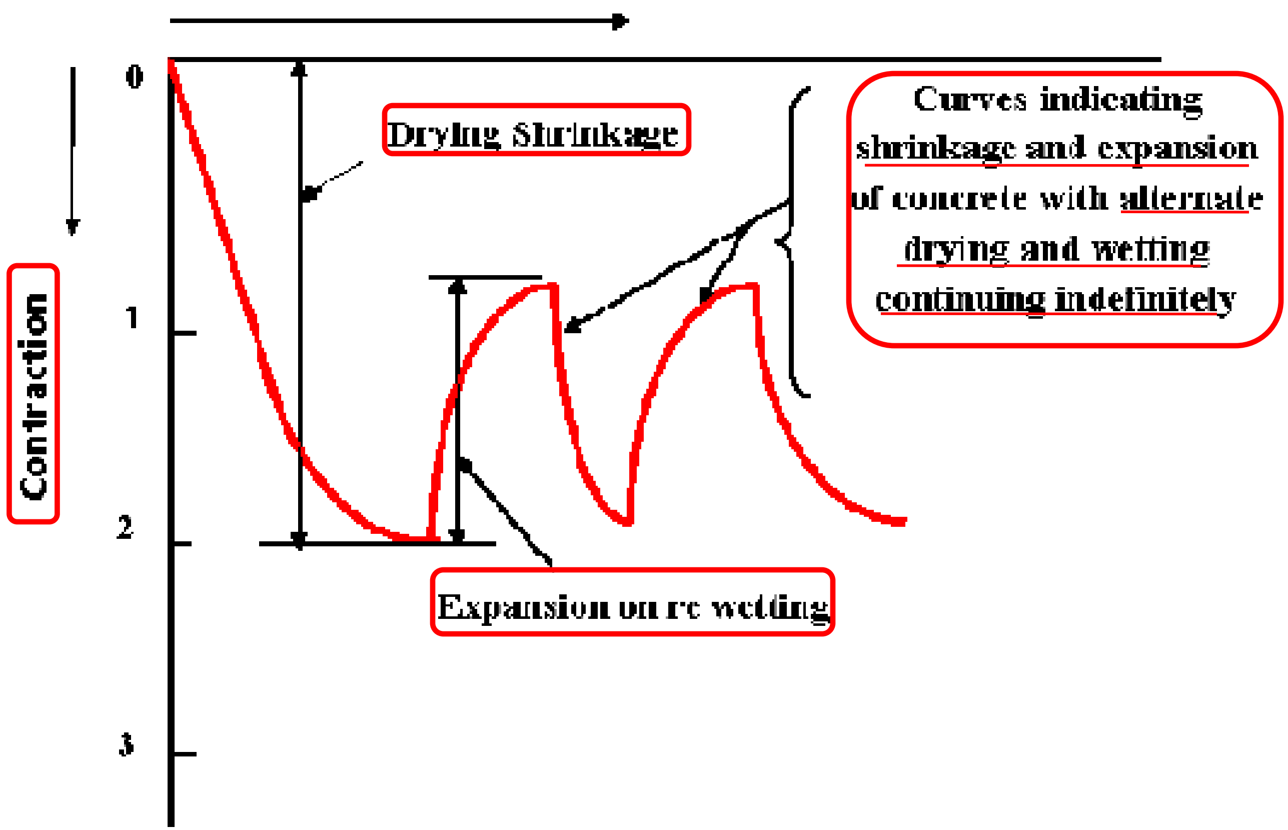
1. Plastic Shrinkage.

- Occurs due to Loss of Water by evaporation from ***Freshly Placed CC***, while the Cement Paste is Plastic
- Plastic Shrinkage is HIGHER → at a HIGHER Rate of Evaporation of Water, which in turn depends on
  - *Air Temp*
  - *CC Temp*
  - *RH of Air*
  - *Wind Speed*
- Plastic Shrinkage of CC is HIGHER → at a LARGER Cement Content (i.e. SMALLER the Agg Content by Volume) of the Mix.

2. Drying Shrinkage

- Occurs due to Loss of Water by evaporation from **Freshly Hardened CC** exposed to air
- As shown in the following Fig., when the CC which has undergone Drying Shrinkage is subsequently placed in Water (or at Higher Humidity) → it will swell due to absorption of Water by the Cement Paste → getting partial recovery from the Shrinkage
  - The amount of Shrinkage recovered on placing the CC in water (or at higher humidity) is called → *"Reversible Moisture Movement or Reversible Shrinkage" and*
  - the un-recovered shrinkage is called →*"Residual or Irreversible Shrinkage"*
- Therefore, Drying shrinkage = Reversible Shrinkage + Irreversible Shrinkage

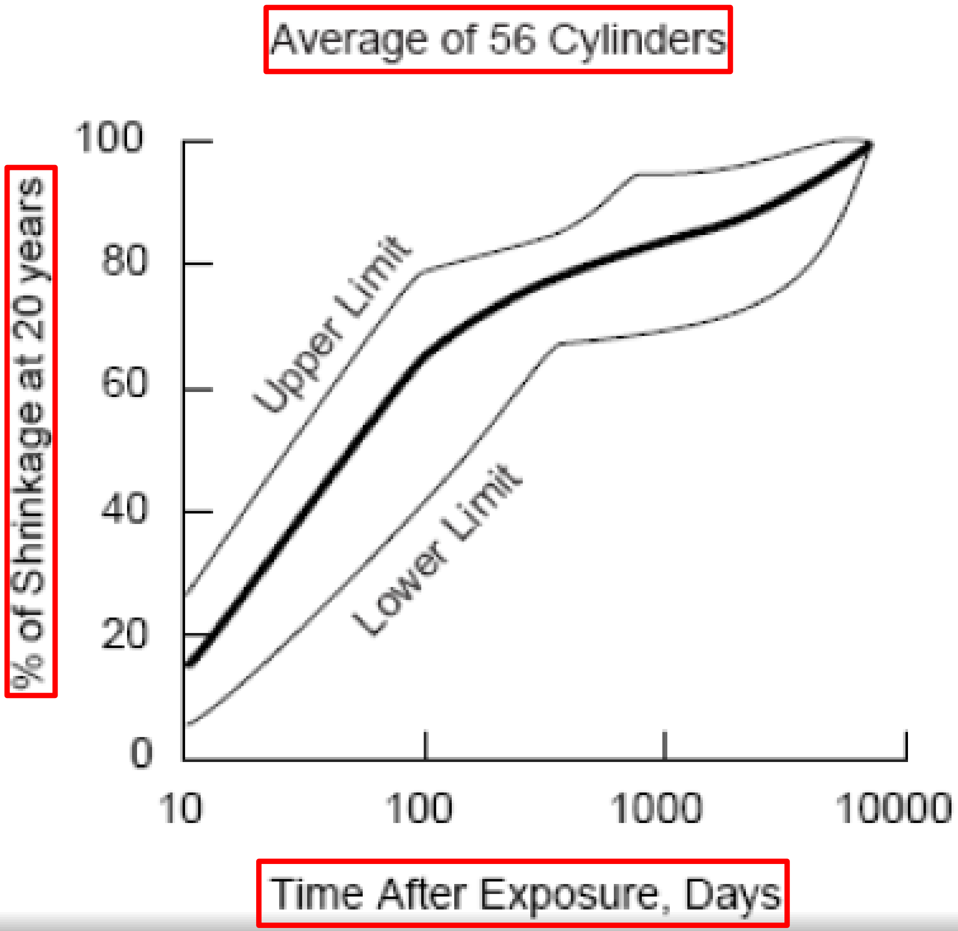
- Reversible Shrinkage
  - 40 to 70 % of Drying Shrinkage
  - Reversible Shrinkage will form a GREATER proportion of the Drying Shrinkage if CC is Cured so that → it is fully Hydrated before being exposed to drying
- Irreversible Shrinkage will form a GREATER proportion of the Drying Shrinkage
  - if CC is NOT fully Hydrated before being exposed to drying, or
  - drying is accompanied by Extensive Carbonation, or
  - Both
- The Pattern of Drying Shrinkage (i.e. Moisture Movement) under alternating Wetting and Drying (a common occurrence in practice) is shown in the following Fig:



0
1
2
3
Contraction
Drying Shrinkage
Curves indicating shrinkage and expansion of concrete with alternate drying and wetting continuing indefinitely
Expansion on re wetting

(3) Effects of Time - Shrinkage and creep increase with time.

Drying Shrinkage versus Time



3. Autogenous shrinkage *occurs due to loss of water by Self-Desiccation of CC* during Hydration

- Self-Desiccation is a phenomenon by virtue of which Concretes, with a Low W/C ratio (theoretically < 0.42), begin to DRY OUT
  - due to the Internal Consumption of Water during Hydration and
  - NOT due to the Loss of Water to the Outside by Evaporation
- Autogenous shrinkage is VERY SMALL → typically 50×10^{-6} to 100×10^{-6}

Types of **SHRINKAGES**, caused *due to* **COOLING** *and* **CARBONATION**

- Types of Shrinkages, caused *due to Cooling and Carbonation*
  - *(a) Thermal Shrinkage occurs due to excessive fall in Temp*
  - *(b) Carbonation Shrinkage occurs due to Carbonation*
- *"Carbonation" is the process in which*
  - *the CO_2 gas present in the atmosphere forms* Carbonic Acid in the presence of Moisture.
  - The Carbonic Acid reacts with the $Ca(OH)_2$ of Hydrated Cement to form $CaCO_3$.
  - This process of Carbonation causes contraction of CC known as → Carbonation Shrinkage.
- Carbonation Shrinkage depends on → the rate of Carbonation; and the rate of Carbonation depends on the various Factors, namely;
  - Permeability of CC,
  - Moisture Content of CC, and on
  - CO_2 content and Relative Humidity of the Atmosphere
- Carbonation Shrinkage is → *in addition to* the Drying Shrinkage and adds to the Total Shrinkage.

Thermal Shrinkage: Thermal Properties of CC

Coefficient of thermal expansion (μ)

– The length change per unit length per degree of temperature change.

– It can be estimated from the weighted average of the coefficients of thermal expansion of its components, i.e. the aggregate and the cement mortar. – Typical value of α for concrete varies from 6 to 12 X 10-6 /°C and for steel = 11 X 10-6 /°C

- Concrete expands on heating and contract on cooling.
- Thermal expansion or contraction strain (εT) is linearly related to coefficient of thermal expansion (μ) and the change in temperature (εT), $\varepsilon T = \mu \, \Delta T$
- If the concrete is fully restrained, the induced stress due to the temperature change (ΔT) will be equal to: $\sigma T = E(\mu \, \Delta T - \varepsilon cr)$

- At the early ages of concrete, concrete usually rises in temperature as the cement hydrates. This results in compressive stresses. However, stress relaxation is high and E is low at early ages. Therefore, the resulting compressive stress will be small, and usually does not cause any problem.

