National Institute of Advanced Industrial Science and Technology (AIST)
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Design, Manufacturing and Application of Structural Concrete

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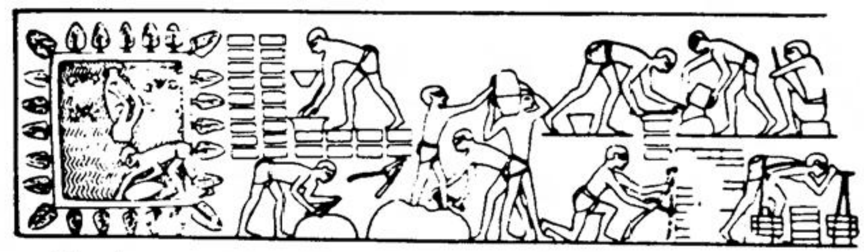
Outline

- A brief history of concrete
- Basics of concrete
- Formation of structural concrete
- Characteristics of structural concrete
- Microscopic description of concrete
- Design of concrete materials
- Design of concrete structures
- Manufacturing of concrete
- Application of concrete
- Deterioration of concrete
- Summary
- References

A Brief History of Concrete

- ~2,700 B.C., the Egyptians used gypsum mortars in the construction of the Pyramid of Cheops.
- ~1,600 B.C., the Chinese in the Shang Dynasty used clay in making bricks for construction.
- ~1,100 B.C., the Assyrians used fine quality clay for their writing tablets and buildings.
- ~600 B.C., the Greeks built the lining of a cistern in Kamiros, the Island of Rhodes, Greece, using the mixture of volcanic ash and lime (known as the Greek cement).
- ~400 B.C., the Babylonians used clay as the bonding substances or cement.

A. *Lepsius recreation suggests workmen are preparing a stack of bricks.*



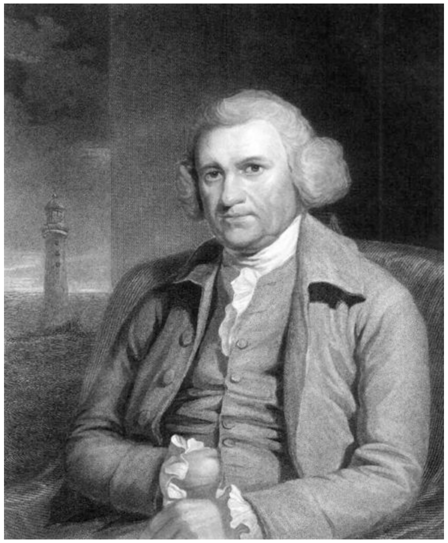
B. *Newberry recreation suggests a stack of bricks.*

A Brief History of Concrete

- ~230 B.C., the Romans improved the Greek cement using the volcanic silicious component to obtain ”Roman cement” known as pozzolana, the name deriving from the port of Pozzuoli,west of Naples and the volcano Vesuvious, Italy.

Colosseum, Roma, Italy
(72~80 A.D.)

- In 1756, John Smeaton (1724~1792) of Austhrope, Leeds, England, made the first modern concrete using hydraulic lime and designed and rebuilt the Eddystone Lighthouse during 1755~1759, who founded the Society of Civil Engineers in 1771 and was regarded as the father of civil engineering.



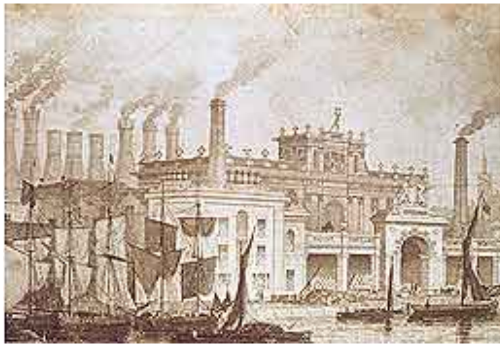
John Smeaton
(1724~1792)

- In 1807, James Frost (1780~1840) of Finchley, North London, England, set up a plant making Roman cement at Harwich. In 1822, he developed a cheaper alternative to make Roman cement and patented it as ”British cement”. In 1825, his cement plant in Swanscombe, Kent, England, began operational.

A Brief History of Concrete

- In 1824 (Oct. 21), Joseph Aspdin (1778~1855) of Wakefield, Yorkshire, England, patented "Portland cement" due to the similarity between the artificial rock and the limestone at the Isle of Portland in southern England. However, it was not clear to the public how Joseph and his son William manufactured their cements.

