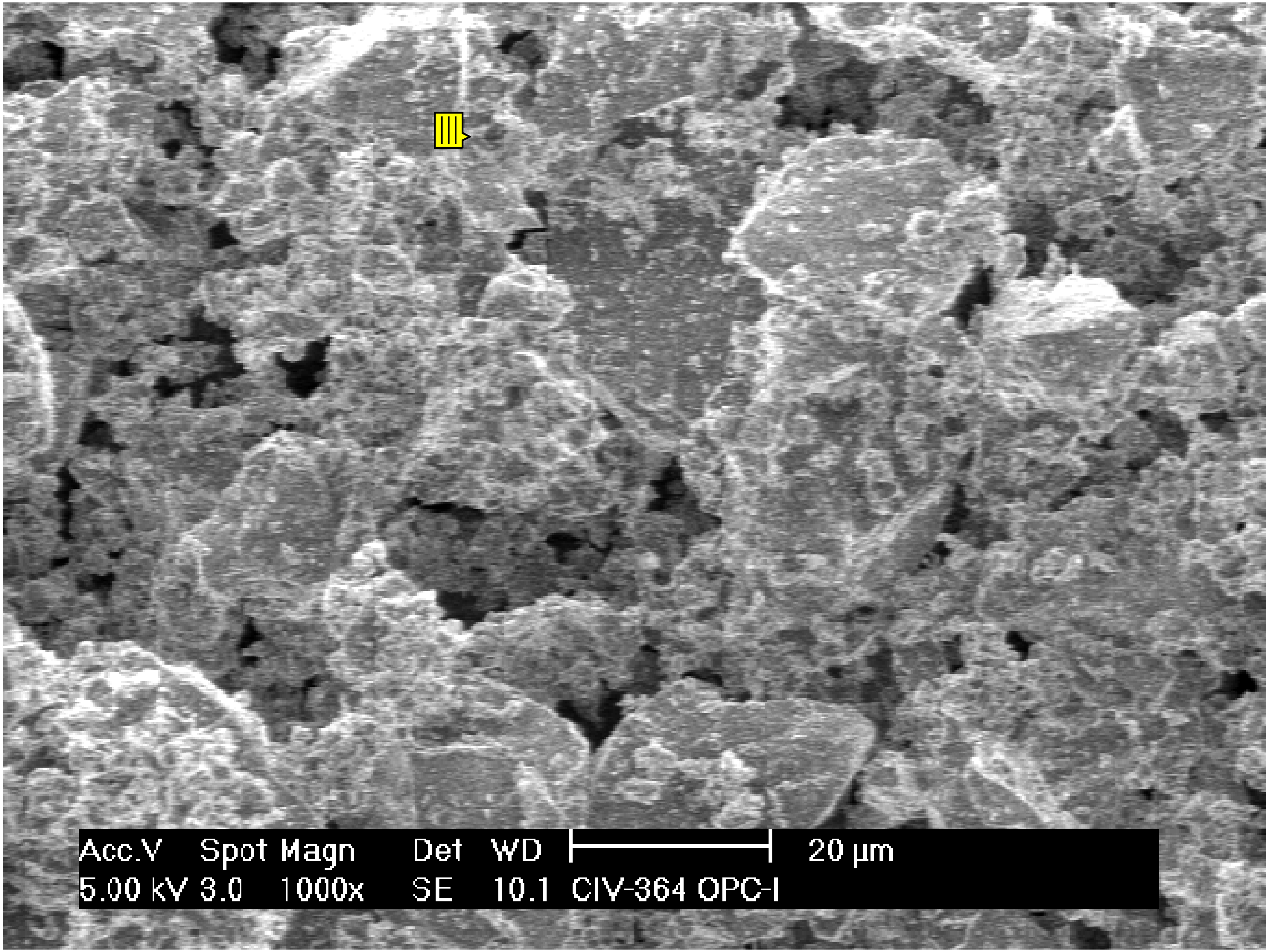
Concrete

- What is it ?
- Ancient history
- Recent history
    - Portland cement
    - Reinforced concrete
    - Pre-stressed concrete
- Properties of concrete
    - Heat of hydration
    - Creep
    - Strength
    - Durability
- New structures
    - Bridges
    - Shells
    - Dams

What is Cement?

- ***Cement*** **is a material capable of binding particles together**
- ***Portland cement*** **is a mixture of calcium silicates and aluminum silicates that react with water to form a binder**
  - **Portland cement is a generic name , not a trade name , and has nothing to do with Portland**
  - **Modern Portland cement was invented in the 19th century , but related materials have been used in construction since Roman times**
- ***Mortar*** **is a mixture of cement and sand**
- ***Concrete*** **is a mixture of mortar and** ***aggregate*** **(i.e., stones larger than ~5 mm and usually smaller than 7 cm)**


Acc.V Spot Magn Det WD 20 µm
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Ancient History

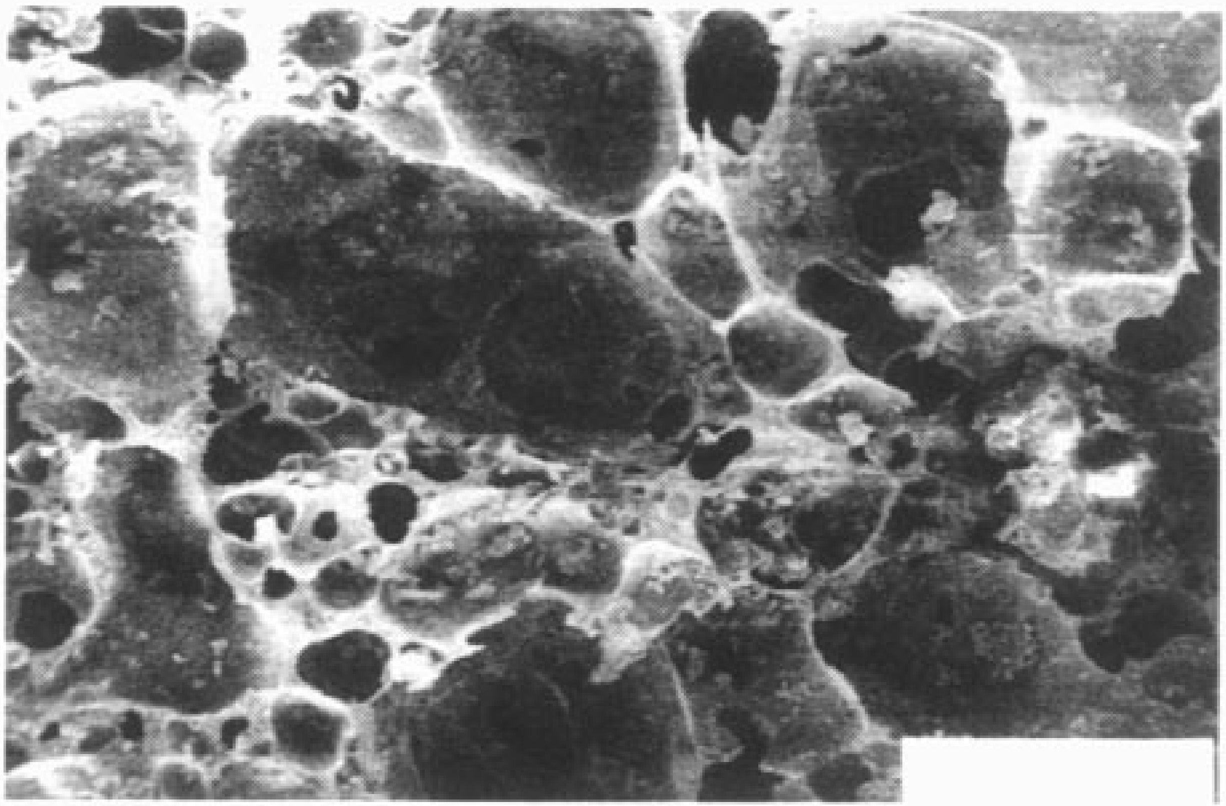
- Lime (CaO) is made by heating limestone (calcium carbonate) above ~900°C to drive off the carbon dioxide