  However, when the concrete cools down to the ambient temperature from its peak temperature, the temperature drop will cause thermal shrinkage and may induce a tensile stress in the concrete.

- In mass concrete, the difference between the peak temperature of the concrete and the ambient temperature could be very large, and the temperature drop could induce a tensile stress to cause thermal cracking of the concrete.

FACTORS INFLUENCING SHRINKAGE

1. Effect of cement paste and aggregate content

- In concrete, shrinkage is induced by the cement paste but restrained by the aggregate
- For a constant water/cement ratio, and at a given degree of hydration, the relation between shrinkage of concrete (s_{hc}), shrinkage of neat cement paste (s_{hp}), and the volumetric content of aggregate (V_a) is given as:

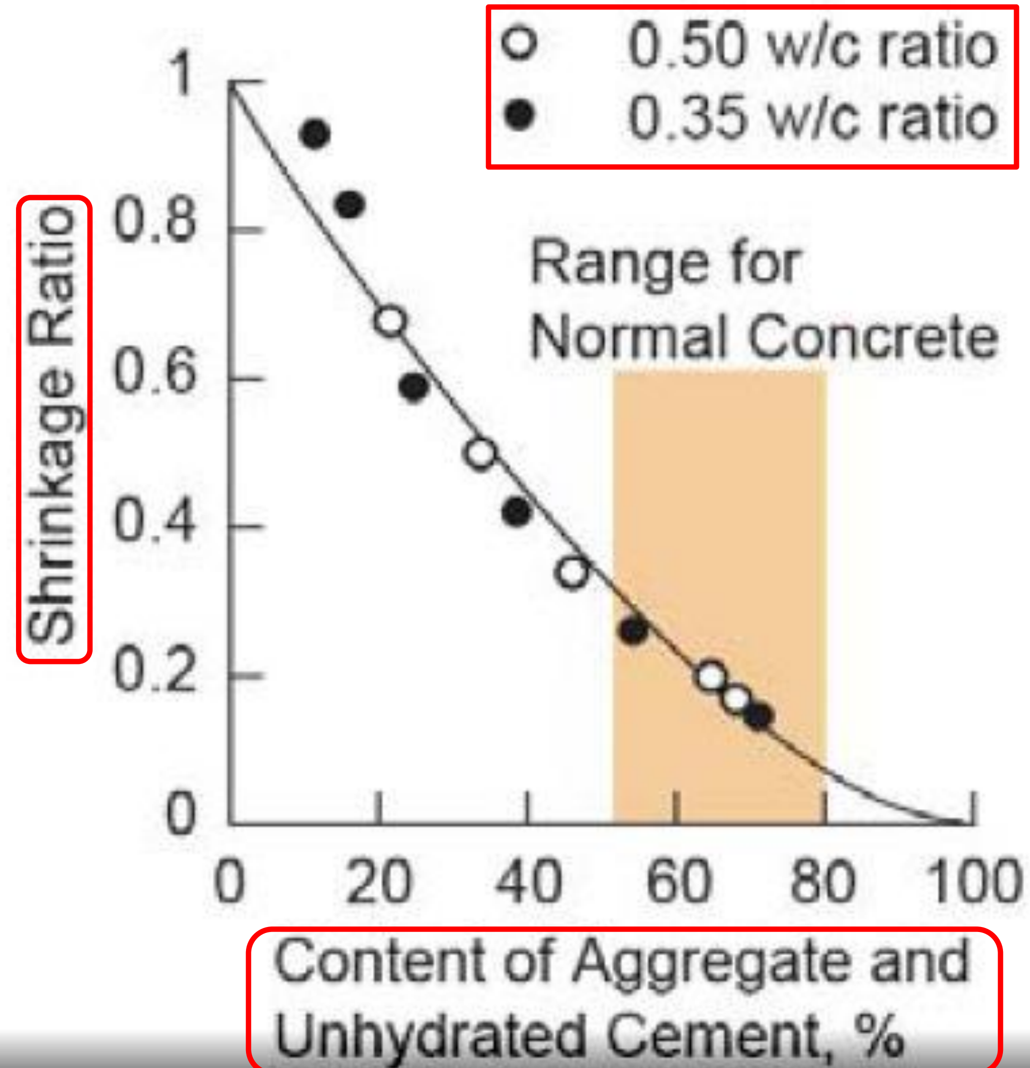
$$s_{hc} = s_{hp}\,(1 - V_a)^n = s_{hp}\,(V_p)^n$$

where, n = a constant which depends on the moduli of elasticity and Poisson's ratios of the aggregate and of the concrete

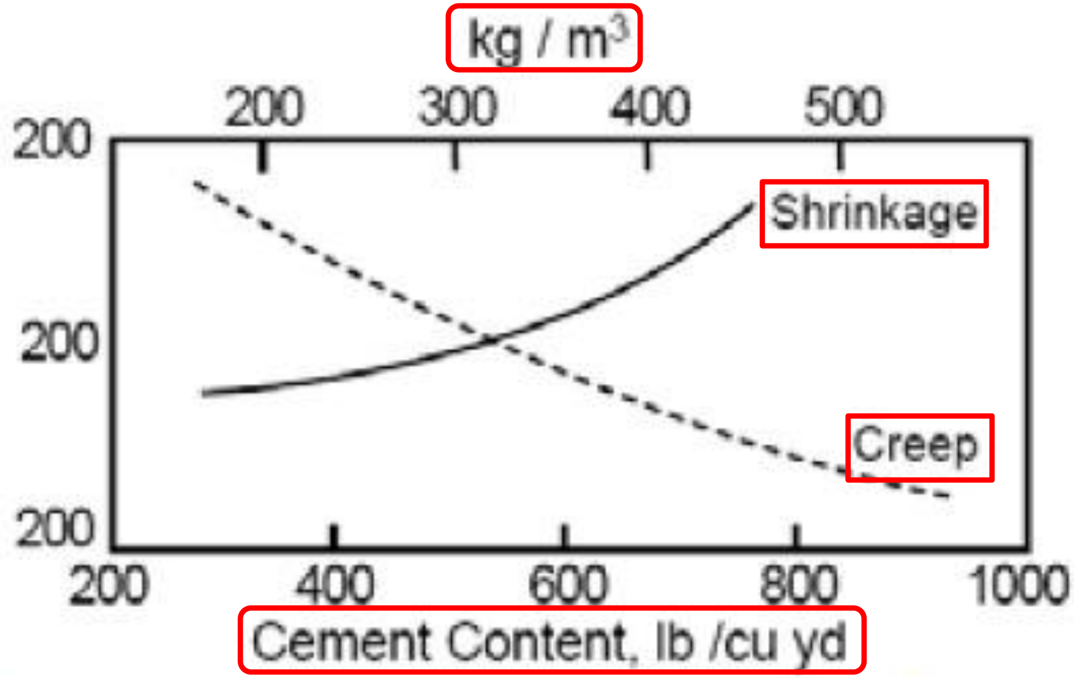
V_a = volumetric fraction of aggregate = $1 - V_p$

Effects of Aggregate Volume Fraction on Shrinkage of Concrete

S_c/S_p



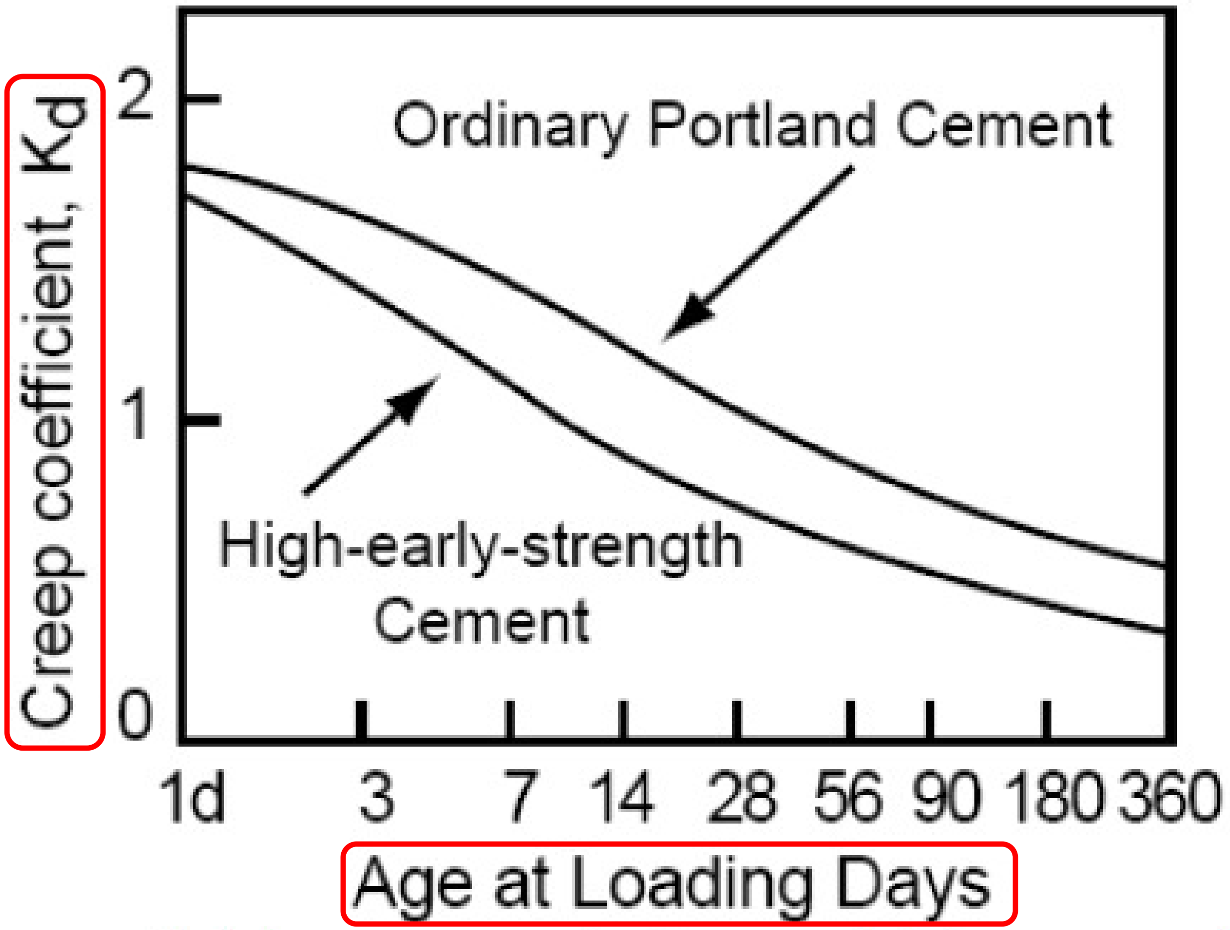
Effects of Cement Content on Drying Shrinkage and Creep



* An increase in cement content increases the cement paste volume, which increases drying shrinkage.

