고성능 콘크리트 공학

High Performance Concrete Engineering

<Hardened Properties>

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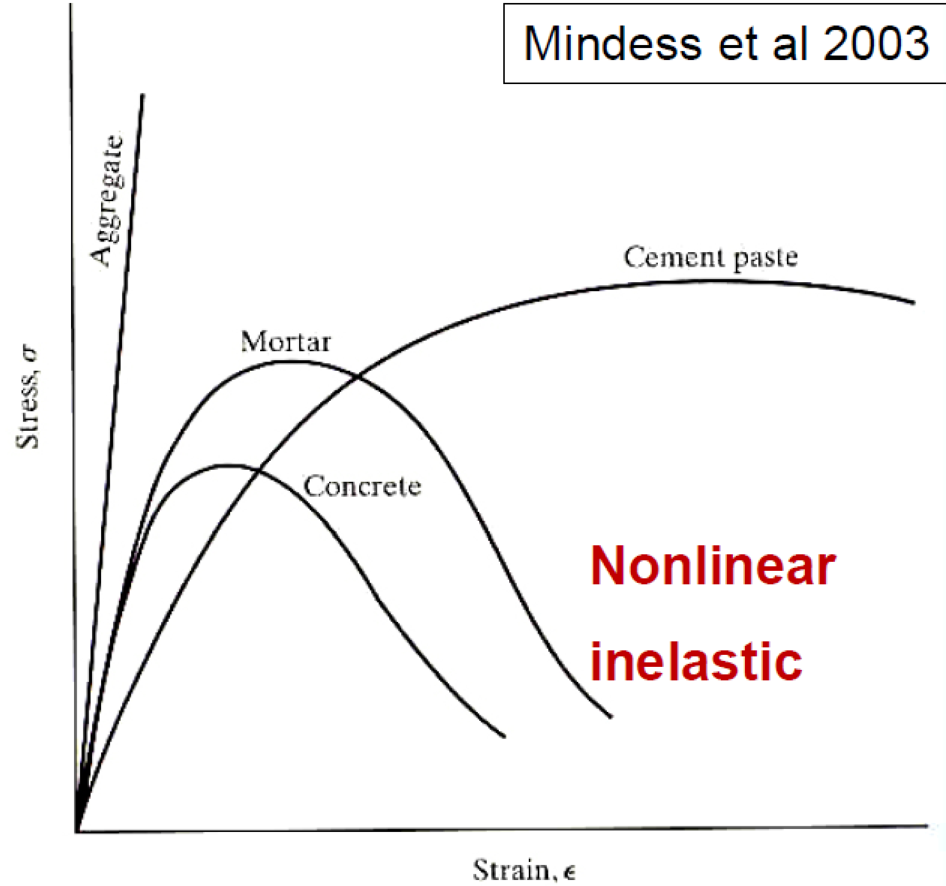
Response of Concrete to Stress & Testing of Hardened Concrete

- Typical σ - ε relationships of cement paste, aggregate, and concrete
- Interfacial transition zone
- Modulus of elasticity
- Tension
- Compression
- Cyclic loading
- Multi-axial states of stress
- Factors affecting strength
  - Characteristics and proportions of materials
  - Curing conditions

Response of Concrete to Stress

- Concrete – a complex heterogeneous material
- Response of concrete to stress depends on
  - Individual components
  - Interaction between the components
- Typical σ - ε curves for aggregate, cement paste, mortar and concrete
  - Coarse aggregate – linear elastic brittle material
  - Cement paste – lower E, higher strength than mortar or concrete



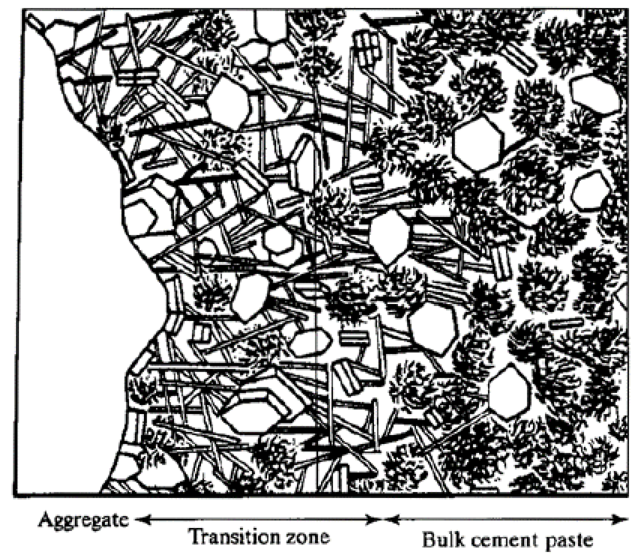
Macroscopic level

Microscopic level

Interface transition zone

Interfacial Transition Zone

- Microstructure of HCP is highly modified in the vicinity of embedded materials: aggregates, fibers, and reinforcing steel
- The modified volume is called interfacial transition zone (ITZ)
- Common features of ITZ
  - Higher w/c due to the wall effect and localized bleeding
  - Increased porosity
  - Less unhydrated cement
  - Less C-S-H
  - Large, oriented crystals of CH
  - Greater concentration of ettringite

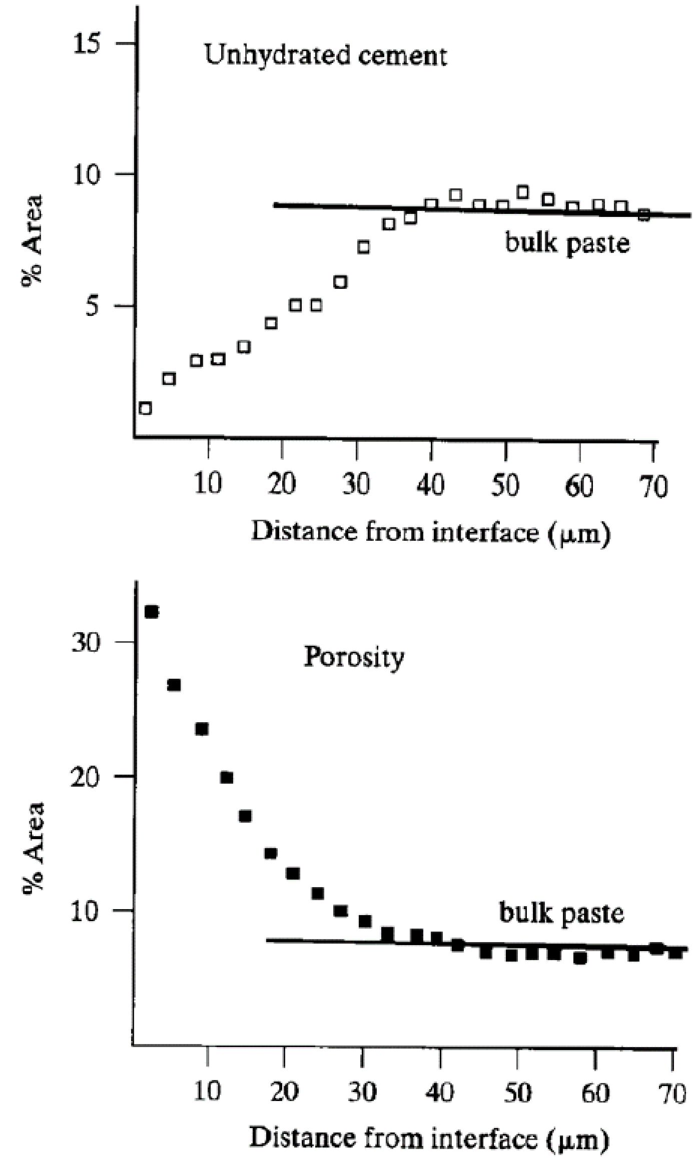


(Mehta & Monteiro 1993)

- Thickness of ITZ: ~20-40 μm
  - vary depends on the size, shape, and volume of aggregate, w/c, mixing and placing procedures

Interfacial Transition Zone (ITZ)

- ITZ makes up 20-40% of total volume of cementitious matrix
- Microcracks may exist in ITZ before concrete is subjected external load
- ITZ plays an important role in mechanical properties and permeability
- In ordinary concrete
  - Fracture occurs preferentially in the ITZ
  - ITZ is "weak link"