$$CaCO_3 \rightarrow CaO + CO_2 \uparrow$$

- Lime reacts with water to form calcium hydroxide (*slaked lime*)

$$CaO + H_2O \rightarrow Ca(OH)_2$$

- Lime plaster is made by compacting slaked lime on a surface (such as a wall or floor) and allowing it to react with CO_2 in the atmosphere to form $CaCO_3$
    - This material was in use 8000 yrs ago
- The ancient Egyptians used gypsum plaster (aka plaster of Paris)
- The ancient Greeks reacted slaked lime with volcanic ash (mostly SiO_2 glass) to make a cement to line cisterns
    - This material is the precursor of modern cement



Volcanic Ash

Ancient History

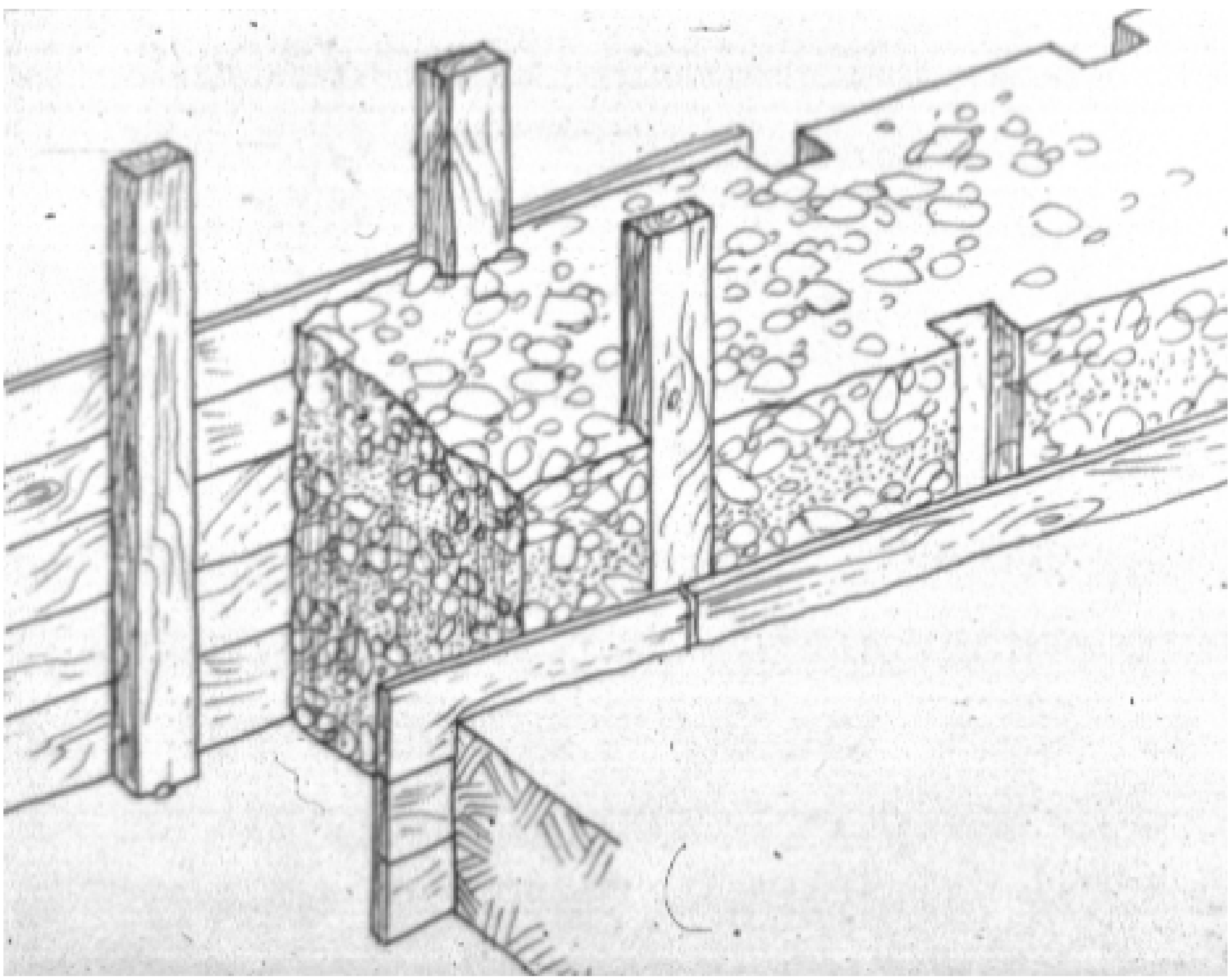
- **From about 200 BC, the Romans developed cement technology based on slaked lime and volcanic ash from Mt. Vesuvius**
  - **The preferred deposits were near Pozzuoli, so the cement is called *pozzolanic* cement**
- **The ash is nearly pure silica glass, which is much more reactive than crystalline silica (i.e., quartz sand)**
- **The reaction produces calcium silicate hydrate gel called C-S-H with the approximate composition**

$$\mathbf{C\text{-}S\text{-}H \approx 3CaO \bullet 2\,SiO_2 \bullet 3H_2O}$$

- **By the first century AD, concrete was used for major construction projects, such as the Pantheon**