* The effect on creep is reversed. The increase in strength due to a higher cement content has a dominating effect in reducing the creep.

(2) Effects of Concrete Strength - An increase in concrete strength reduces shrinkage and creep.

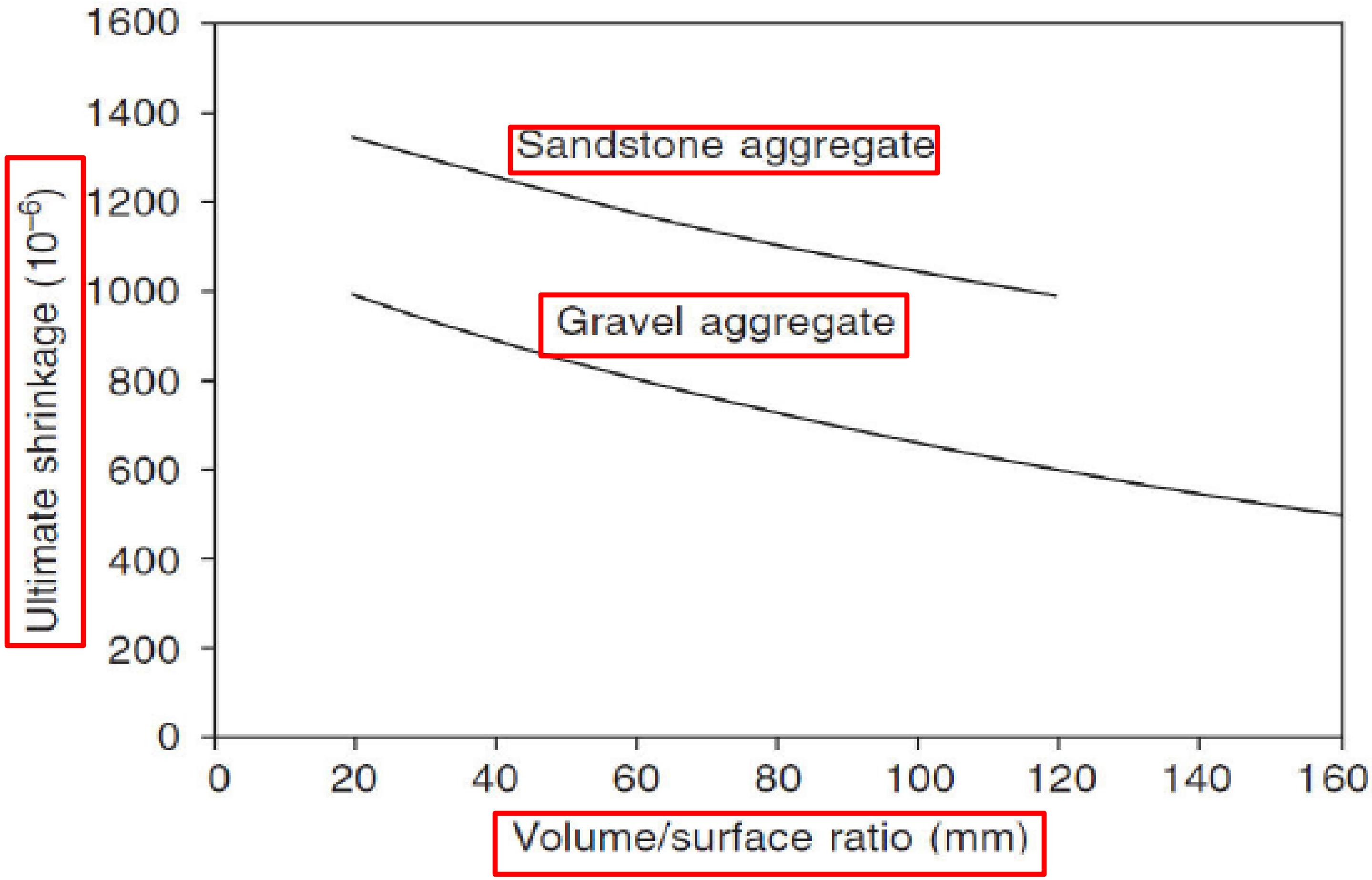


Effects of Cement Type on Creep of Concrete

* A lower creep is due to a higher strength of the concrete.

2. *Effect of type of aggregate*
(Strictly speaking effect of modulus of elasticity of aggregate)

A *lightweight concrete* made with lightweight aggregate *exhibits a higher shrinkage than normal weight concrete* made with normal weight aggregate. This is because of the lower modulus of elasticity of lightweight concrete as compared to normal weight concrete

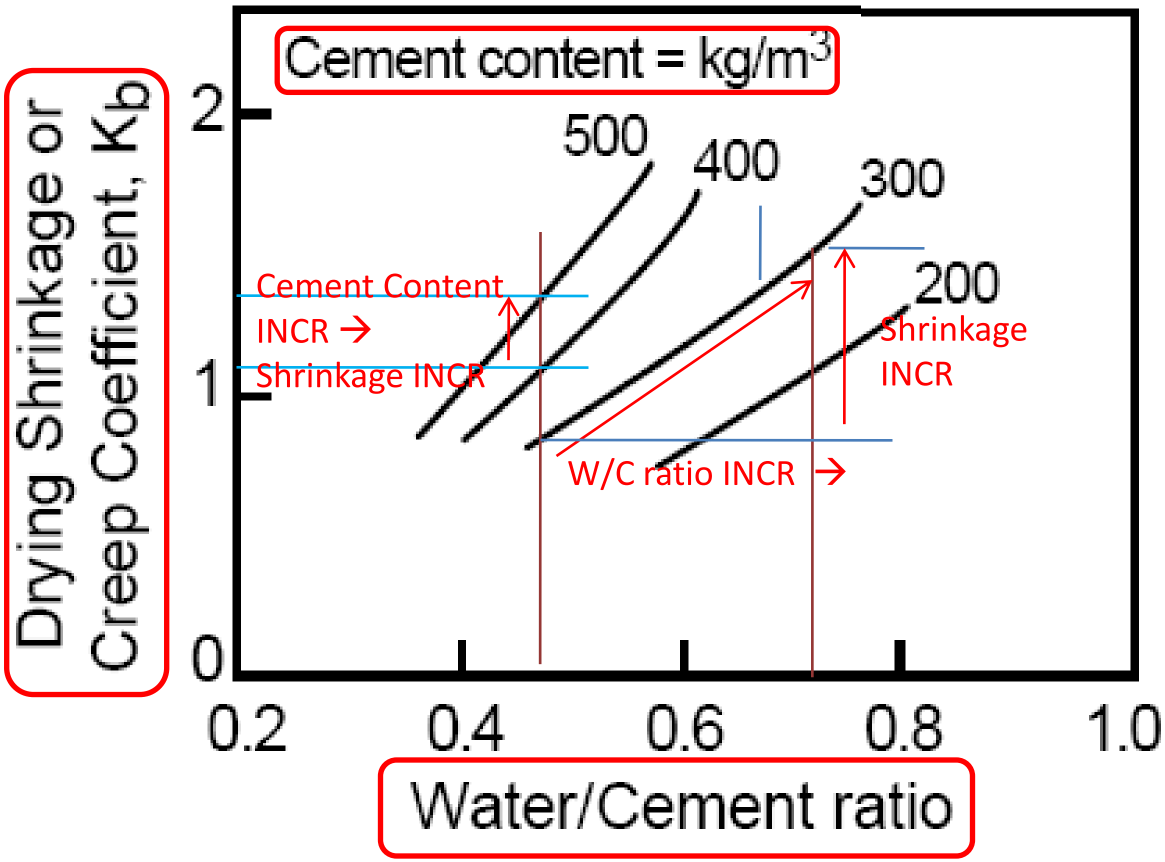


Influence of volume/surface ratio on shrinkage of concrete

3. Effect of W/C ratio

- HIGHER the W/C ratio → LARGER the Shrinkage

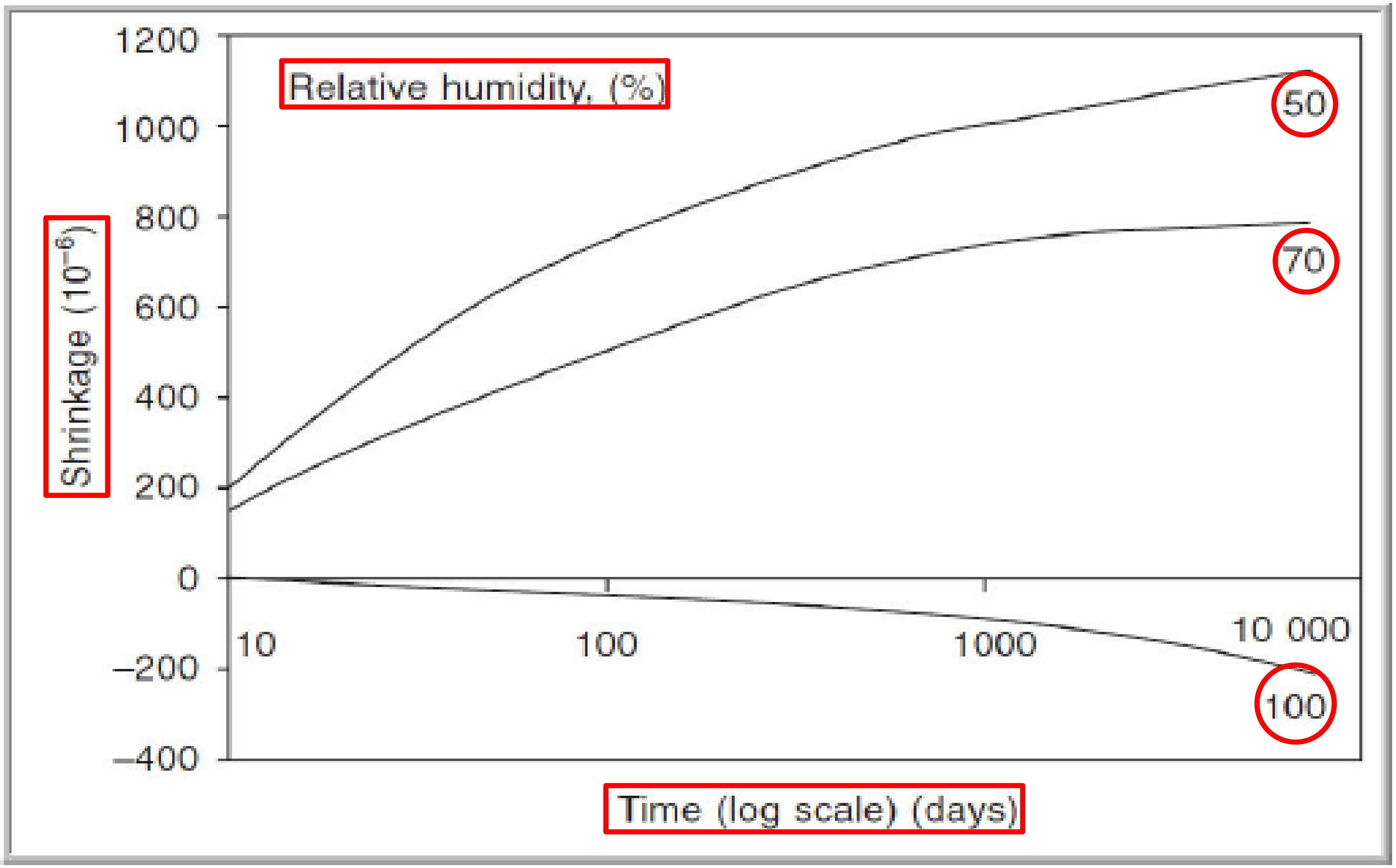
Effects of Cement Content and Water-Cement Ratio on Drying Shrinkage of Concrete