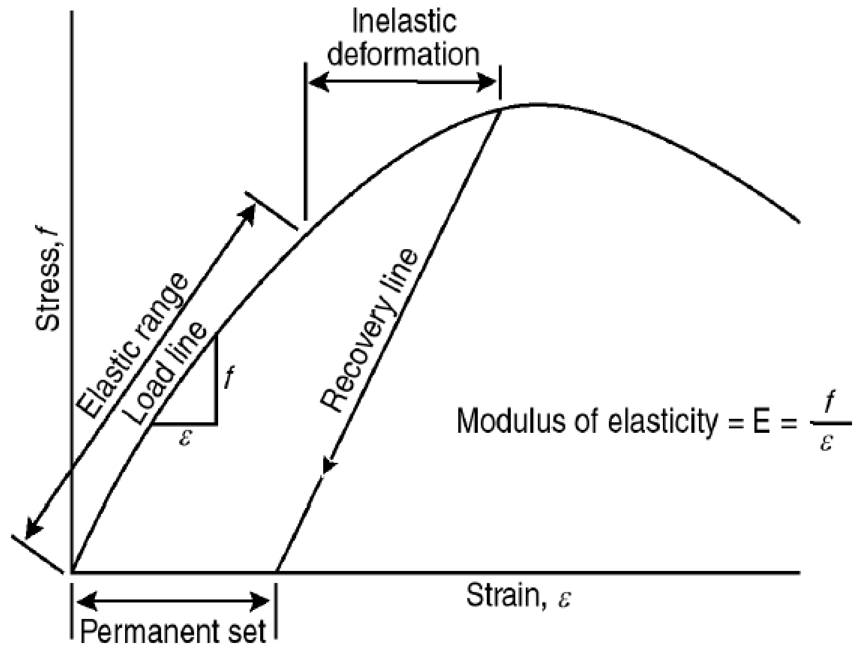
Mindess et al. 2003

Effect of ITZ on Mechanical Properties

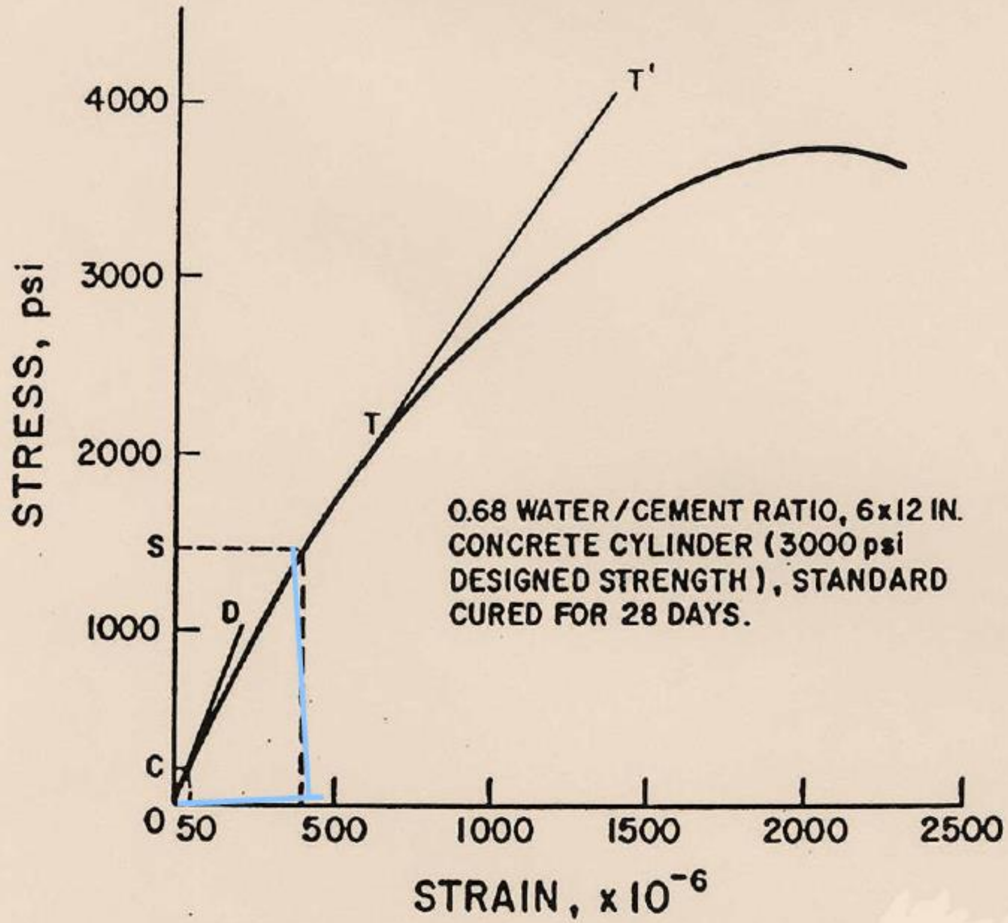
- As the paste-aggregate bond strength ↑, the concrete strength in tension, flexure, or compression also ↑
- For high strength concrete (>70 MPa)
  - ↓ w/c has much greater effect on matrix than ITZ
  - Most effective way of improving ITZ – add silica fume
    - Eliminate large pores
    - Eliminate the growth of CH, transform the CH to C-S-H by pozzolanic reaction
    - Filler effect to reduce bleeding

Modulus of Elasticity

- Concrete is a nonlinear inelastic material both in tension and compression
- Initial tangent modulus
  - Not used in structure design
  - Correspond to small σ and ε
  - Generally 20 – 30 % higher than static E



- Secant modulus
  - Often used in design
  - Difficult to measure, involve error due to
    - Seating
    - Close up of pre-existing cracks under loading
- Chord modulus



Mehta & Monteiro 1993

CALCULATING THE ELASTIC MODULI

σ_{ULT} = 3600 psi
40% σ_{ULT} = 1440 psi = SO

Secant Modulus: Slope of the line corresponding to stress SO = 1440/400 × 10^{-6} = 3.6 × 10^6 psi

Chord Modulus: Slope of the line corresponding to stress SC = (1440-200)/(400-50) × 10^{-6} = 3.5 × 10^6 psi

Tangent Modulus: Slope of the line TT^1 drawn tangent to any point on the σ-ε curve = 2.5 × 10^6 psi

Dynamic Modulus (Initial Tangent Modulus): Slope of the OD from the origin = 1000/200 × 10^{-6} = 5 × 10^6 psi

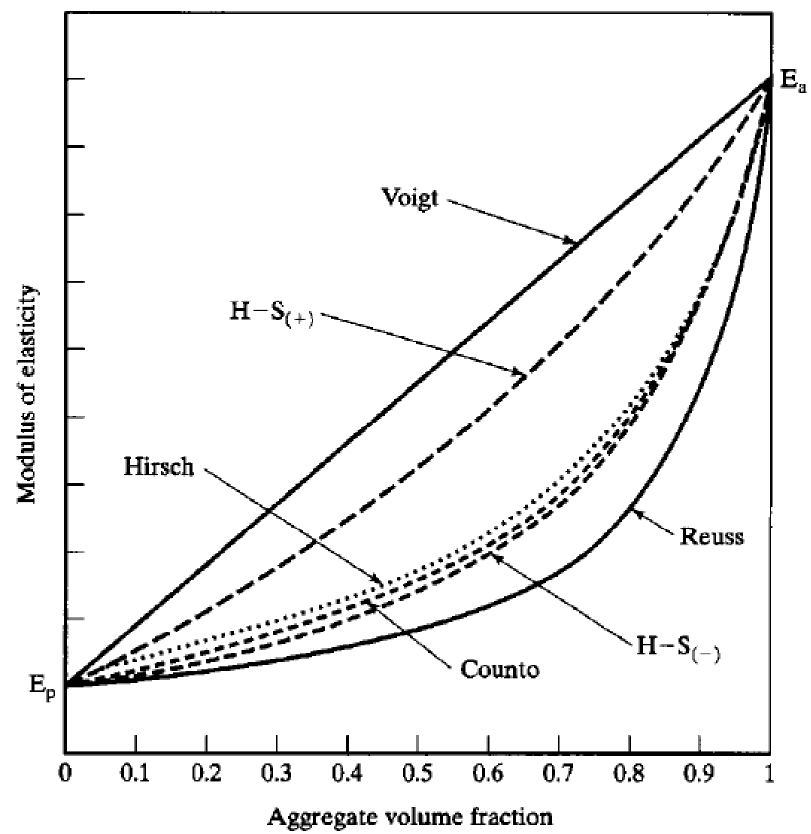
Chord modulus = $(\sigma_s - \sigma_c) / (\varepsilon_s - \varepsilon_c)$

ASTM C 469: ε_c = 50 $\mu\varepsilon$, σ_s = 40% fc

BS 1881, Part 121: σ_c= 0.5 MPa, σ_s = 33% fc

Response as a Composite Material

- Concrete is often modeled as
  - Two-phase composite with aggregate embedded in cement paste (or coarse aggregate in mortar matrix)
  - Three-phase composite in which a 3rd phase represents ITZ
- Two extreme cases
  - Neither models is correct since the components of concrete are subjected to neither uniform stress nor uniform strain under load
- Other models

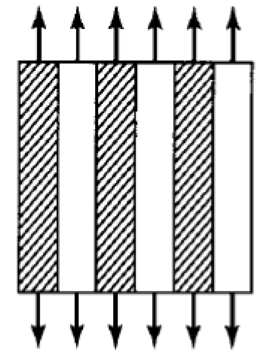


(Mindess et al 2003)

Response as a Composite Material

- Parallel (Voigt) system
  - Uniform strain, upper bound solution

$$E_c = V_p E_p + V_a E_a$$

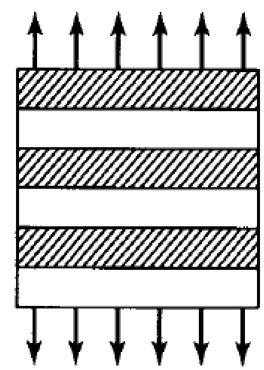


(a) Parallel model

- Series (Reuss) system
  - Uniform stress, lower bound solution

$$\frac{1}{E_c} = \frac{V_p}{E_p} + \frac{V_a}{E_a}$$

  - Underestimate Ec by ~10% for concrete with natural aggregates



(b) Series model

Practical Prediction of E Modulus

- **ACI Building Code 318**

$$E_c = 0.043\, w^{1.5}\, (f'_c)^{0.5} \qquad \text{MPa}$$

Where E_c – secant E (at ~45% of the ultimate strength)

w – unit weight of the concrete

f'_c – compressive strength of 150x300 mm cylinder

($1440 < w < 2480$ kg/m^3, $f'_c < 41$ MPa)

- – Effect of the type of aggregate

TABLE 4–1 EFFECT OF TYPE OF AGGREGATE ON MODULUS OF ELASTICITY

Aggregate type	α_e
Basalt, dense limestone	1.2
Quartzitic	1.0
Limestone	0.9
Sandstone	0.7

(Mehta & Monteiro 1993)

Factors Affecting the Modulus of Elasticity

- **Aggregate**
  - porosity or stiffness of aggregate
  - volume of aggregate
  - max size, shape, surface texture, composition
- **Cement paste matrix**
  - porosity
    - w/c
    - air content
    - mineral admixtures
    - degree of cement hydration

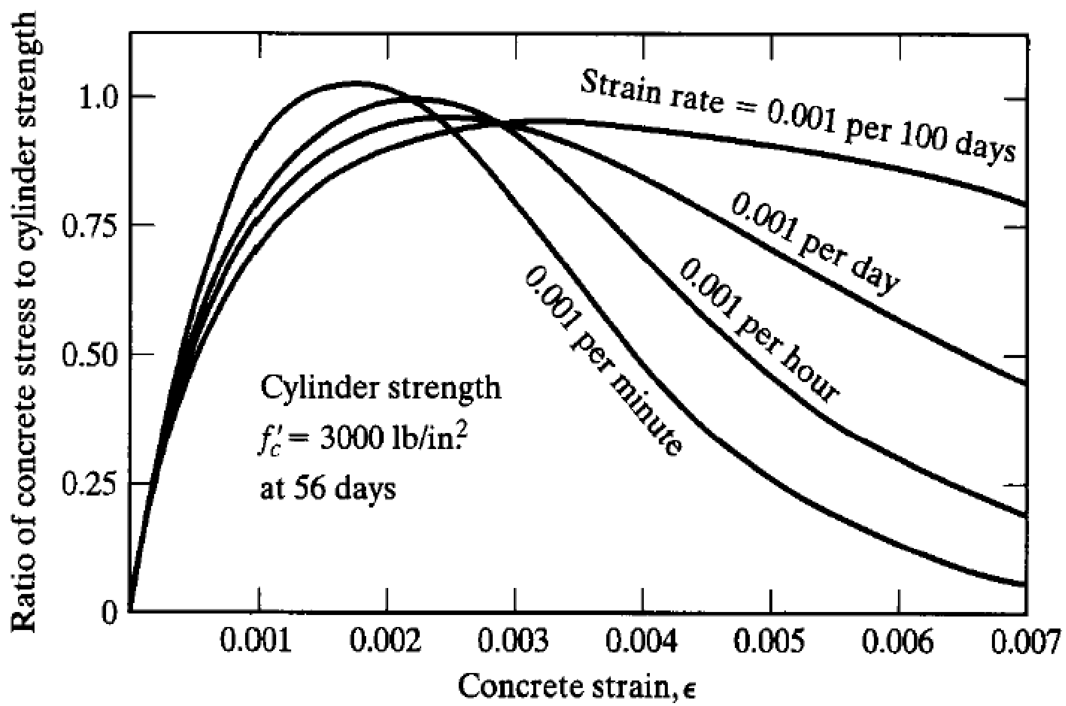
TABLE 13.3 Moduli of Elasticity for Concrete and Its Components, GPa (lb/in.^{2})