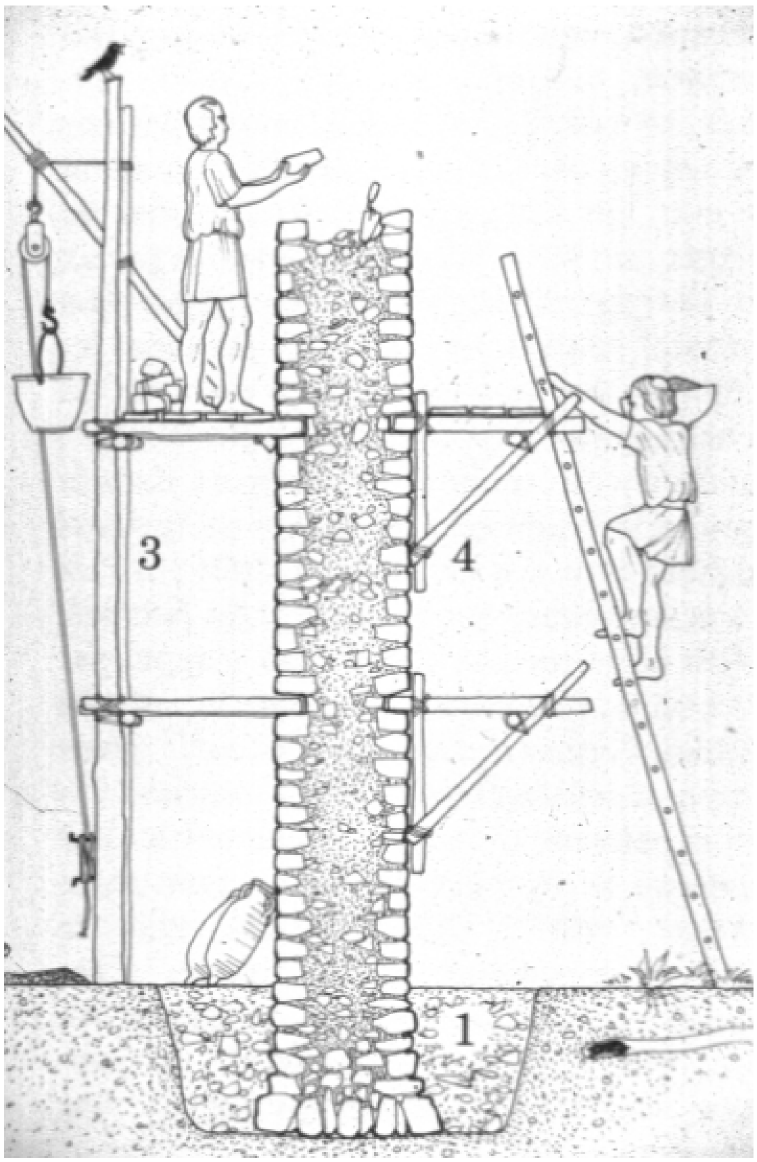
Roman Concrete

- As in modern construction , the Romans used wooden forms and cast the concrete into them
    - In tall structures , dense stone was used as aggregate at the bottom and light stone was used higher up



Roman Concrete

- Often , forms were built up using stone or brick

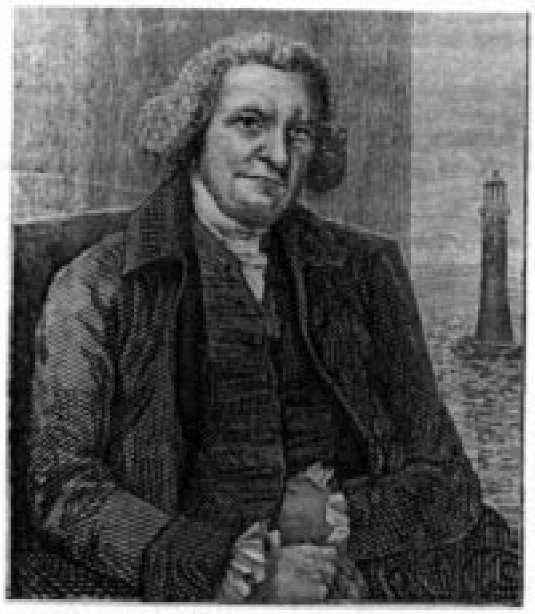


Roman Concrete

- The Roman concrete had great advantages
  - It was strong and easier to use than stone for making smooth shapes (such as domes)
  - It could set under water , so it could be used for piers and pediments of bridges and aqueducts
- It also had some disadvantages
  - It takes a long time (up to a year) to reach high strength (so structures can sag before hardening)
  - The raw materials (viz., volcanic ash) are not widely available
    - When Herod built a harbor from concrete in Israel , he imported the materials from Italy on barges
- After the fall of Rome , concrete technology was lost in Western Europe until the 19th century

Rebirth of Concrete

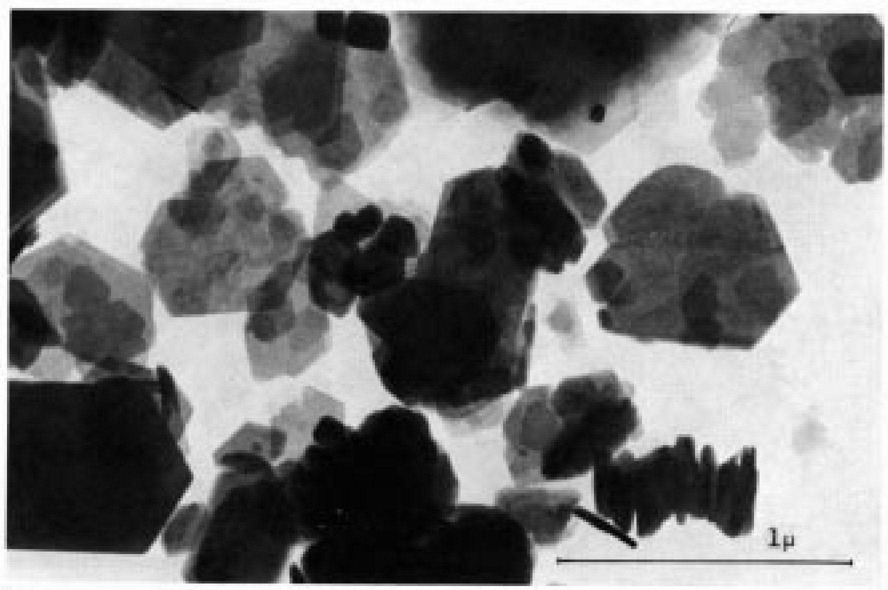
- In 1756 , John Smeaton was commissioned to build the Eddystone Lighthouse off the Cornwall coast (England)
    - Contemporary mortars would not set under water , so he experimented with various local limestones
    - When limestones containing clay were fired , the resulting lime gained strength under water
- In 1824 , Joseph Aspdin patented Portland Cement (so named because it was said to resemble Portland stone - a high quality limestone quarried near Portland)
    - Made by firing clay and limestone (but at too low a temperature)
- In 1845 , Isaac Johnson made the type of cement now known as Portland cement
    - Fired at high enough temperature (~1500˚C) to make highly reactive calcium silicates