* Higher drying shrinkage is caused by a higher cement paste volume fraction.

4. Effect of relative humidity

- As shown in the following Fig., the relative humidity of the air surrounding the concrete greatly affects the magnitude of shrinkage



- Shrinkage is more at lower relative humidity

5. Effect of time

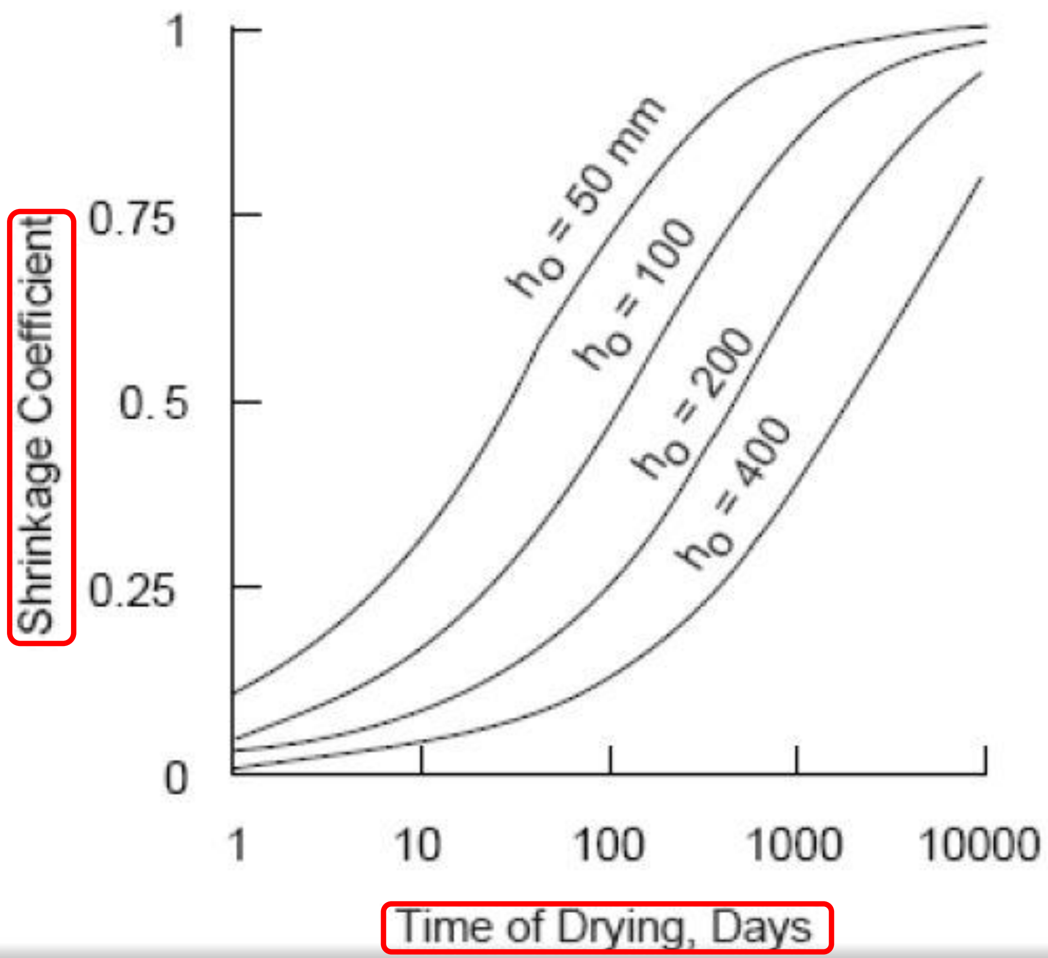
- Shrinkage takes place over long periods. However, *large fraction* of the ultimate shrinkage (which is mainly the drying shrinkage) *takes place at early times* and the *small fraction* of the ultimate shrinkage (which is mainly the carbonation shrinkage) *takes place over long periods*

Percent of 20-year shrinkage	*Occurs in*
14 to 34	2 weeks
40 to 80	3 months
66 to 85	1 year

6. Effect of Size and Shape of the CC Member

- The Actual Shrinkage of a given CC member is affected by its Size and Shape
- Generally, *Shrinkage is expressed as a function of the ratio Volume/Exposed Surface*
- Relation between the Logarithm of Ultimate Shrinkage (vs) Volume/surface ratio → Linear

Influences of Exposure Time and Specimen Size on Shrinkage



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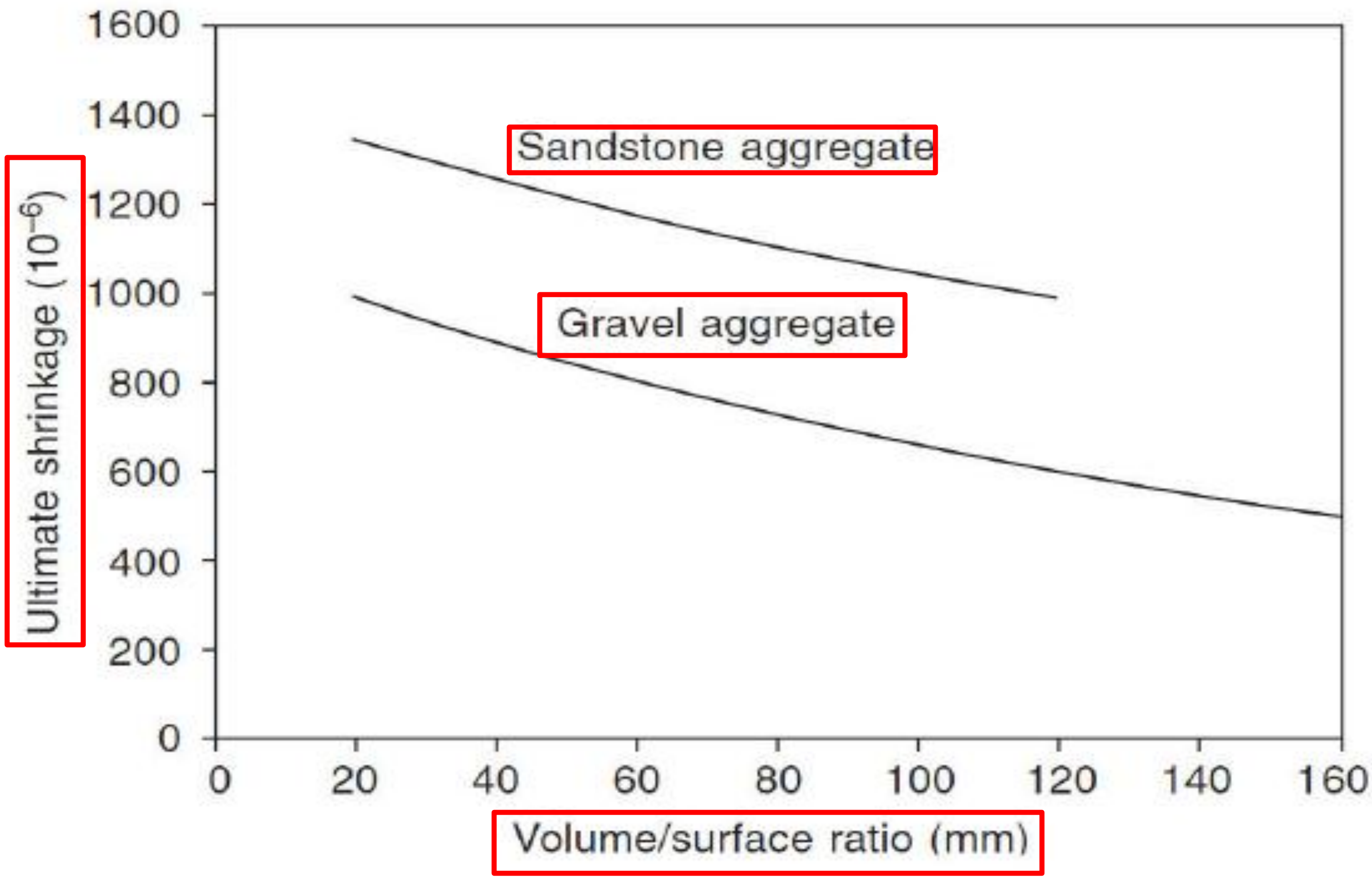
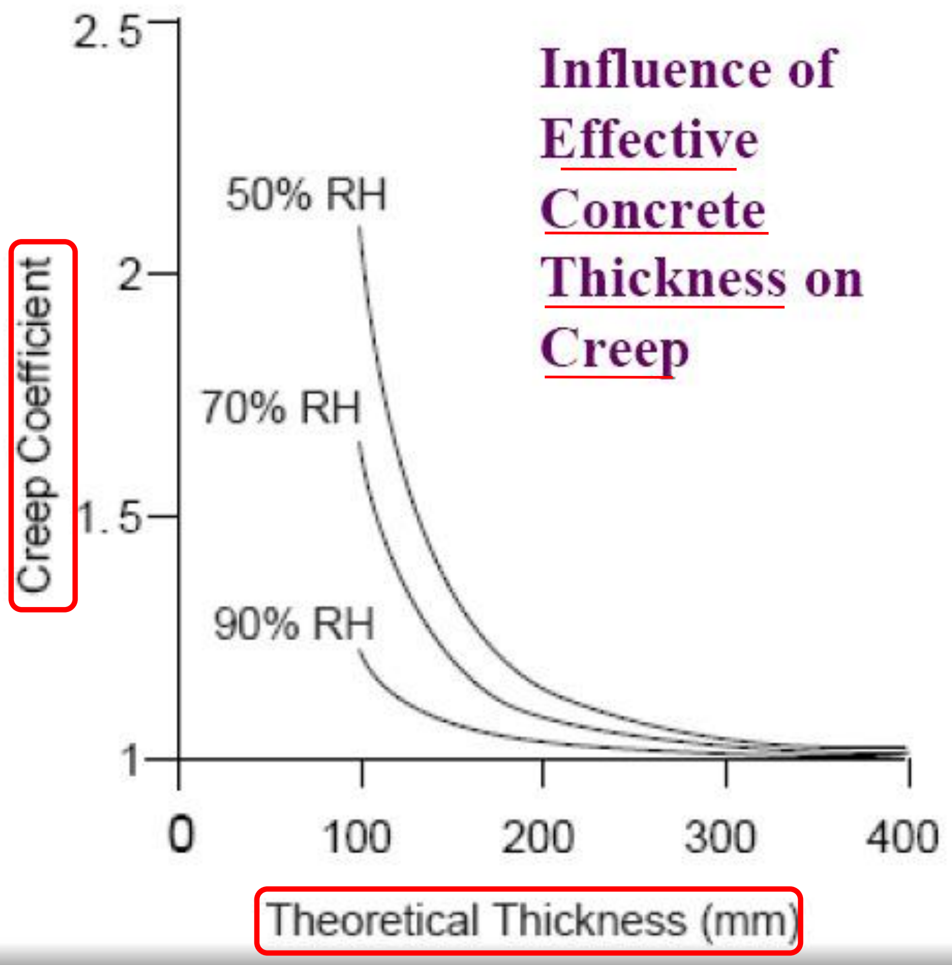