	Normal-Weight	*Lightweight*
Aggregate	70–140 ($10–20 \times 10^6$)	14–35 ($2–5 \times 10^6$)
Cement paste	7–28 ($1–4 \times 10^6$)	7–28 ($1–4 \times 10^6$)
Concrete	14–42 ($2–6 \times 10^6$)	10–18 ($1.5–2.5 \times 10^6$)

(Mindess et al 2003)

Factors Affecting the Modulus of Elasticity

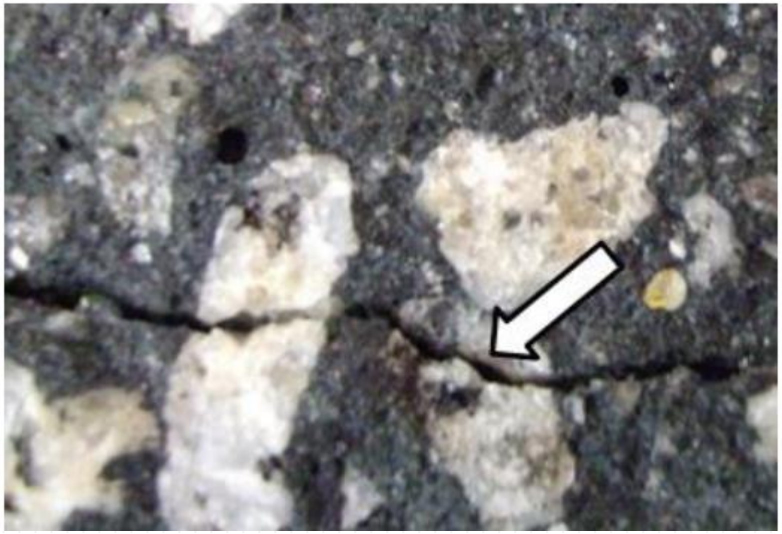
- **Interface transition zone**
  - High porosity, microcracks, oriented $Ca(OH)_2$ crystals
- **Moisture condition of specimens**
  - Saturated specimens show ~15% higher E than those tested in dry conditions; this is opposite to the effect on compressive strength
- **Testing parameter**
  - Loading rate ↑, E ↑ or no significant change
  - Ordinary lab testing condition (2 – 10 min.), effect of loading rate is small



(Rusch 1960)

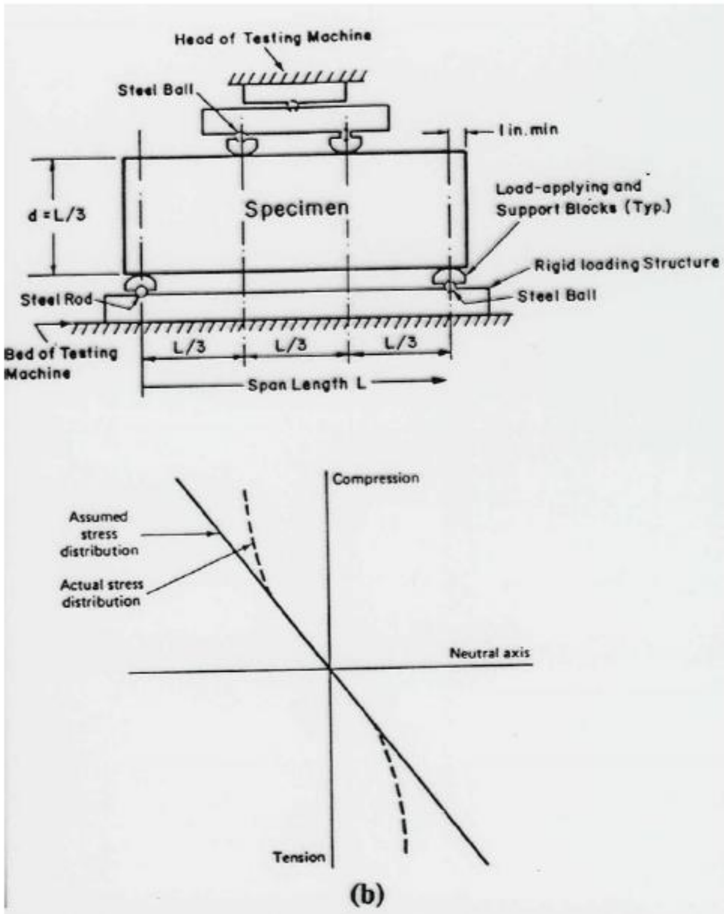
Tensile Strength

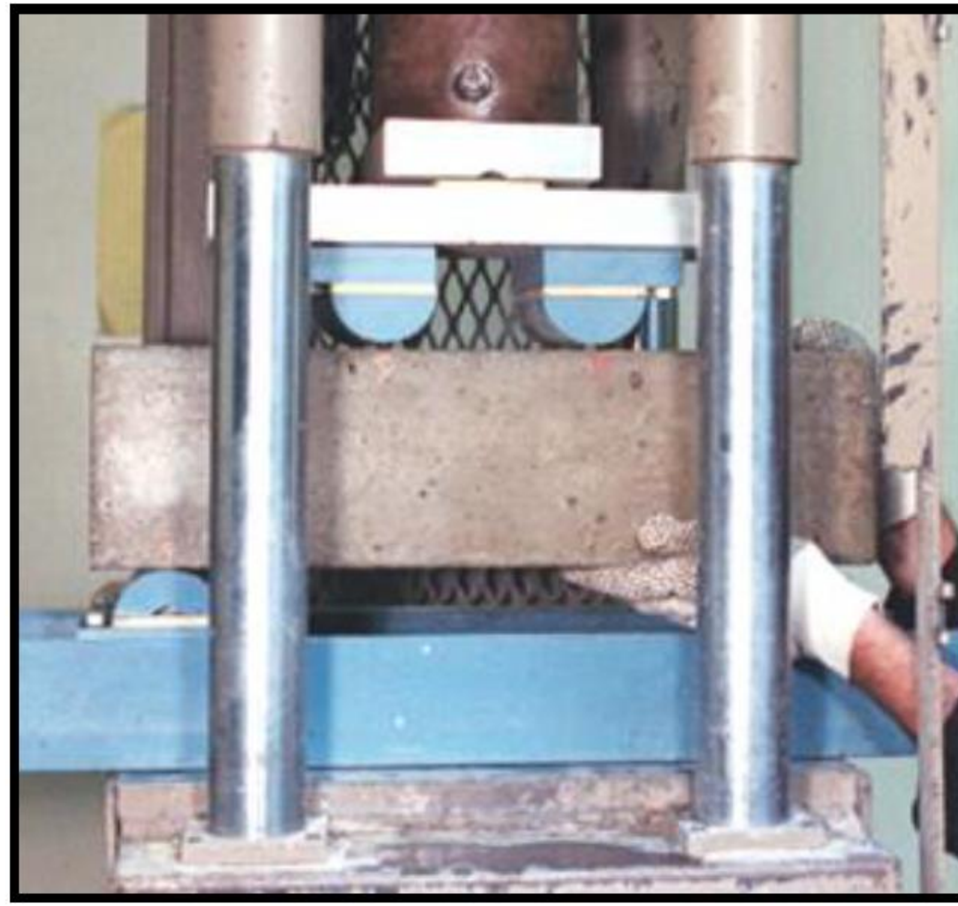
- **Design assumption**
  - Concrete would resist the compressive but not tensile stresses.
- **Tensile stress can not be ignored because**
  - cracking of concrete is often the outcome of a tensile failure, e.g. restrained shrinkage
  - when concrete is subject to bending loads, e.g. highway pavement
- **As a tensile crack propagates through concrete**
  - Leading edge consists of multiple branching microcracks
  - Eventually becomes a single macrocrack
- **Appearance of failure surface**
  - Weak aggregate relative to ITZ:
    - relatively smooth
  - Strong aggregate relative to ITZ:
    - more uneven, rough



Tensile Strength Test (1)

- **Flexure tensile strength test**

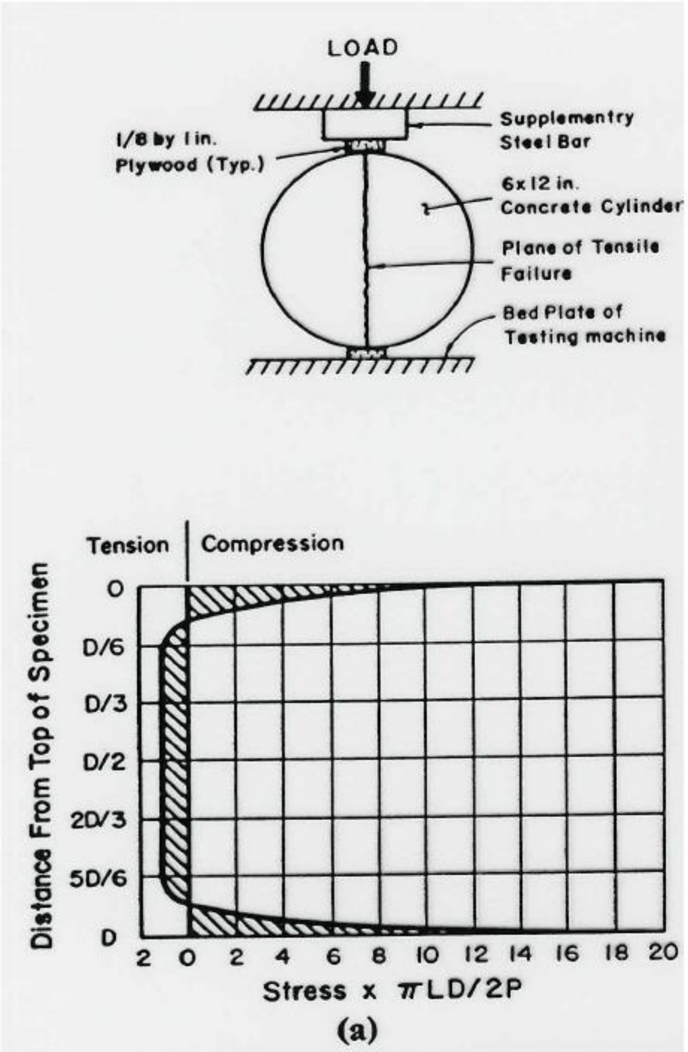




(Mehta & Monteiro 1993)

Tensile Strength Test (2)

- **Splitting tensile strength test**



(Mehta & Monteiro 1993)

Relationship between the compressive and tensile strengths

- Compressive and tensile strengths are closely related, however, there is no direct proportionality.