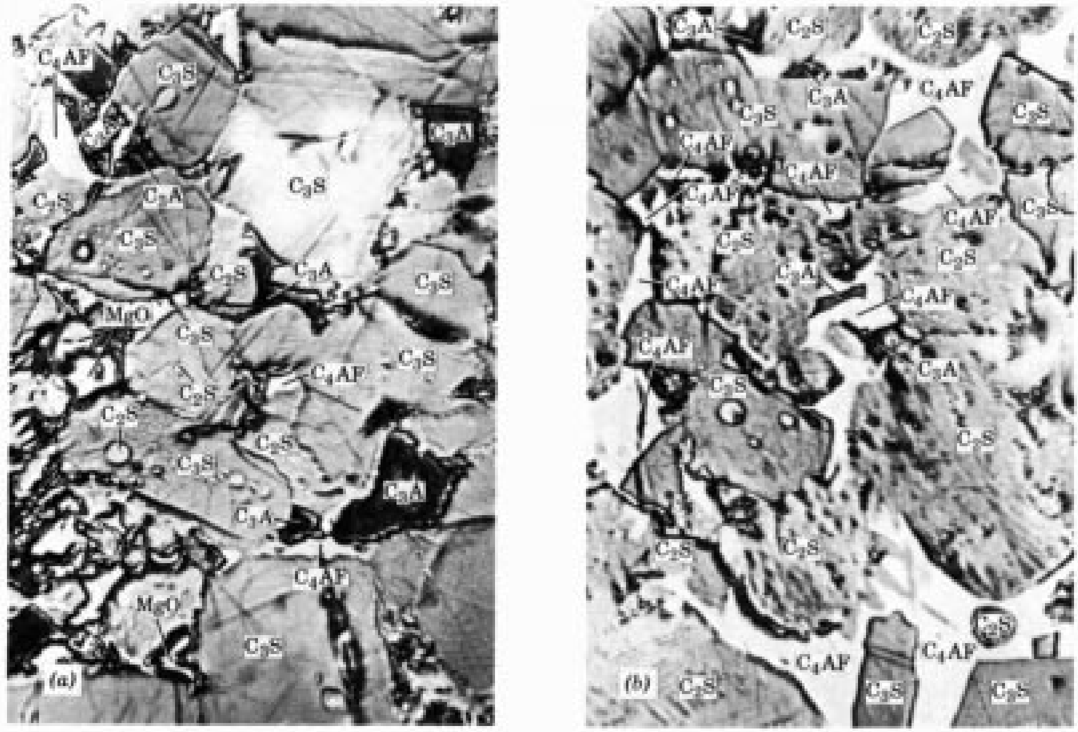
John Smeaton, civil engineer and father of the English cement industry. (Born 1724; died 1792.) The Eddystone lighthouse, off the coast of Cornwall, stands in the background. Smeaton's structure stood for 123 years before being replaced.

Portland Cement

- Portland cement is made by heating limestone and clay to ~1500°C to cause partial melting of the mixture
    - Products are not naturally occurring, as they are highly reactive with water
- Portland cement consists of three main ingredients (in increasing order of reactivity with water)
    - $C_3S = 3CaO \bullet SiO_2$
    - $C_2S = 2CaO \bullet SiO_2$
    - $C_3A = 3CaO \bullet Al_2O_3$
- Silica and alumina come from clay
    - Clay is naturally abundant mineral consisting of sheets of silica and / or alumina
        - Occurs in very fine particles, so it reacts easily with lime
- Product of hydration is the same C-S-H obtained from pozzolanic cements



Electron micrograph of kaolinite; a stacked pack of plates is shown in the lower right corner. Micrograph by H. P. Studer.



Micrographs of portland cement clinker (835×). (*a*) Type I, high in $3CaO \cdot SiO_2$ (major gray phase is C_3S, dark gray phase C_3A, light gray phase C_2S, white phase mainly C_4AF); (*b*) type II, containing nearly equal parts of $3CaO \cdot SiO_2$ and $2CaO \cdot SiO_2$ (gray C_3S, light gray C_2S, black C_3A, white C_4AF). Courtesy Portland Cement Association.