Influence of volume/surface ratio on shrinkage of concrete

(5) Effects of Effective Thickness - Shrinkage and Creep decrease as the length of path traveled by water to the atmosphere increases.



Influence of Effective Concrete Thickness on Creep

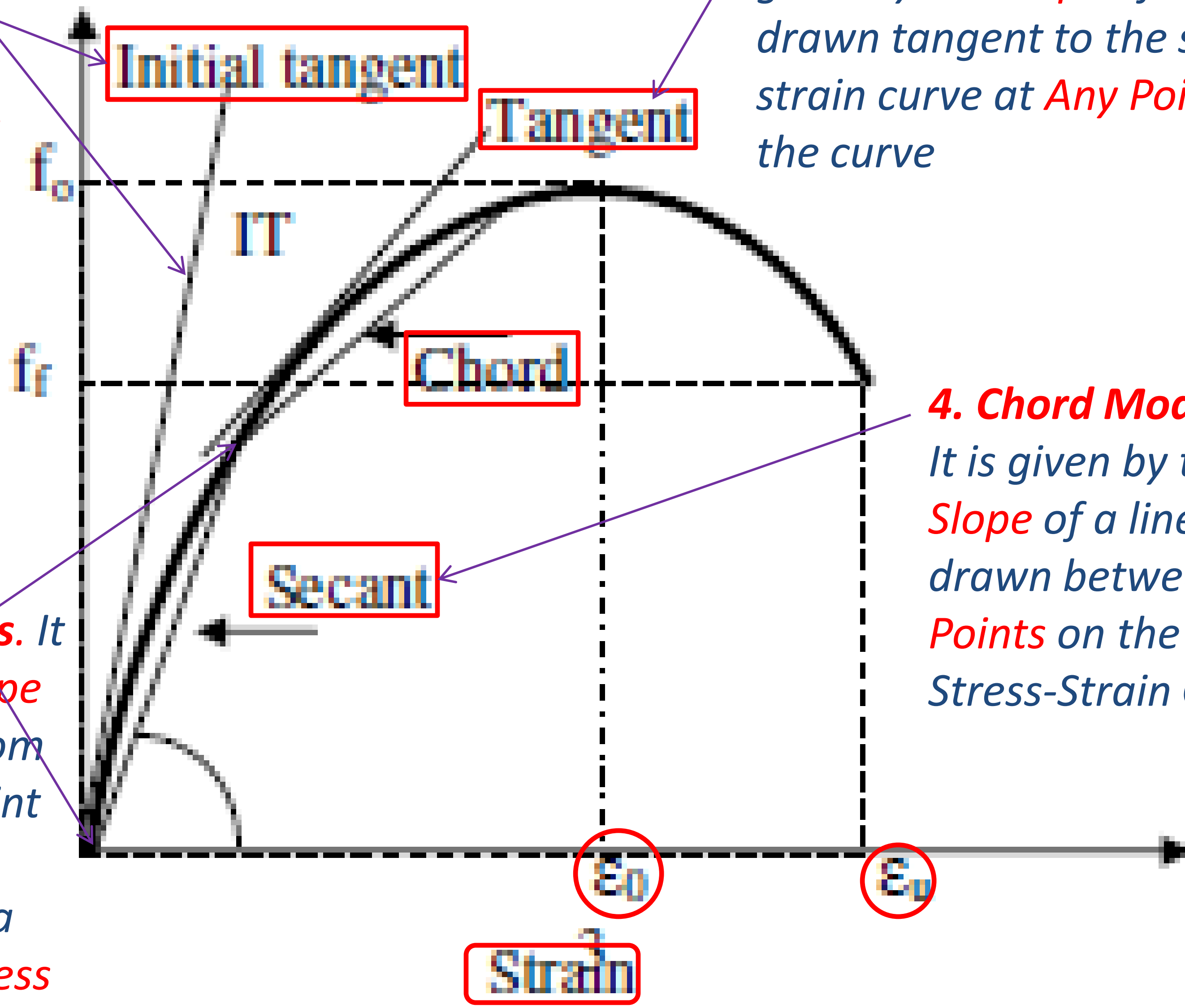
CREEP

CREEP

- Creep is defined as
  - the INCREASE in Strain under a sustained Constant Stress
  - after taking into account other Time-Dependent Deformations not associated with Stress viz.
    - *Shrinkage*
    - *Swelling and*
    - *Thermal Deformations*
- Creep is counted from → Initial Elastic Strain, $б_0$ */E, where*
  - $б_0$ *is Compr Stress* applied to the CC, after curing for time *t0 and*
  - *E is the Secant Modulus of Elasticity* of CC.
- *Stress Relaxation*
  - It is DECREASE in Stress with Time due to Creep of a CC member: (loaded and restrained so that → it is subjected to a Constant Strain).

1. Initial Tangent Modulus. It is given by the Slope of a line drawn Tangent to the Stress-Strain Curve at the Origin

2. Tangent Modulus. It is given by the Slope of a line drawn tangent to the stress-strain curve at Any Point on the curve

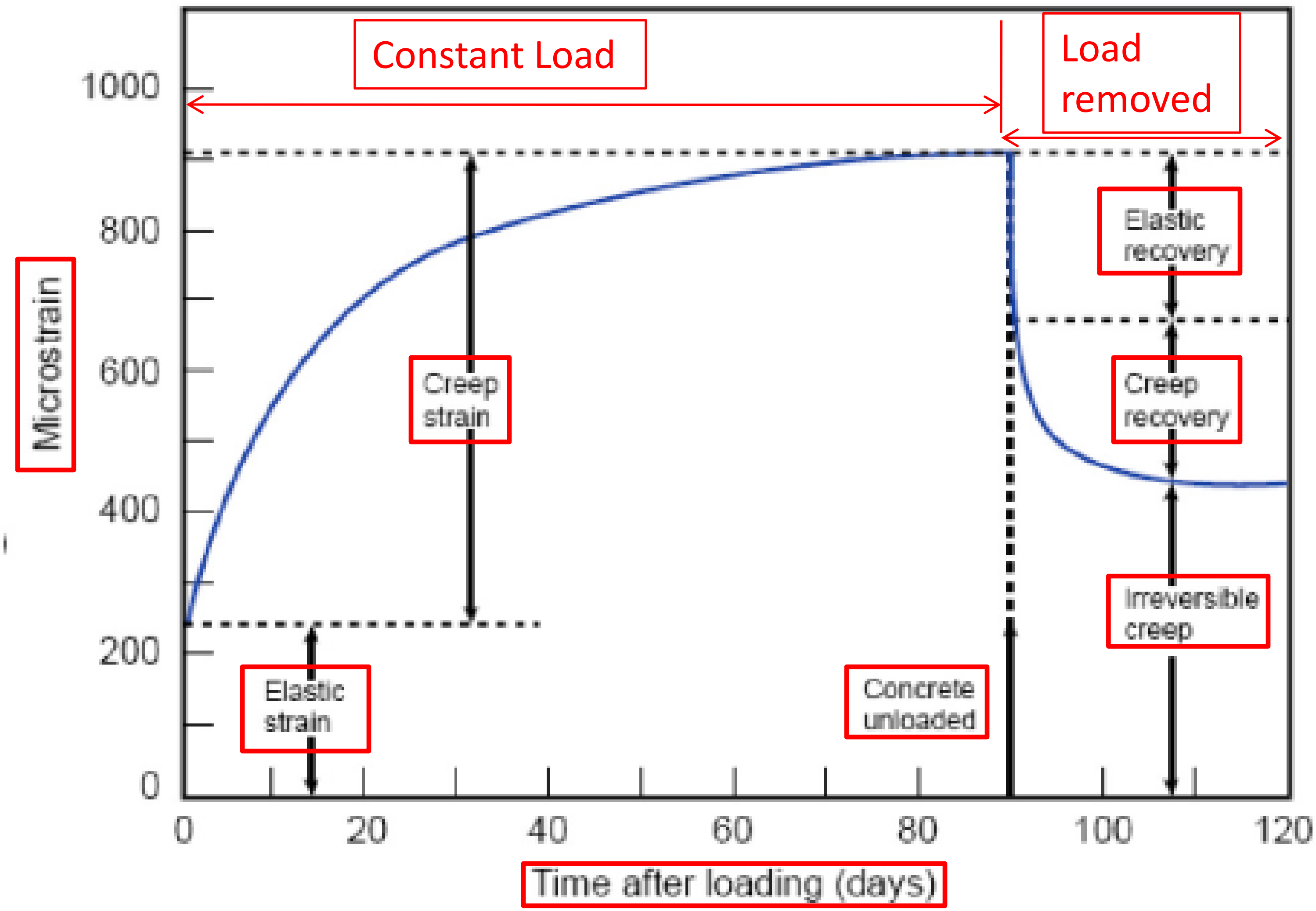


3. Secant Modulus. It is given by the Slope of a line drawn from the Origin to a Point on the Curve corresponding to a 40% of Failure Stress