- As the age and compressive strength ↑, f_t / f_c ↓

- Ratio of tensile to compressive strength
  - Splitting tensile strength / f_c 0.08 – 0.14
  - Flexural tensile strength / f_c 0.11 – 0.23

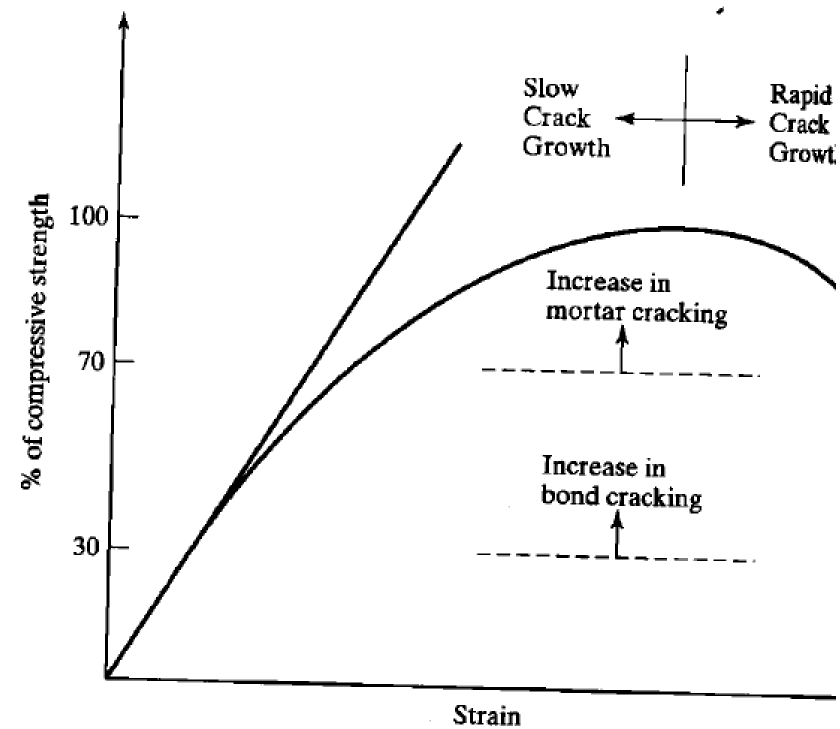
Compression

- Compressive strength is considered to be the most important property of concrete
  - In concrete design and quality control, compressive strength is the property generally specified
    - The 28-day compressive strength of concrete determined by a standard uni-axial compression test is accepted universally as a general index of concrete strength.

- Failure modes under stresses
  - are complex
  - vary with the type of stress

Behaviour of Concrete under Uniaxial Short-Term Compression

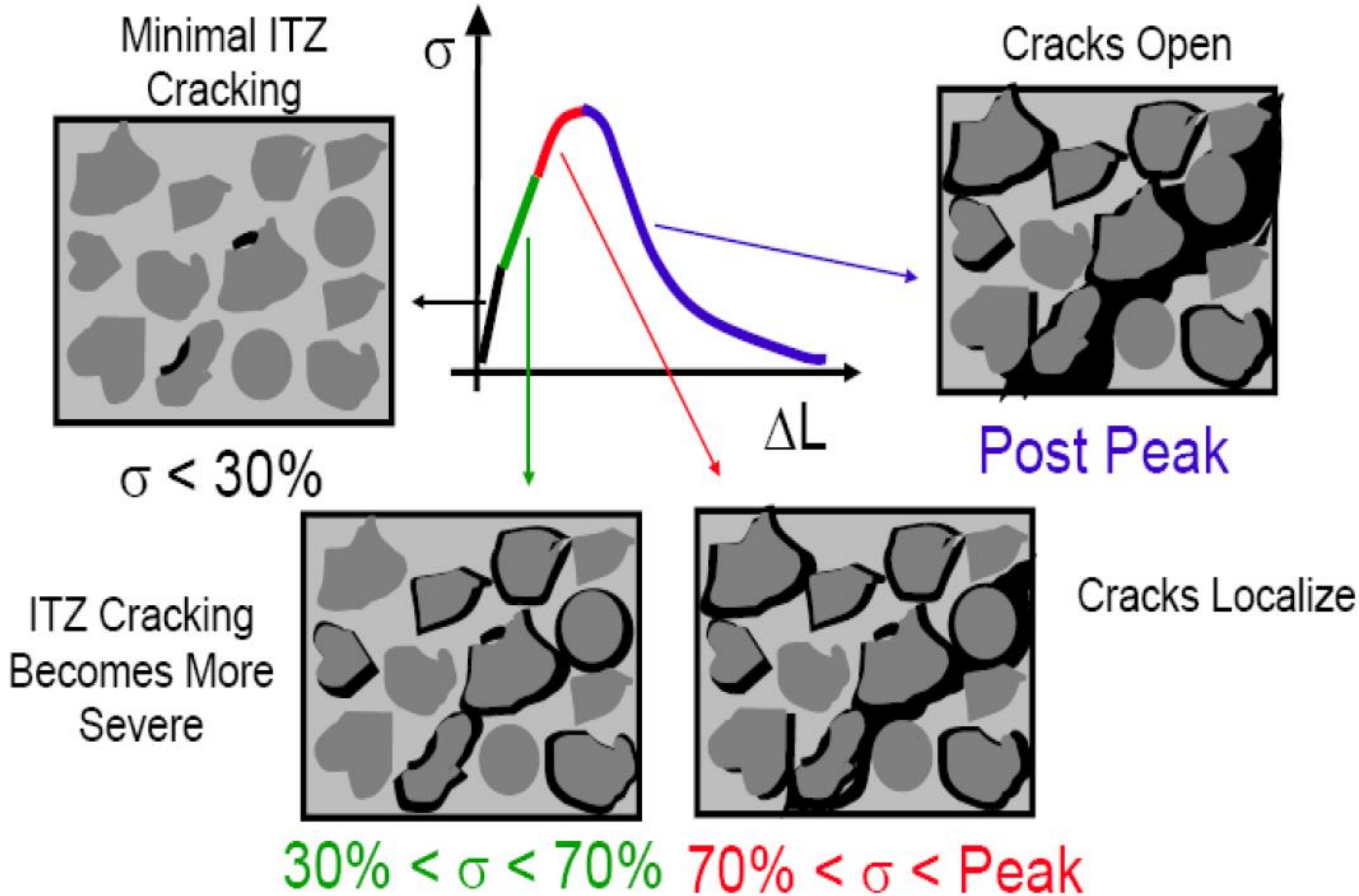
- Microcracks exist in ITZ before the application of external load
- Crack propagation
  - Up to ~30% of the ultimate load, microcracks remain stable, σ/ε curve straight;
  - Above 30-40% of ultimate load, microcracks begin to increase in length, width, and numbers, σ/ε curve deviate from a straight line;
  - At ~70%, cracks begin to form through the mortar; bridging bond cracks, σ/ε curve bend toward the horizontal



(ACI Committee 224, 1972)

Concrete

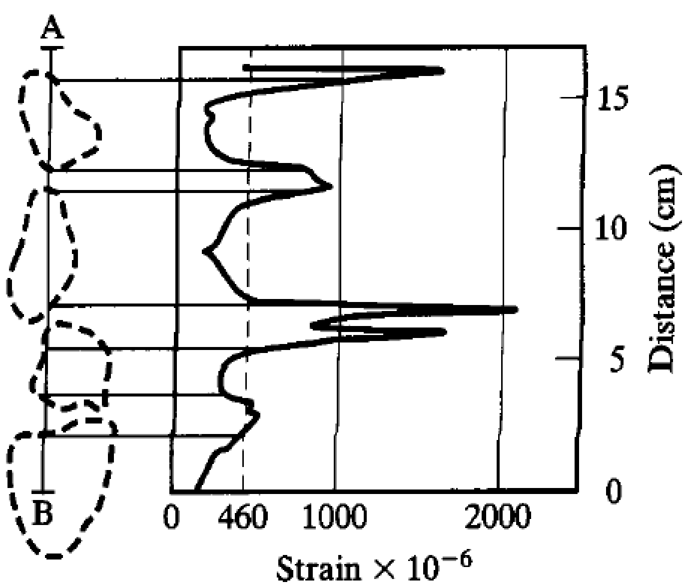
Cement paste

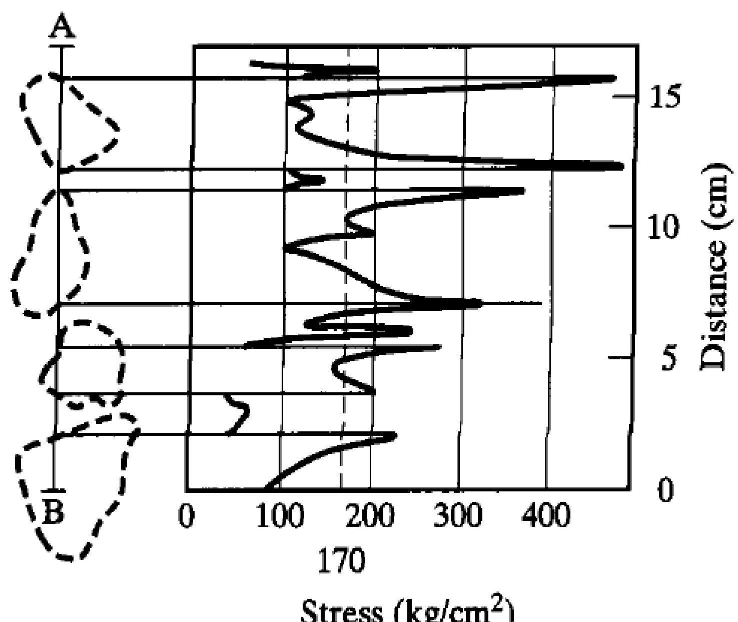

Minimal ITZ Cracking
σ
Cracks Open
ΔL
Post Peak
σ < 30%
ITZ Cracking Becomes More Severe
Cracks Localize
30% < σ < 70%
70% < σ < Peak