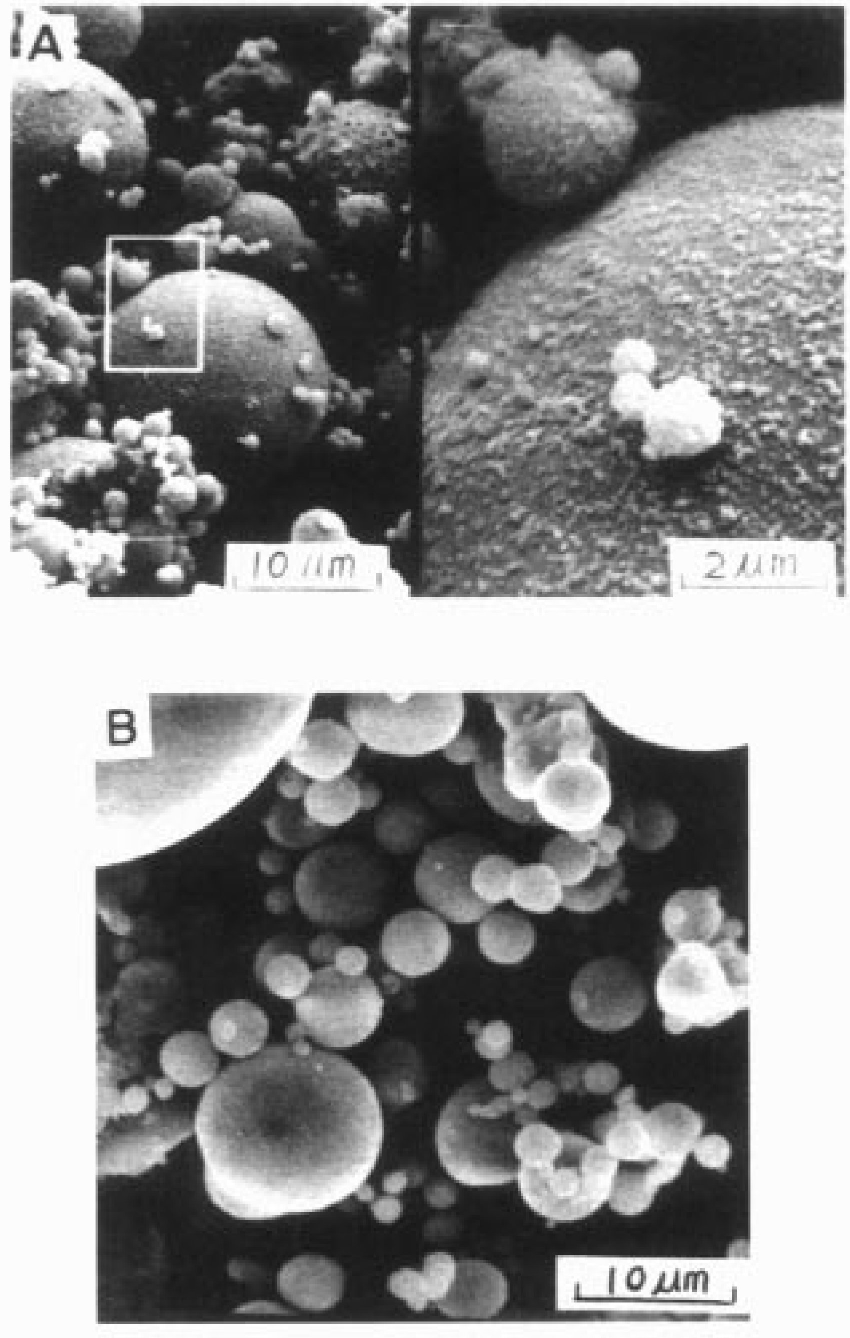
Lattice image of C-S-H gel (AM is amorphous matrix, SRO is short-range-ordered region, and NC is nanocrystalline region). See related feature article, "Mesostructure of Calcium Silicate Hydrate (C-S-H) Gels in Portland Cement Paste: Short-Range Ordering, Nanocrystallinity, and Local Compositional Order," by Dwight Viehland, Jie-Fang Li, Li-Jian Yuan, and Zhengkui Xu

Portland Cement

- Advantages of Portland cement
  - Limestone and clay are widely available , so cement can be made locally (low transportation cost)
  - Convenient rate of hardening
    - Hardens in hours , so there is enough time to cast it
    - Gains most strength in 24 h (but continues to harden for years)
  - Durable and fire - resistant
- Disadvantages of Portland cement
  - Weak in tension
    - Must be reinforced with steel (but steel subject to corrosion)
  - Porosity makes it susceptible to damage by frost and salts

Pozzolanic Additives

- Pozzolanic materials do not react with water , but they react with lime
- Advantages of pozzolans :
  - Retard reaction (important for dams)
  - Produce C-S-H from excess $Ca(OH)_2$
    - Improves strength
    - Reduces porosity (better durability)
  - Reduces cost of cement
  - Removes waste product from environment
- Typical pozzolans
  - Fly ash (from burning coal)
  - Blast furnace slag (from iron-making)
  - Volcanic ash (where available)
  - Rice husk ash (mostly in Asia)



Scanning electron micrograph: (A)-ASTM Class C, (B)-ASTM Class F fly ash.

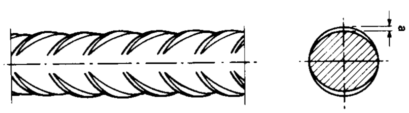
Rice-husk ash

Reinforced Concrete

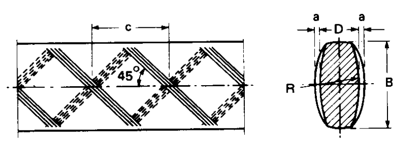
- Concrete is weak in tension , so it must be reinforced with steel

- Concrete cracks , but steel holds crack closed and prevents catastrophic failure

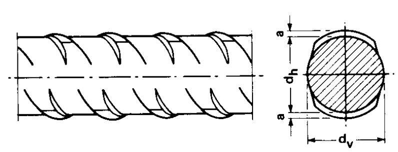
    - Friction between concrete and steel bar prevents crack surfaces from moving apart



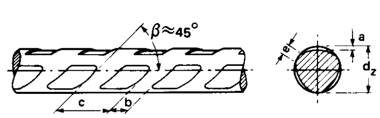
Round deformed rod, hot rolled.



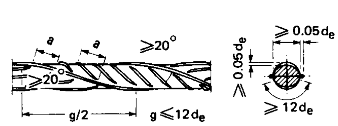
Oval deformed rod, hot rolled.



Round deformed bar, hot rolled.



Indented wire, cold drawn.



Round deformed bar in twisted condition.

Possible shapes of hot rolled deformed bars.

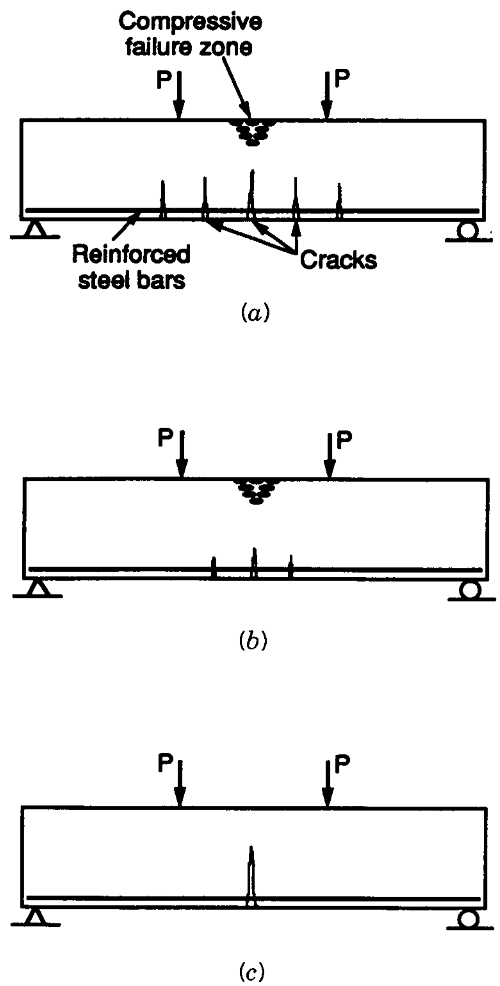
Coulomb, Charles Augustin de

The Bettmann Archive

Steel Reinforcement

- **If beam bends enough to permit concrete to fail in compression , collapse is sudden**

- **Optimal reinforcement limits crack growth and prevents compressive failure**



Failure modes of concrete beams reinforced by different amounts of reinforcement: (*a*) an under-reinforced concrete beam (yielding of steel and compressive failure of concrete), (*b*) an over-reinforced concrete beam (compressive failure of concrete), and (*c*) a beam with the minimum reinforcement ratio (yielding of steel).