4. Chord Modulus. It is given by the Slope of a line drawn between 2 Points on the Stress-Strain Curve

CREEP AND CREEP RECOVERY

The creep and creep recovery are illustrated with the help of a typical creep curve for plain concrete, as follows:



DEFORMATION OF HARDENED CC

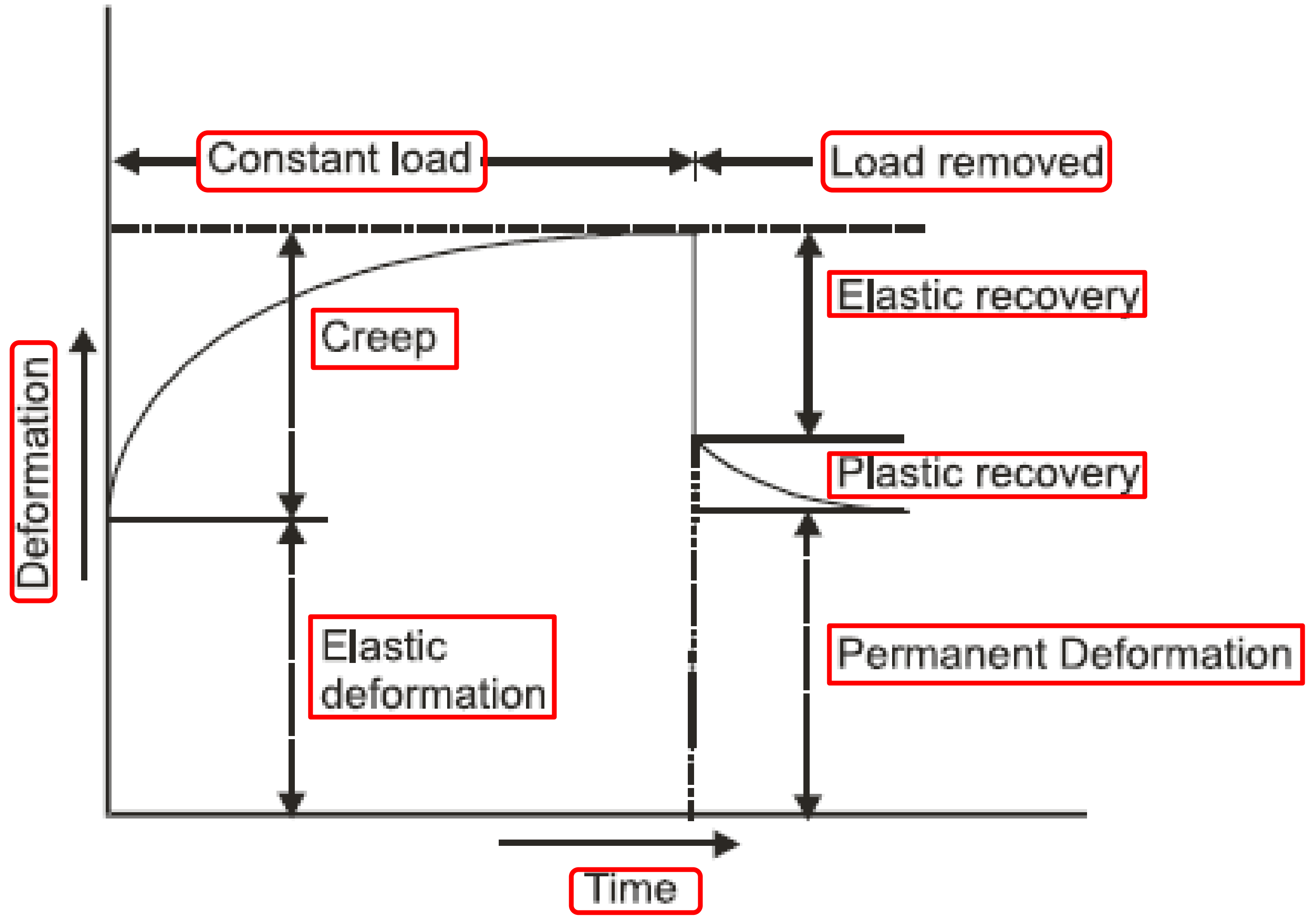


Fig. 10.37 Deformation of Hardened Concrete

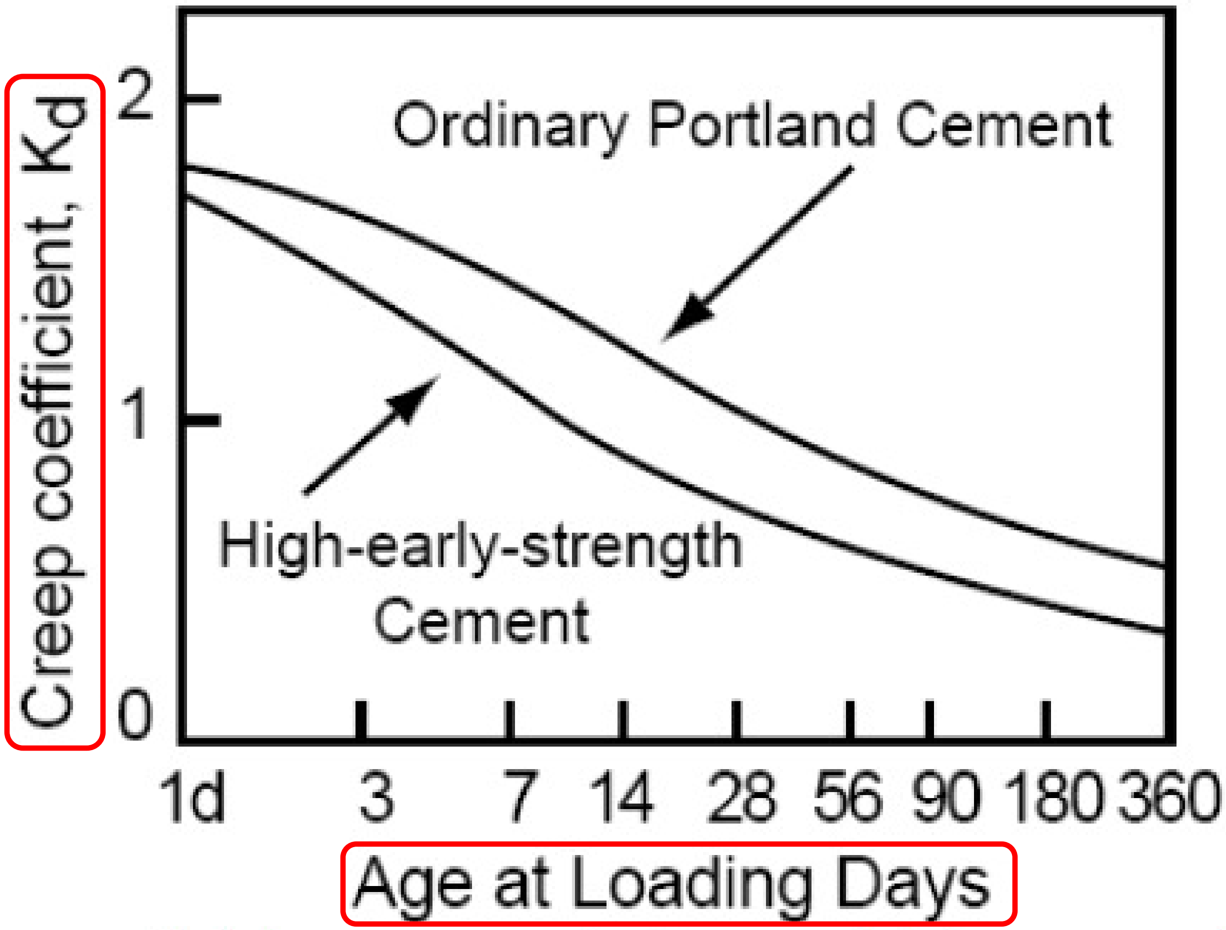
Factors influencing CREEP

- 1. Modulus of Elasticity of Agg
- 2. Agg Content
- 3. W/C ratio
- 4. Age at Application of Load
- 5. Relative Humidity
- 6. Volume/Surface ratio of Member
- 7. Temp
- 8. Time

Creep development with time

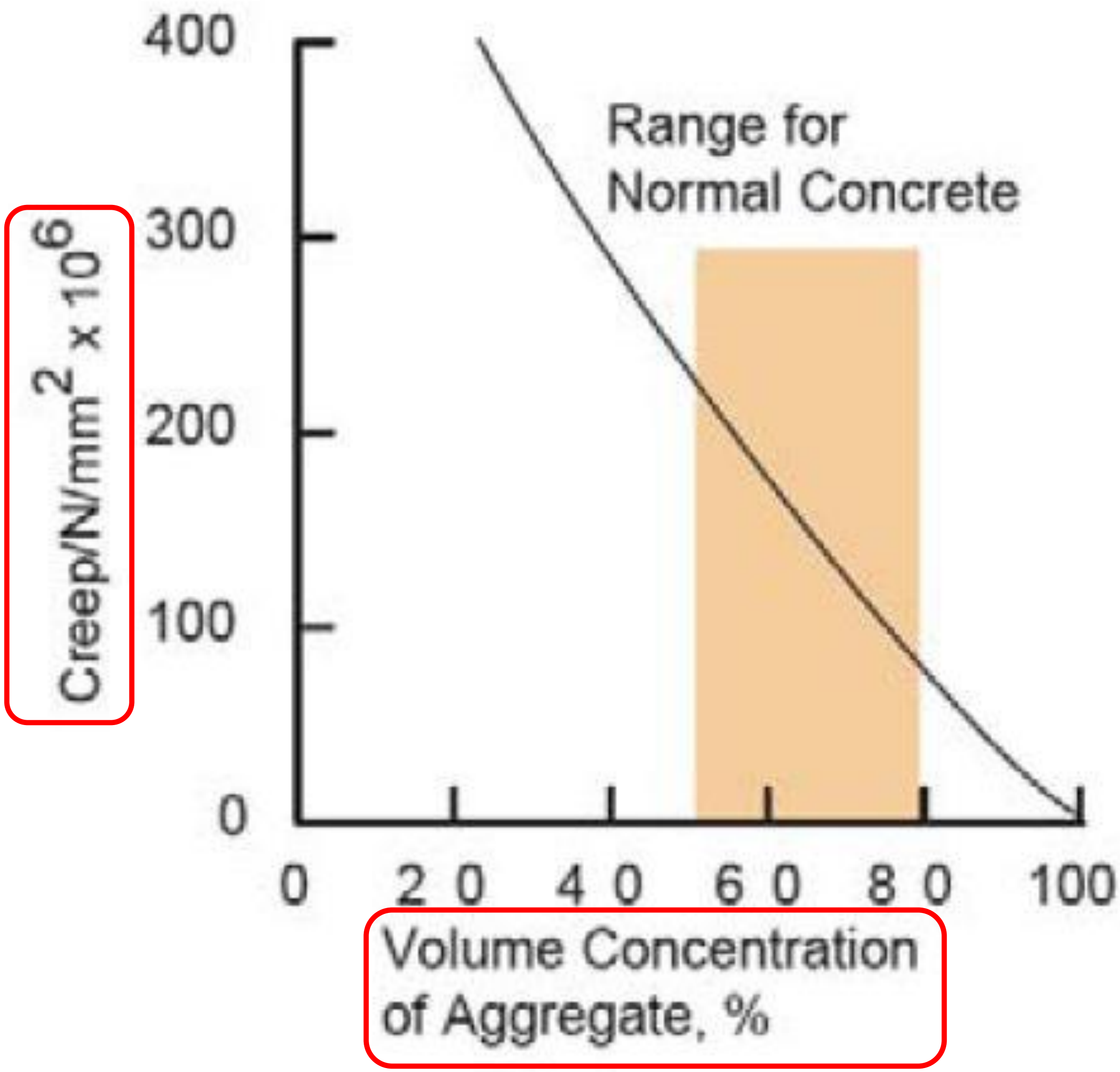
Percent of 20-year creep	*Occurs in*
25	2 weeks
50	3 months
75	1 year