(Jason Weiss)

Distributions of Strain and Stress in Mortar and Aggregate

- Heterogeneous nature of concrete
- Stress concentration
  - The localized strains may be as much as 4.5 times the average strain
  - The localized stresses may be more than twice as high as the average stresses
  - The largest strains occur at the ITZ

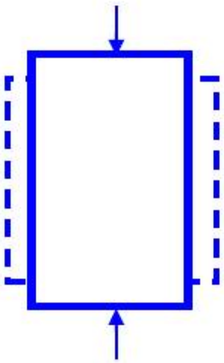




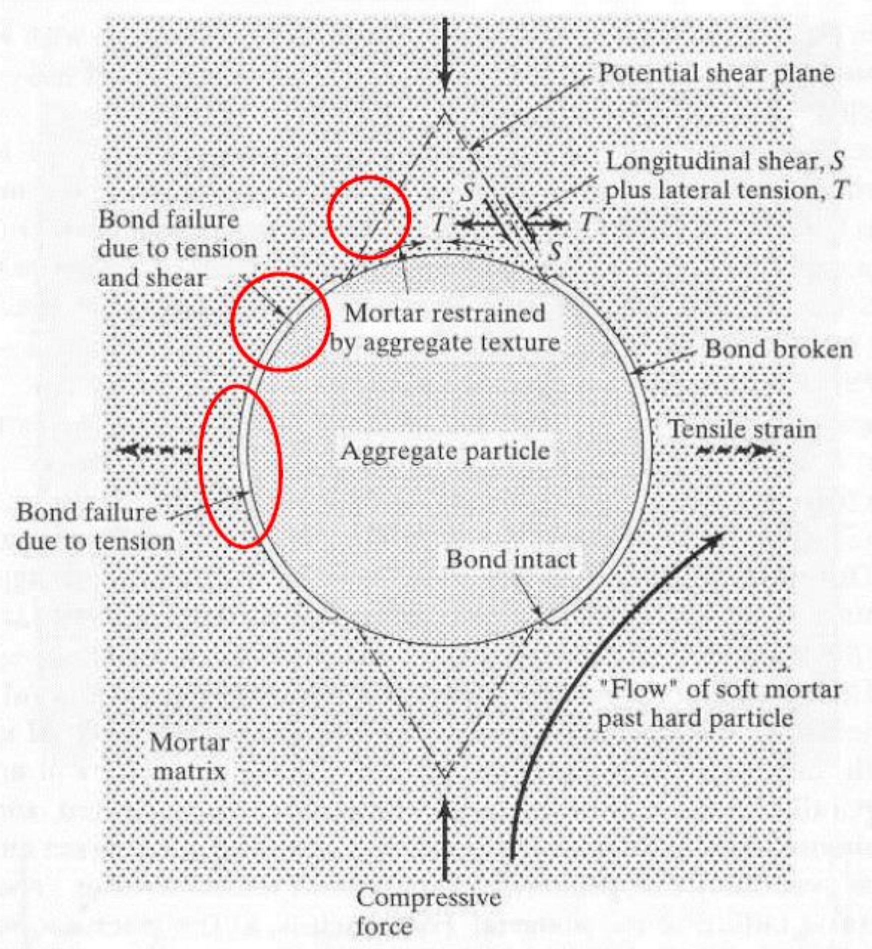
(Dantu 1958)

Behaviour of Concrete under Uniaxial Compression

- **Order of failure under short-term loading in cases where aggregate is stiffer than matrix**
  - **Tensile bond failure**
  - **Shear bond failure**
  - **Tensile matrix failure**
  - **Occasional aggregate failure**

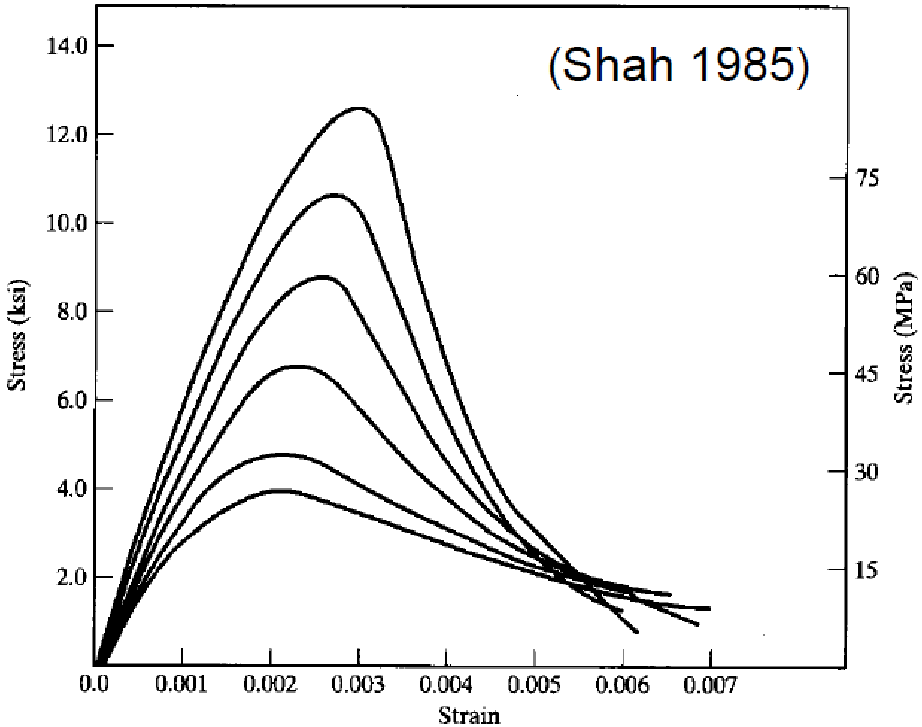


- **It has also been suggested that failure is controlled not by limiting the tensile stress, but by a limiting tensile strain, in the order of 1 to 2 x 10^{-4}.**



(Vile 1968)

Stress-Strain Curves of Concrete under Compression

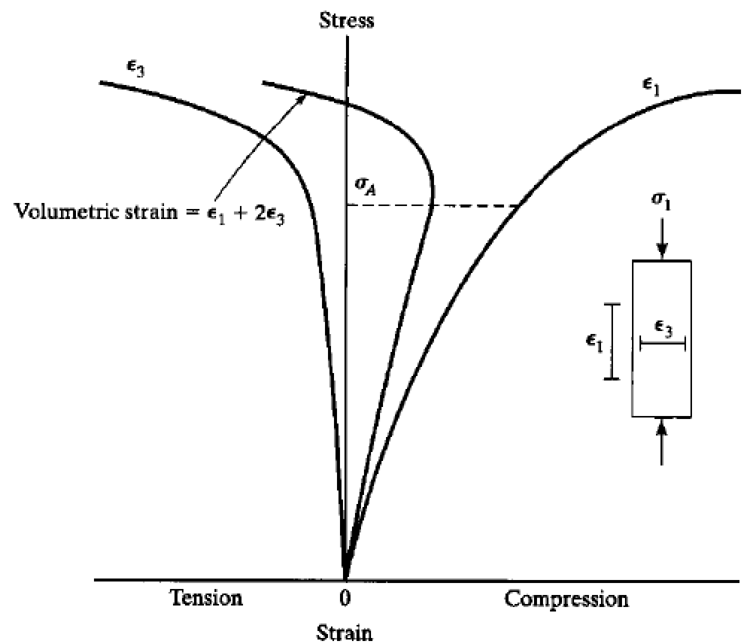


- E ↑ with increasing strength

- With increasing strength, strain corresponding to the peak compressive stress ↑, while the descending portion becomes steeper

-The beginning of mortar micro-cracking corresponds to an apparent ↑ in Poisson ratio above σ_A

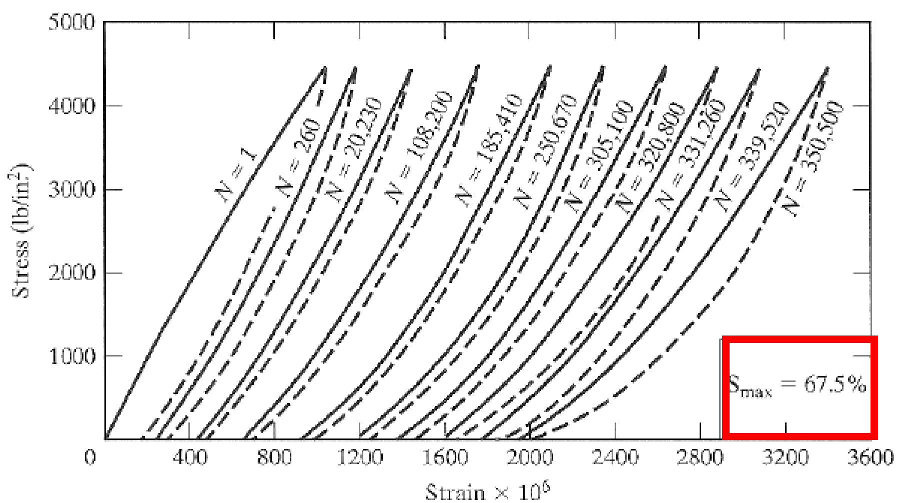
- At the onset of mortar micro-cracking, the volume of concrete also begins to increase



(K. Newman & J.B. Newman 1971)