Pre - Stressed Concrete

- If steel is pulled into tension before concrete is cast , then it compresses the concrete and provides additional strength

- Depends on fact that steel can be stretched much more than concrete before it fails

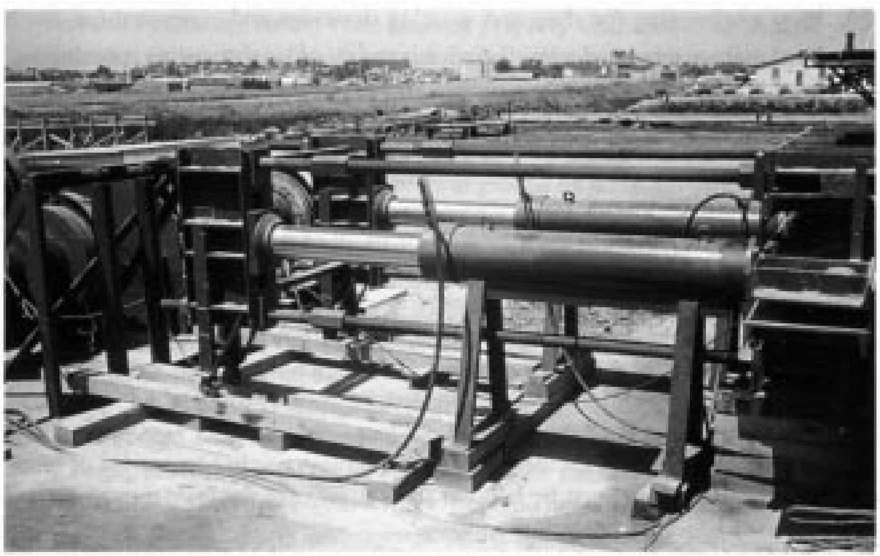
  - Requires good quality steel that does not creep (flow) under load , which would gradually release compression

  - Requires dense concrete to protect steel from water , since steel under tension corrodes rapidly

- Pre-tension applied in factory , then pieces transported to building site

- Post-tension applied on - site , using cables or rods passed through channels cast into concrete

Placing and vibrating concrete.



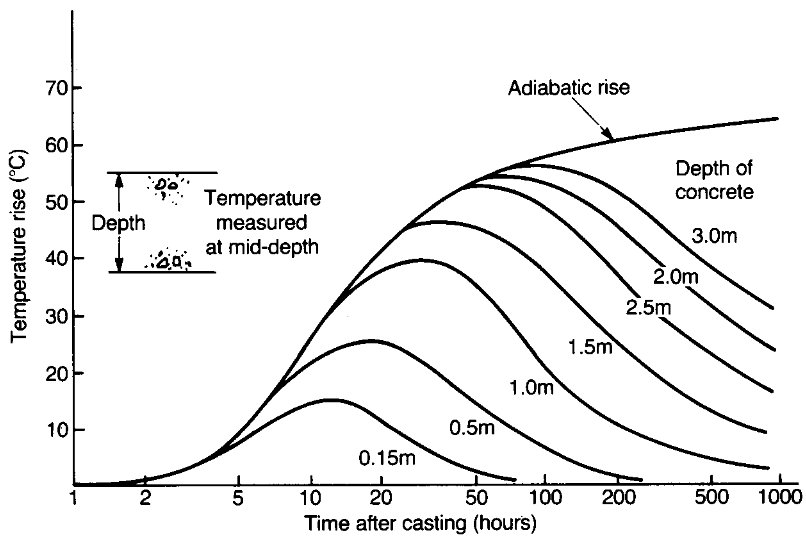
Long-stroke hydraulic jacks for stressing tendons.

Stressing stand takes reaction of stressed tendons.

Screeding and finishing surface of pretensioned concrete piles.

Hydration of Cement

- Reaction of cement with water is *hydration*
- Hydration releases heat
  - If heat does not escape , concrete temperature approaches boiling point
  - Thick concrete bodies (such as dams) become very hot inside



  - Cracking occurs if surface is much cooler than interior
  - To prevent cracking , must remove heat from interior or insulate surface

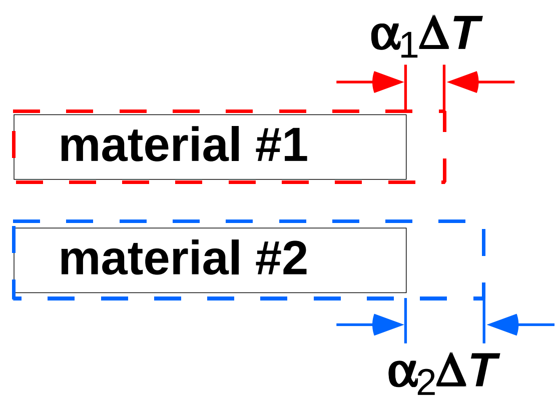
Thermal Stress

- **Increase in temperature causes materials to expand**

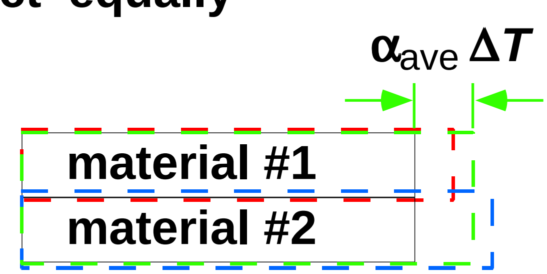
  - **Change in length $\Delta L / L$ is related to change in temperature ΔT by thermal expansion coefficient α**