(2) Effects of Concrete Strength - An increase in concrete strength reduces shrinkage and creep.



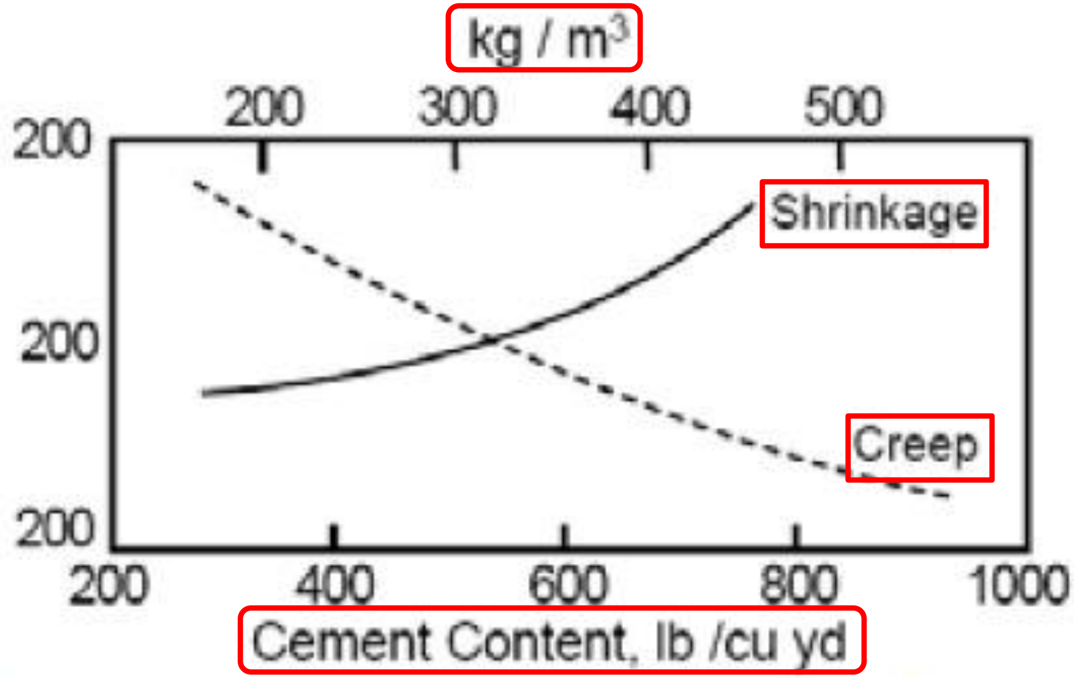
Effects of Cement Type on Creep of Concrete

* A lower creep is due to a higher strength of the concrete.



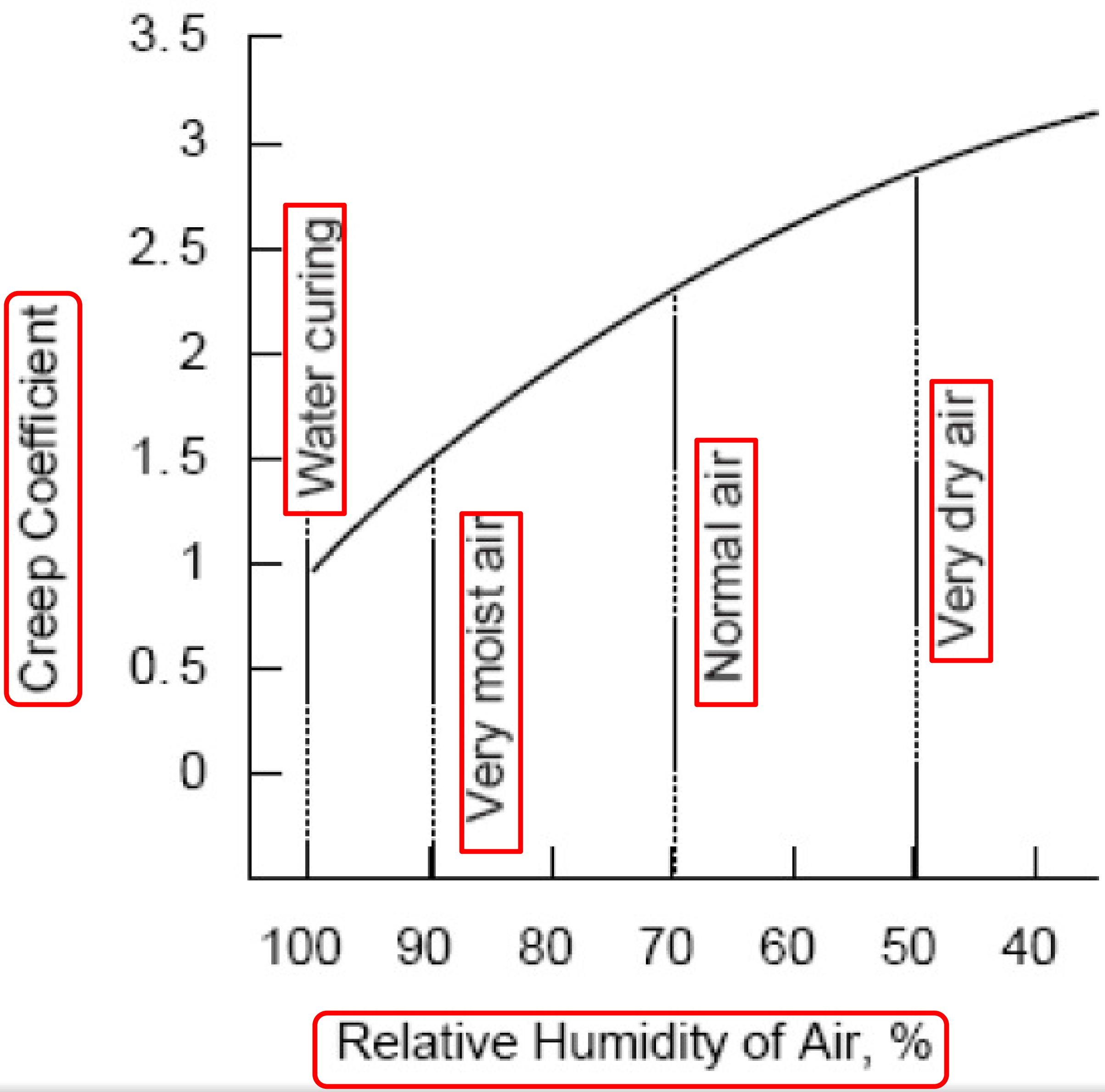
Effects of Aggregate Volume Fraction on Creep of Concrete

Effects of Cement Content on Drying Shrinkage and Creep



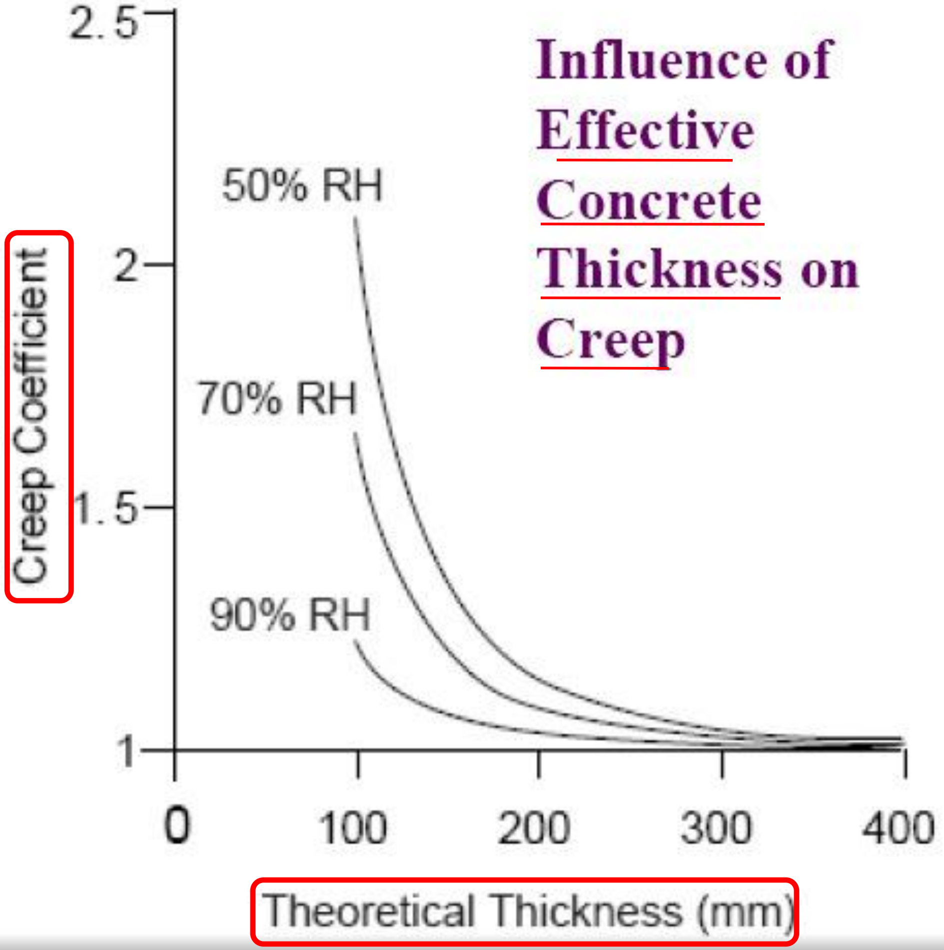
* An increase in cement content increases the cement paste volume, which increases drying shrinkage.