Cyclic Loading

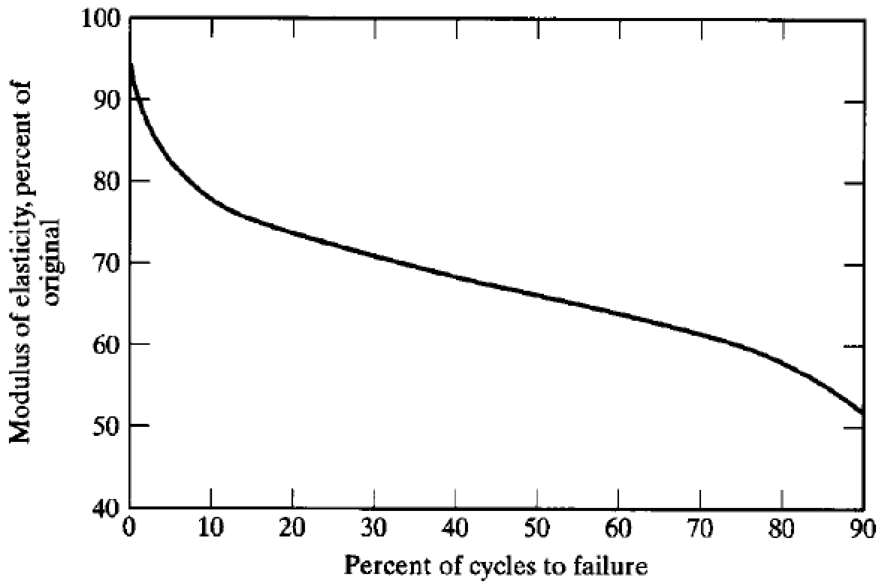
- Repeated or cyclic loading conditions
  - has adverse effect on concrete strength at stress level > 50% f_c
    - Stress level = 50-75% f_c, gradual degradation on strength and elastic modulus
    - As the number of loading cycles ↑,
      - Shape of σ - ε curve changes
      - Modulus of elasticity reduces
      - Strain increases with cyclic loading



Peak stress = 67.5% of compressive strength

(Bennett & Razu 1971)

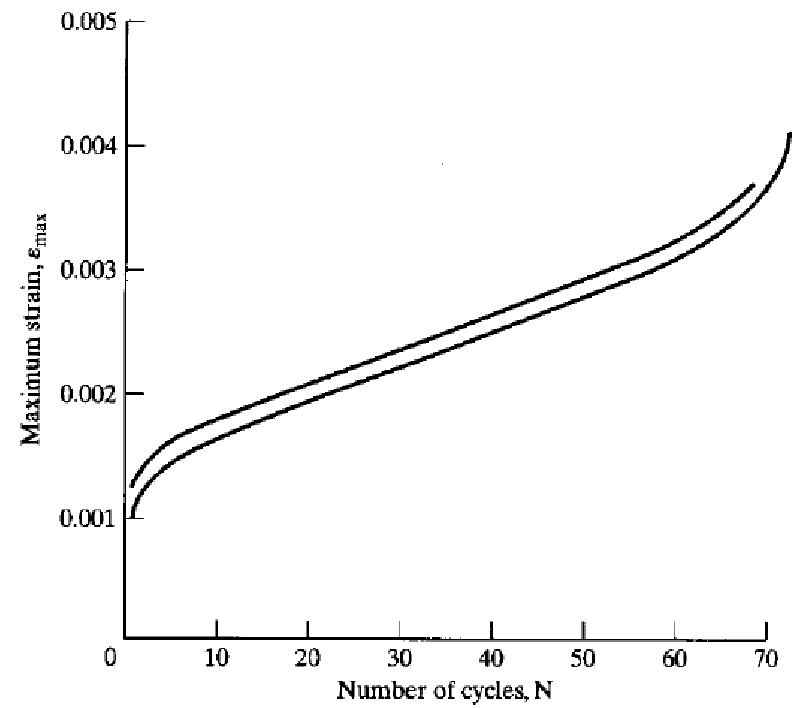
(Linger & Gillespie 1966)



(a)

→ Increase microcracking

(Maher & Darwin 1980)

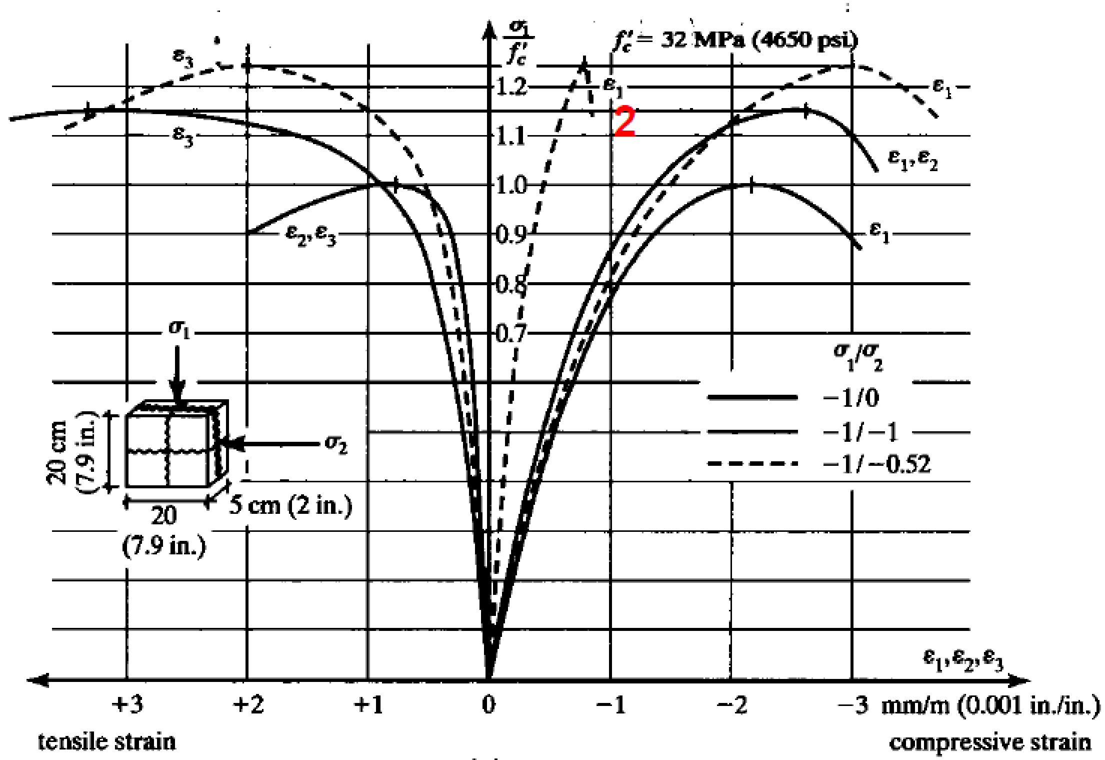


(b)

- Strain accumulated under cyclic compression > strain for similar specimens subjected to sustained loading equivalent to the mean stress of the cycles
- Cyclic loading causes both <u>damage & viscous flow</u> in concrete

Biaxial Loading

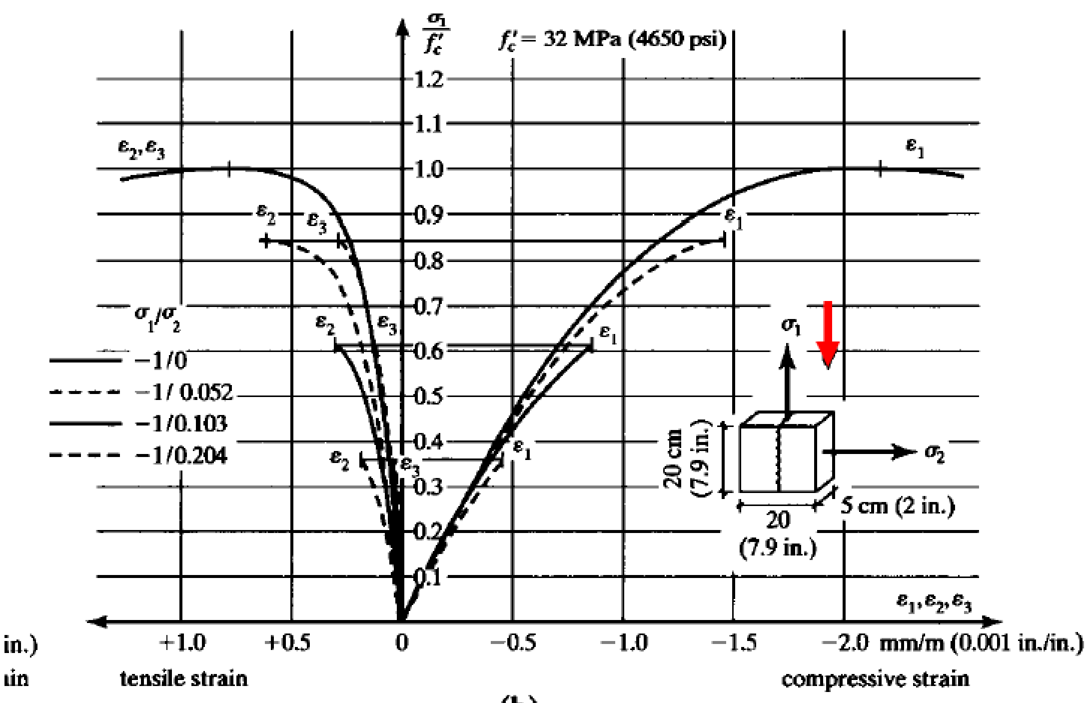
- **Stress-strain curves for concrete under biaxial compression**
  - Strain corresponding to the peak stress ↑
  - Strength is higher than the uniaxial strength
  - Principal failure mode is tensile, with cracking parallel to the plane in which biaxial stresses are applied



(Kupfer et al 1969)