$$\frac{\Delta L}{L} = \alpha \Delta T$$

- **Different materials may expand by different amounts**

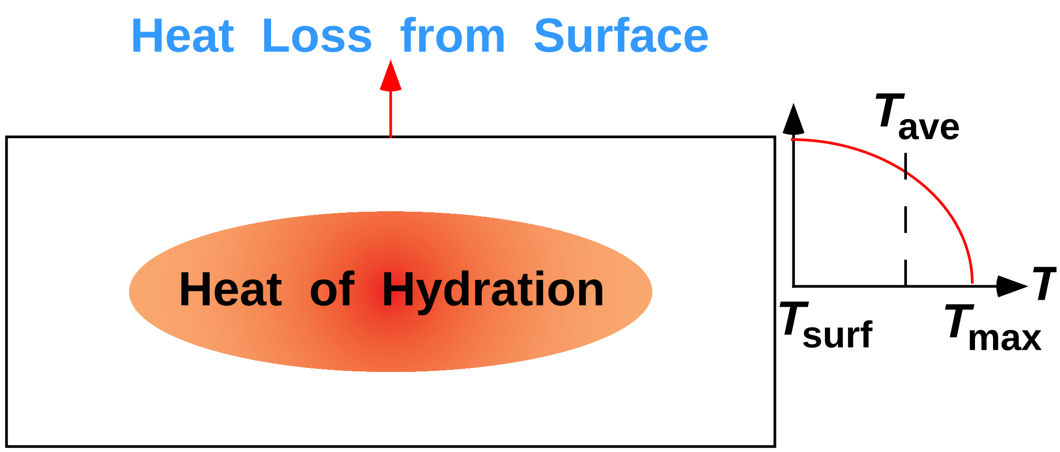


- **When two different materials are joined together, they are obliged to expand or contract equally**



Thermal Stress

- If a thick body of concrete loses heat from the surface , then the inside expands more than the outside



- Stress at surface of plate with internal temperature variation

$$\sigma_x = \frac{E\,\alpha}{1-\nu}\left(T_{average} - T_{surface}\right)$$

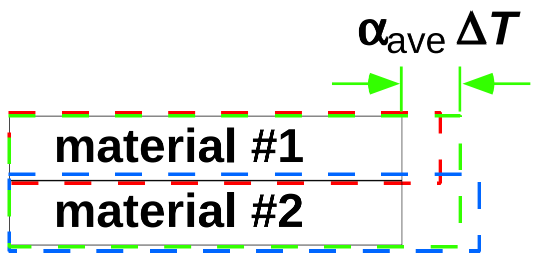
- For concrete , modulus $E \approx 40$ GPa , Poisson's ratio ≈ 0.25 , $\alpha \approx 90$ ppm/°C , so

$$\sigma_x\,(\text{MPa}) \approx \left(T_{ave} - T_{surf}\right)/\,2$$

- Since the tensile strength of concrete is only ~3-5 MPa , ΔT exceeding ~10°C could cause cracking

    - Cracking usually prevented by *creep*

Thermal Stress in Composite



- Material #1 is *stretched* by $(\alpha_{ave} - \alpha_1)\Delta T$
- Material #2 is *compressed* by $(\alpha_2 - \alpha_{ave})\Delta T$
- For thin bars of equal thickness, resulting stress in material #1 is

$$\sigma_1 = \frac{(\alpha_1 - \alpha_2)\Delta T}{\frac{1}{E_1} + \frac{1}{E_2}}$$

where E_1 and E_2 are elastic moduli

- Example:
  - Aluminum: $\alpha = 23.6 \times 10^{-6}/^{\circ}C$, $E = 70$ GPa
  - Steel : $\alpha = 11 \times 10^{-6}/^{\circ}C$, $E = 200$ GPa

$$\sigma_{Al}\ (\text{MPa}) \approx 0.65\,\Delta T$$

$$\sigma_{Al}\ (\text{psi}) \approx 95\,\Delta T$$

∴ 100°C change creates 65 MPa (9500 psi)

Thermal Expansion Coefficients

Material	Thermal expansion coefficient (ppm/°C)
Limestone	3.9
Granite	5.3
Sandstone	9.7
Portland cement	10-20
Concrete	6-10
Iron	12.9
Fe_3C	6.0
Steel	11-12
Aluminum	23.6
Copper	16.8
Silicon	2.9
Window glass	9.0
Pyrex glass	3.5
Silica glass	0.5

- **Expansion coefficient of concrete is average of stone and cement components**
- **Value matches steel quite well**

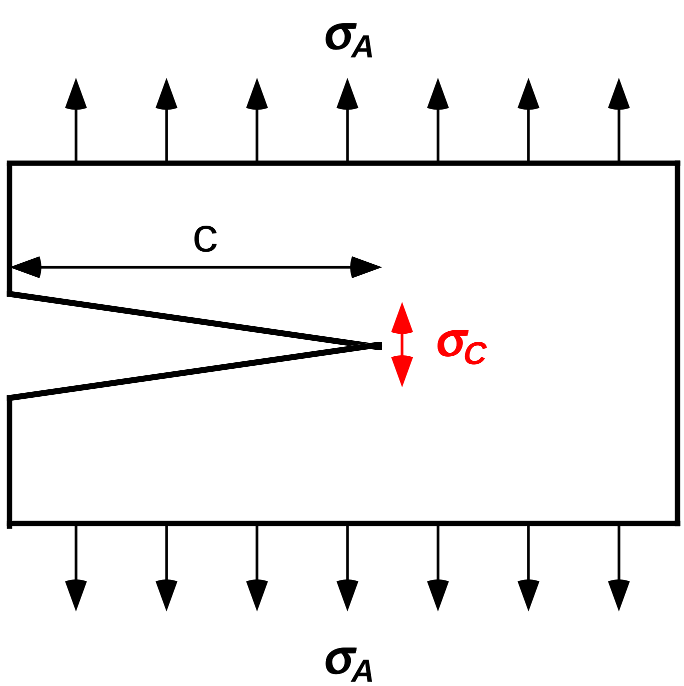
Creep

- Young concrete deforms (creeps) under high load
    - Prevents cracking from thermal gradients
    - Causes sagging of arches and domes
        - Resisted by reinforcement
    - Causes loss of pre - tension
- Creep rate decreases as concrete gets older and harder
    - Post - tension easier to sustain
- Cause of creep deformation controversial
    - Squeezing water from layers of C-S-H
    - Slipping of particles
    - Dissolution and reprecipitation

<u>Strength</u>

- **The *intrinsic* strength of a solid depends on the strength of interatomic bonds**
  - **Intrinsic strength of window glass is ~7 GPa (~ 1 million psi)**
- **Actual strength of brittle materials (glass , ceramics , concrete , stone) depends on surface flaws**
- **Stress at tip of flaw of depth *c* is amplified by a factor of $2\sqrt{c/a}$, where *a* is atomic bond length (~10^{-10} m)**

$$\sigma_C \approx 2\,\sigma_A \sqrt{c/a}$$



Strength

- **Most common objects have invisibly small defects that control their strength , which is *far* below their intrinsic strength**