* The effect on creep is reversed. The increase in strength due to a higher cement content has a dominating effect in reducing the creep.



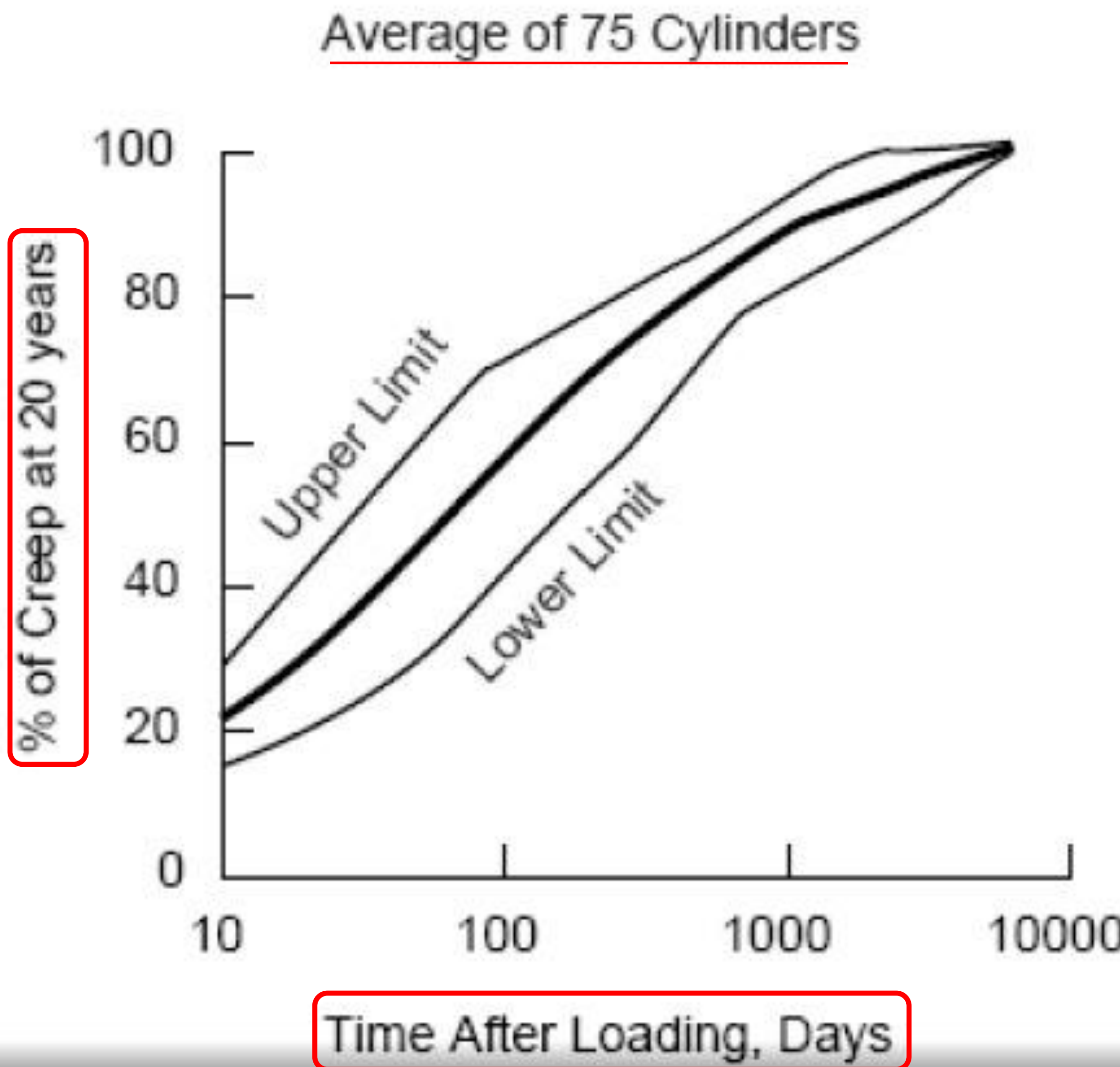
Influences of Relative Humidity on Creep

(5) Effects of Effective Thickness - Shrinkage and Creep decrease as the length of path traveled by water to the atmosphere increases.



Influence of Effective Concrete Thickness on Creep

Creep versus Time



Relation between S_c and S_p; C_c and C_p

(1) Effects of Cement Paste and Aggregate : Drying shrinkage and creep increase as the cement paste volume fraction increases.

* Equation for predicting drying shrinkage of concrete (Sc) from the drying shrinkage of the cement paste (Sp):

Sc = Sp (1 - g)n

where g = volume fraction of aggregate + unhydrated cement

n = 1.2 to 1.7, depending on the elastic modulus of the aggregate. (n decreases as the elastic modulus increases.)

* Equation for predicting the creep of concrete (Cc) from the creep of the cement paste (Cp):

Cc = Cp (1 - g)n

SIMILARITIES between DRYING SHRINKAGE and CREEP

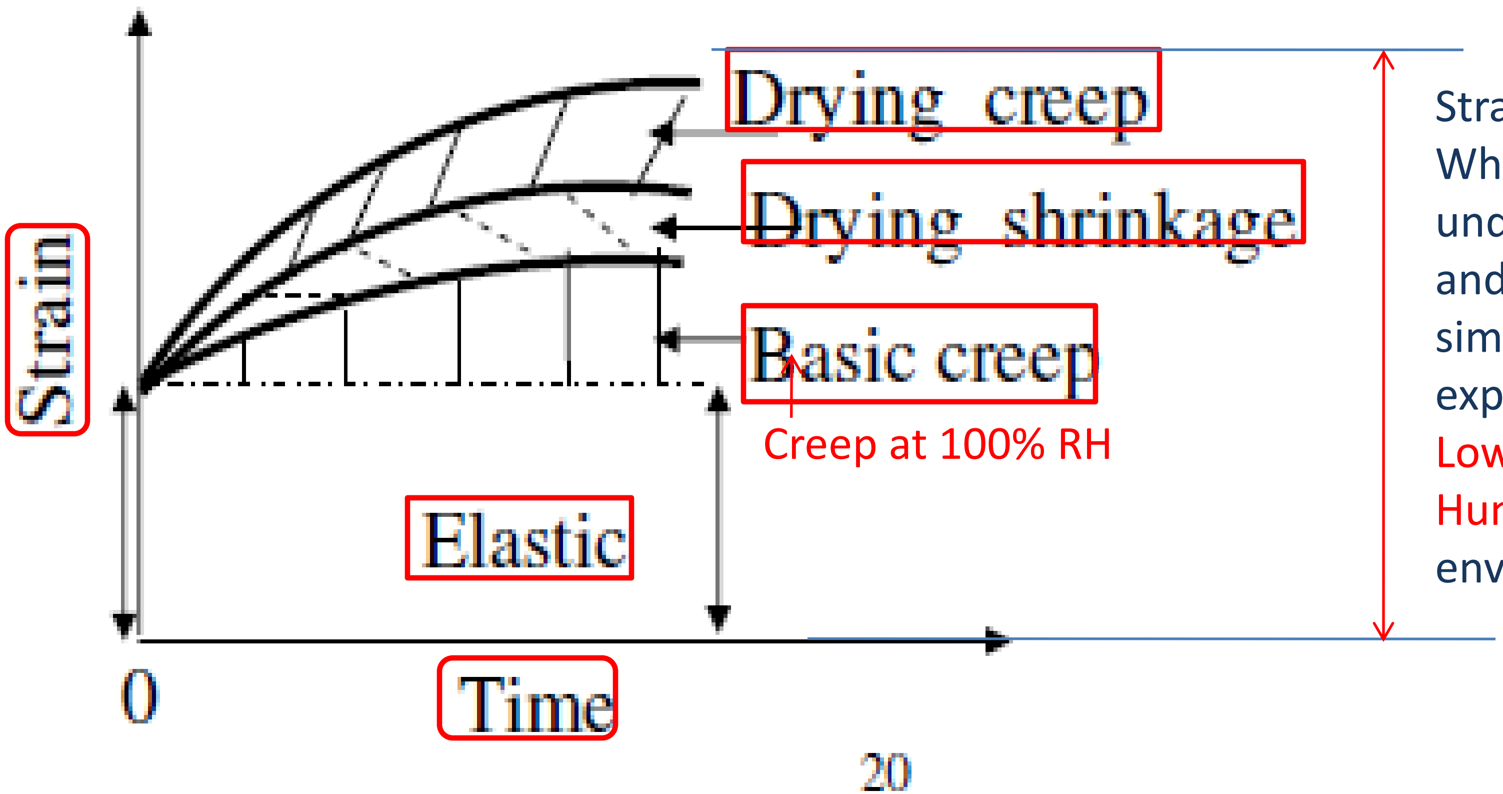
- Both originate from the same source, → Hydrated Cement Paste.
- Their Strain-Time Curves are → SIMILAR.
- Factors that influence Drying Shrinkage also influence the Creep generally → in the SAME manner.
- Both are → Partially Reversible.
- Strains from both Drying Shrinkage and Creep → *can NOT be ignored* in Structural Design

Terminology used in Drying Shrinkage and Creep

- **Basic Creep -** Creep (the increase in Strain over Time under a sustained Stress) of a CC specimen under 100% Relative Humidity.
- **Free Drying Shrinkage -** Drying Shrinkage of a CC when it is Unloaded.
- **Drying Creep.**
  - When CC is under Load and simultaneously exposed to Low Relative Humidity environments,

    Total Strain > Elastic Strain + Free Shrinkage Strain + Basic Creep Strain.
  - The Additional Creep is called → Drying Creep.
- **Specific Creep -** Creep Strain per Unit of applied Stress.
- **Creep Coefficient - Creep Strain / Elastic Strain.**

Strain and Contributing Creep, Shrinkage



Strain
When CC is under Load and simultaneously exposed to Low Relative Humidity environments,