Biaxial Loading

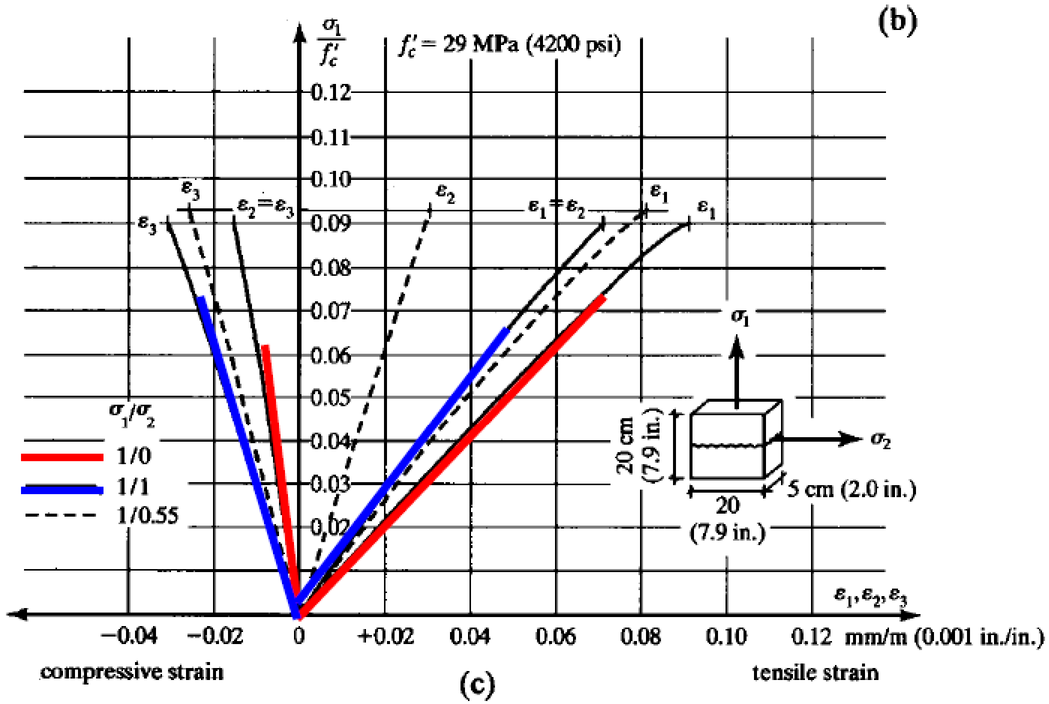
- Stress-strain curves for concrete under **biaxial compression-tension**
  - Strength and strain corresponding to the peak compressive and tensile stresses ↓ as the ratio of tensile to compressive stress ↑
  - Cracks form ⊥ to the direction of principal tensile stress



(Kupfer et al 1969)

Biaxial Loading

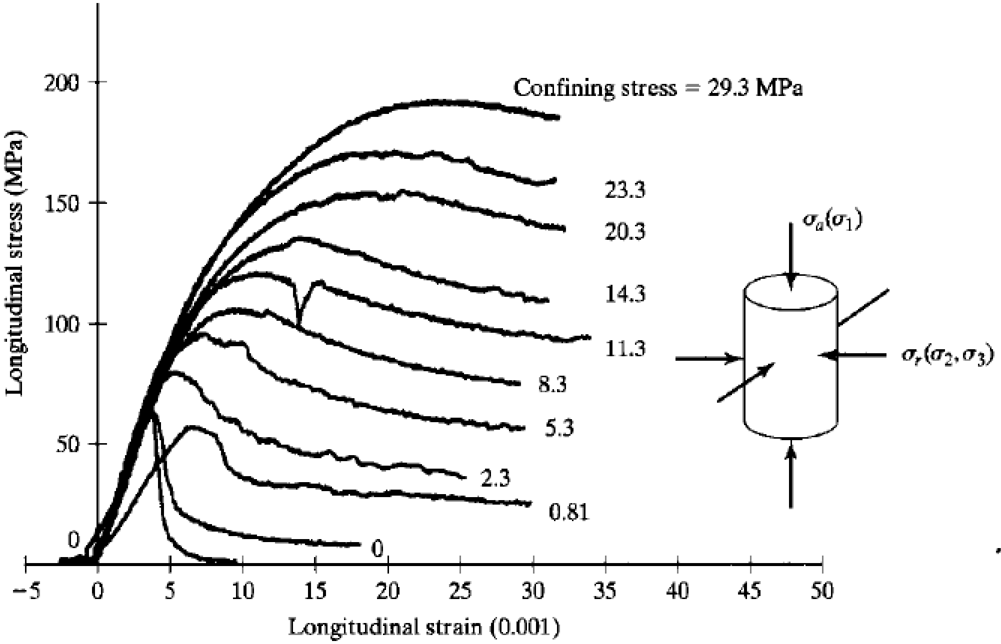
- **Stress-strain curves for concrete under biaxial tension**
  - Strength of concrete is approximately equal to the uniaxial tensile strength
  - Cracks form ⊥ to the principal tensile stress, with no orientation of preference when the biaxial stresses are equal



(Kupfer et al 1969)

Triaxial Loading

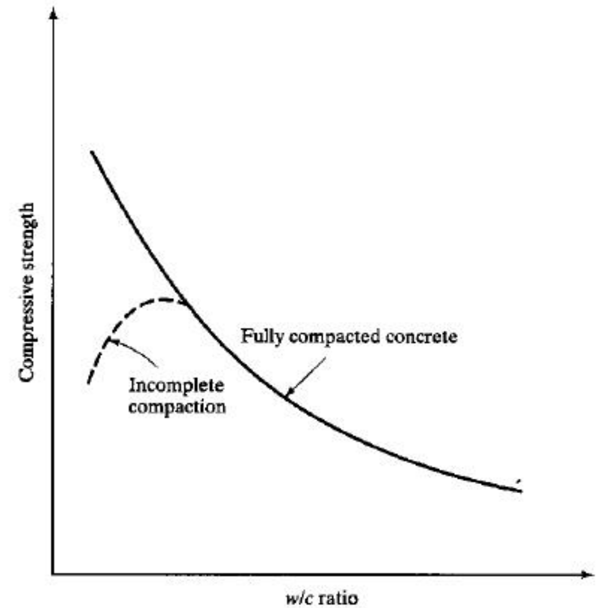
- Concrete confined by reinforcement is under triaxial restraint
- Concrete under tri-axial compression
  - Strength and strain corresponding to the peak compressive stress ↑ as the confining stress is increased
  - Descending portion of σ - ε curves reach a nearly constant stress – residual strength
  - For confining stress up to ~15% fc, the principle failure mode is longitudinal splitting
  - For very high confining stress, failure by crushing



(Xie et al 1995)

Factors Affecting Strength

- **Water/cement ratio (w/c)**
  - **In low- to medium-strength concrete with normal-weight aggregate**
    - **the transition zone and the matrix porosity determine the strength**
    - **a relationship between strength and w/c holds**
  - **In high-strength concrete**
    - **Before reaching the limit of aggregate, disproportionately high increase in compressive strength can be achieved for small reduction in w/c; can be attributed to the improvement of transition zone**
    - **Aggregate often determines the strength**



(Mindess et al 2003)

Figure A.3.6.2 Honeycomb

(ACI Committee 201)

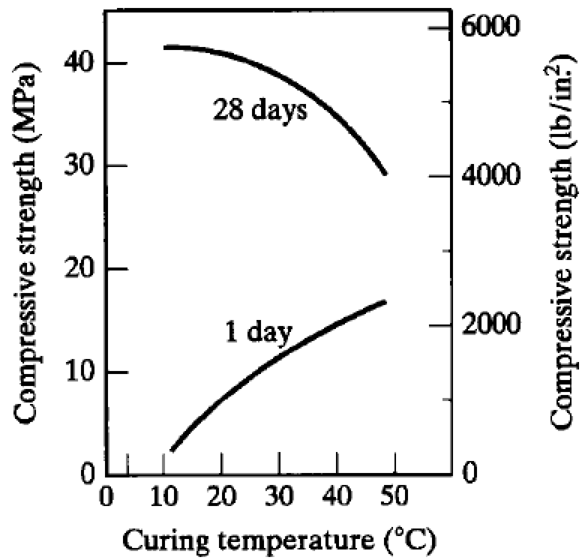
Factors Affecting Strength

- **Age**
  - At a given w/c, moist curing period ↑, strength ↑
  - As a general rule, $f_{c,28\text{-}d} / f_{c,7\text{-}d} = 1.3 - 1.7$, usually <1.5

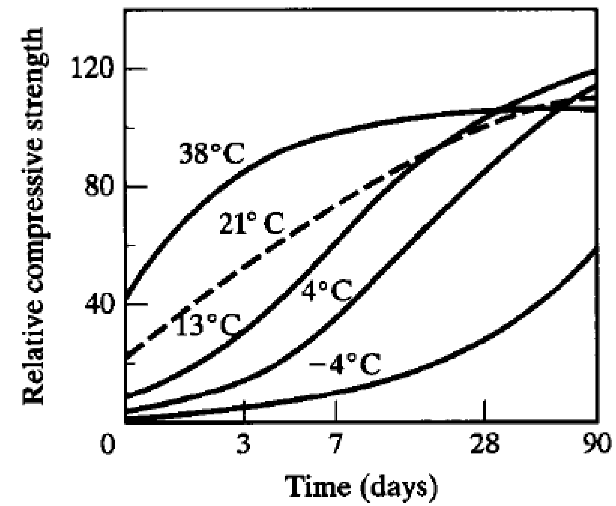
- **Curing conditions**
  - Temperature
    - In general, temperature ↑, rate of hydration ↑
    - However, it has been observed that the higher the casting and curing temperature, the lower the ultimate strength
    - Concrete cured in tropical climate can be expected to have a higher early strength but a lower ultimate strength than the same concrete cured in colder climate.
    - Concrete cast in cold climate must be maintained above a certain minimum temperature for a sufficient length of time.