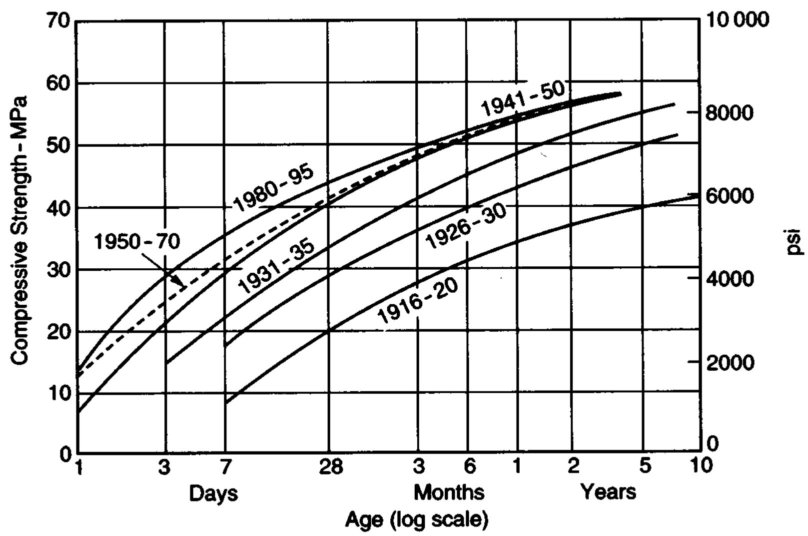
- **Example :**

  If $c = 10^{-4}$ meter (≈ thickness of human hair) , then $\sqrt{c/a} = 1000$, so strength of glass drops to ~7 MPa (1000 psi)

- **Concrete contains tiny air pockets , and weak spots near surfaces of aggregate**

  - **Practical tensile strength of concrete is ~3 MPa (450 psi) , which is ~1000 times less than intrinsic strength**

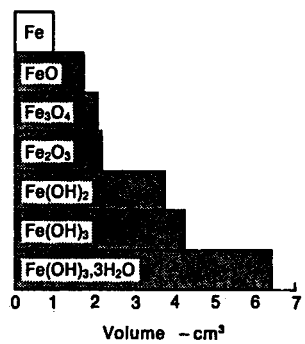
- **Compressive strength of concrete is ~10 times higher than tensile strength , so concrete is used in compression**



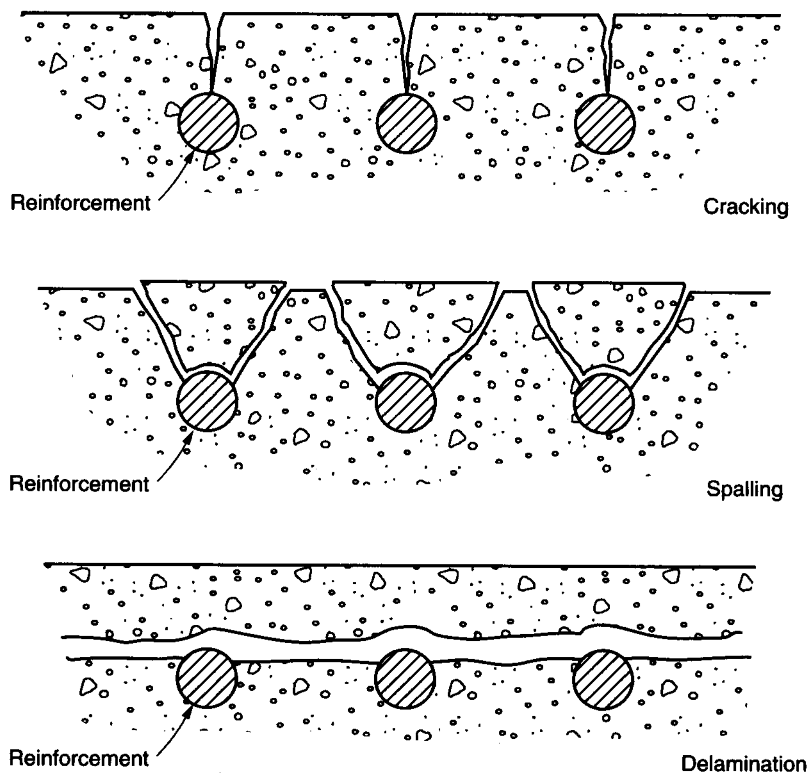
Changes in gain of strength of cements with age between 1916 and the 1990s (measured on standard cylinders of concrete with a water/cement ratio of 0.53

Durability

- Concrete can be damaged by
  - Corrosion of reinforcing steel
    - Accelerated by chlorides
      (esp. from de-icing salts)
  - Freeze / thaw cycles
  - High temperatures (destroyed ~600°C)
- To optimize durability
  - Minimize porosity
    - Low water / cement ratio
    - Add pozzolan (e.g., fly ash)
    - Dense aggregate
    - Surface coatings (e.g., silicone)
  - Avoid chlorides
  - Passivate steel (galvanize , epoxy)



The relative volumes of iron and its corrosion reaction products



Diagrammatic representation of damage induced by corrosion: cracking, spalling, and delamination

Why Use Concrete ?

- Raw materials are available everywhere
- Cost is low compared to metal

ENERGY CONSUMPTION IN MANUFACTURE OF VARIOUS ENGINEERING SOLIDS

	Energy/mass, GJ/1000 kg	Energy/mass-stiffness, m^3/1000 kg	Energy/mass-strength, m^3/1000 kg
Aluminum	200	2.8	870
Cast iron	45	0.3	300
Low-carbon steel	50	0.24	240
Glass	20	0.3	333
Brick	6	0.1	30
Concrete	2	0.05	80
Wood	1	0.07	10
Polyethylene	45	90	1500
Carbon-fiber-reinforced composite	4000	27	6000

  - Energy invested per unit of stiffness or strength is 3 - 4 times less than steel

- Low cost and high performance of reinforced concrete permits

  - Longer spans (bridges)
  - Taller buildings
  - Thin shells
  - Huge dams
  - Casting of monolithic forms

Concrete

- Technology transforms nature
    - Clay + limestone → Portland cement
    - Concrete + steel → Reinforced concrete
        - Ancient materials combined into novel composite allows innovation
- Technology transforms society
    - Cheaper construction
        - Bridges connect isolated villages
    - Enabling technology for dams
        - Electrical power
    - Ubiquity of raw materials prevents monopolization of business
- Symbolism
    - Construction of forms not found in nature