Factors Affecting Strength

(Verbeck & Helmuth 1968)



(a)



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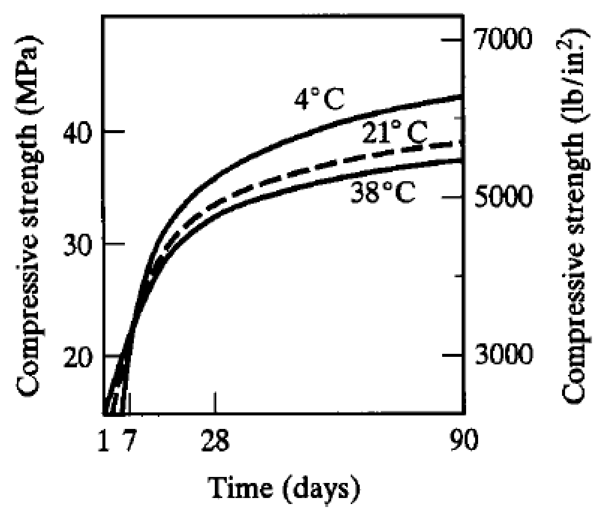
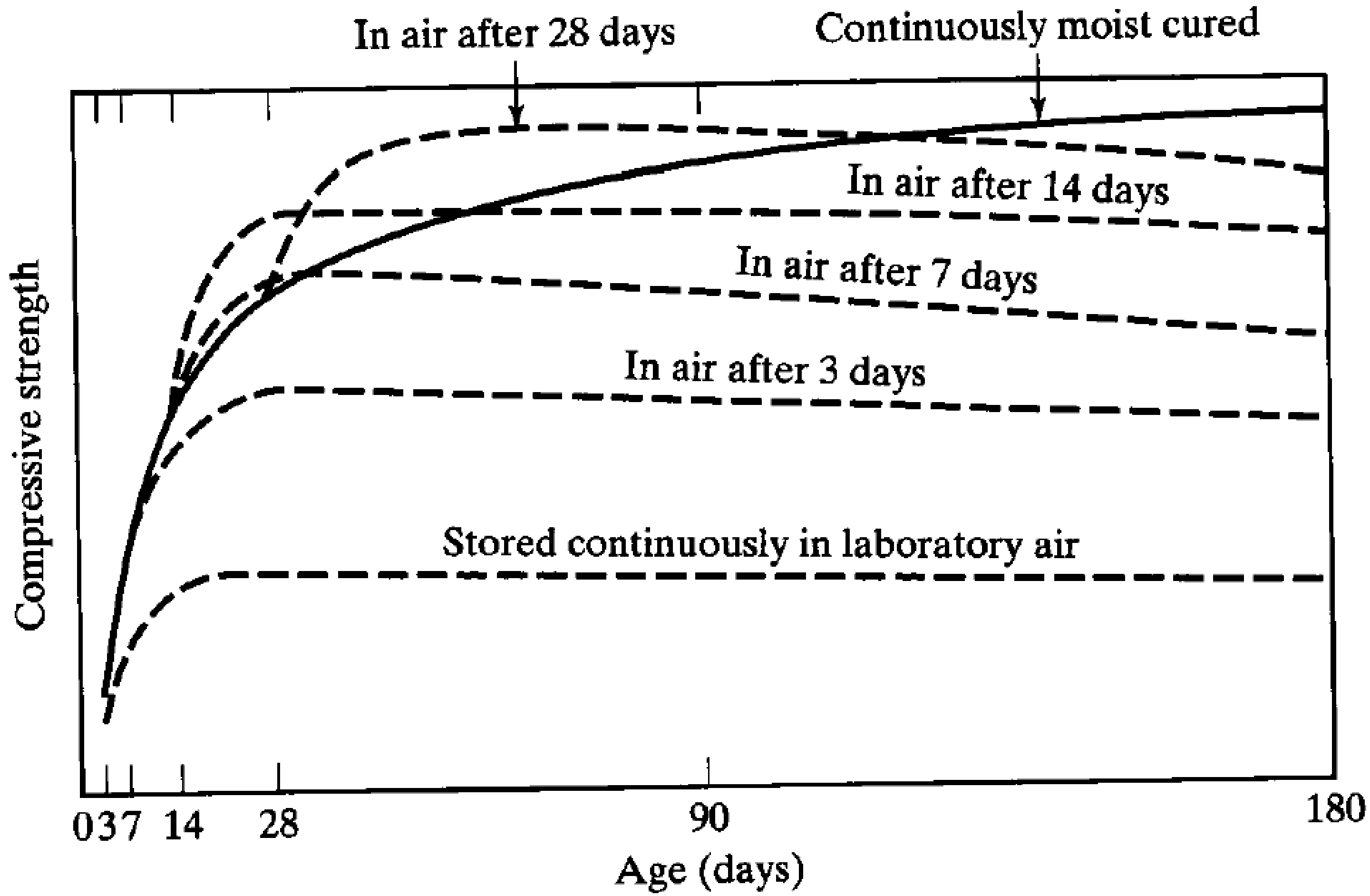


(Price 1951)

Factors Affecting Strength

- Humidity
  - If water is lost by evaporation, strength will not increase.
    - If humidity in capillaries < 80% RH, cement hydration will cease. This can happen in sealed concrete or concrete with low w/c.
  - The rate of water loss from concrete depends on
    - surface/volume ratio
    - temperature
    - relative humidity of environment
    - wind velocity
  - General recommendation for curing
    - Ordinary Portland cement concrete: moist cure for 7 days
    - Concrete with blended cements: longer curing is desired
  - Moist curing
    - wet burlap or cotton mats
    - curing membrane



(Price 1951)

The curing age would not have any beneficial effect on the concrete strength unless curing is carried out in the presence of moisture.

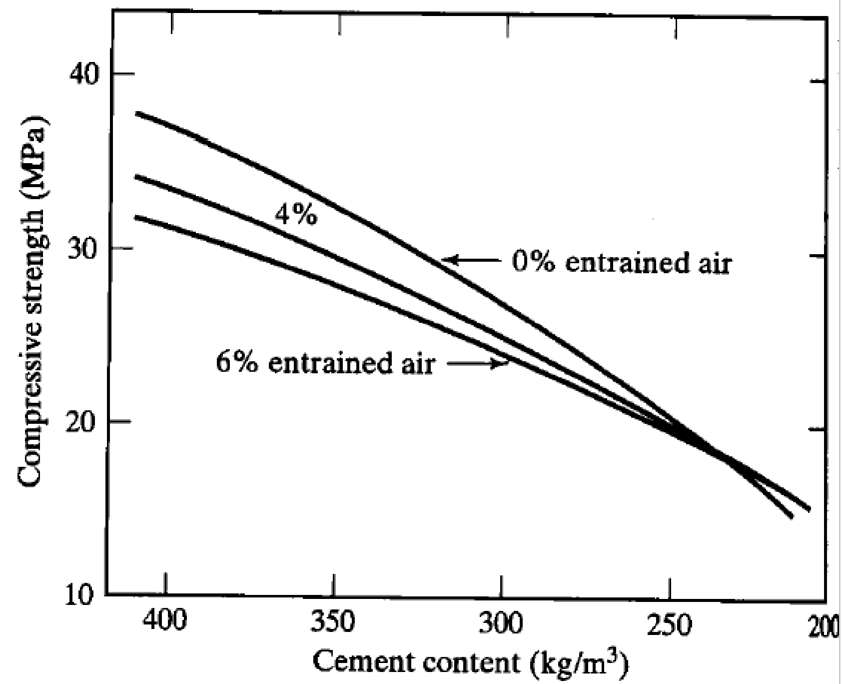
Factors Affecting Strength

- Cement
  - Porosity of a hydrated cement paste is determined by w/c and degree of hydration
  - The degree of hydration for different cements at 90 days and beyond is usually similar; therefore, the influence of cement composition and fineness on strength is limited to early ages
  - Hydration rate at normal temperature
    - ASTM Type III > I > II > V > IV
    - ASTM Type I > IS (IP)

Factors Affecting Strength

- Mineral admixtures (pozzolanic and cementitious by-products)
  - Fly ash or slag: usually retards the rate of strength gain, improve long-term strength
  - Silica fume: ↑ strength even at the same w/c as OPC concrete (filler effect, pozzolanic reaction, improve ITZ)

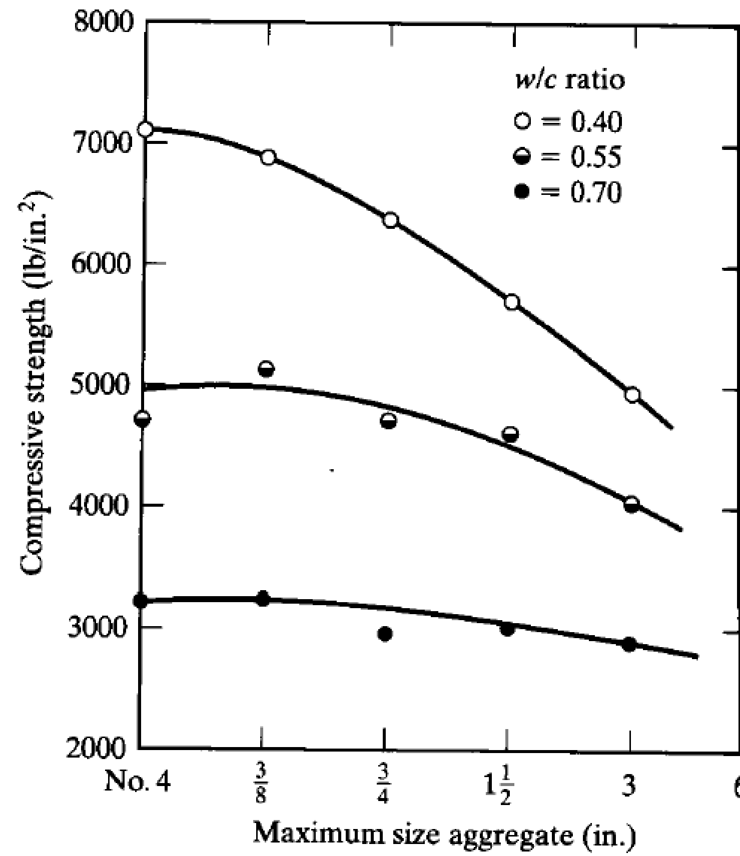
- Chemical admixtures
  - Air-entraining admixtures
    - ↑ porosity and ↓ strength
  - Water-reducing admixtures
  - Retarding admixtures
  - Accelerating admixtures



(Cordon 1979)

Factors Affecting Strength

- Aggregate
  - Aggregate strength is usually not a factor except for LWC or HSC
  - Concrete strength is affected by
    - Surface texture
      - Affect f_t, f_r, & E, but has little effect on f_c
      - Has more effect on concrete with low w/c
    - Size
      - ↑ size, ↓ water requirement, ↑ f_c
      - ↑ size, cause greater stress concentration, ↓ f_c
      - Has more effect on concrete with low w/c
    - Quality and content



(Cordon & Gillespie 1963)

EN 12390 Testing hardened concrete

- Part 1: Shape, dimensions and other requirements for specimens and moulds
- Part 2: Making and curing specimens for strength tests
- Part 3: Compressive strength of test specimens
- Part 4: Compressive strength – Specification for testing machines
- Part 5: Flexural strength of test specimens
- Part 6: Tensile splitting strength of test specimens
- Part 7: Density of hardened concrete
- Part 8: Depth of penetration of water under pressure
- Part 9: Freeze-thaw resistance – Scaling (draft 2006)
- Part 10: Determination of the relative carbonation resistance of concrete (draft 2007)