Joseph Aspdin
(1778~1855)

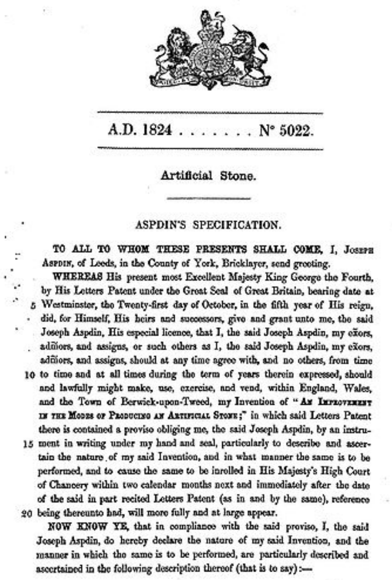


A Brief History of Concrete

- In 1833, Isaac Charles Johnson (1811~1911) of Mayfield, Gravesend, England, who was the manager of John Bazeley White's cement plant which producing "artificial cement" and Roman cement, deciphered the manufacturing and proportioning of Portland cements.

- – In 1871, the first American patent on Portland cement by David Saylor.

Isaac Charles Johnson
(1811~1911)



A.D. 1824 . . . . N° 5022.

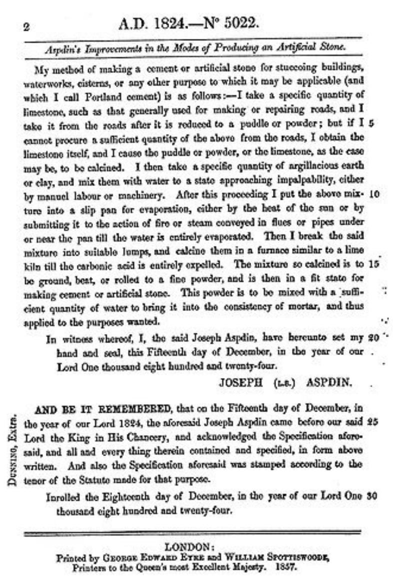
Artificial Stone.

ASPDIN'S SPECIFICATION.

TO ALL TO WHOM THESE PRESENTS SHALL COME, I, JOSEPH ASPDIN, of Leeds, in the County of York, Bricklayer, send greeting.

WHEREAS His present most Excellent Majesty King George the Fourth, by His Letters Patent under the Great Seal of Great Britain, bearing date at Westminster, the Twenty-first day of October, in the fifth year of His reign, did, for Himself, His heirs and successors, give and grant unto me, the said Joseph Aspdin, His especial licence, that I, the said Joseph Aspdin, my exors, admors, and assigns, or such others as I, the said Joseph Aspdin, my exors, admors, and assigns, should at any time agree with, and no others, from time to time and at all times during the term of years therein expressed, should and lawfully might make, use, exercise, and vend, within England, Wales, and the Town of Berwick-upon-Tweed, my Invention of "AN IMPROVEMENT IN THE MODES OF PRODUCING AN ARTIFICIAL STONE;" in which said Letters Patent there is contained a proviso obliging me, the said Joseph Aspdin, by an instrument in writing under my hand and seal, particularly to describe and ascertain the nature of my said Invention, and in what manner the same is to be performed, and to cause the same to be inrolled in His Majesty's High Court of Chancery within two calendar months next and immediately after the date of the said in part recited Letters Patent (as in and by the same), reference being thereunto had, will more fully and at large appear.

NOW KNOW YE, that in compliance with the said proviso, I, the said Joseph Aspdin, do hereby declare the nature of my said Invention, and the manner in which the same is to be performed, are particularly described and ascertained in the following description thereof (that is to say):—



2 A.D. 1824.—N° 5022.

Aspdin's Improvements in the Modes of Producing an Artificial Stone.

My method of making a cement or artificial stone for stuccoing buildings, waterworks, cisterns, or any other purpose to which it may be applicable (and which I call Portland cement) is as follows:—I take a specific quantity of limestone, such as that generally used for making or repairing roads, and I take it from the roads after it is reduced to a puddle or powder; but if I cannot procure a sufficient quantity of the above from the roads, I obtain the limestone itself, and I cause the puddle or powder, or the limestone, as the case may be, to be calcined. I then take a specific quantity of argillacious earth or clay, and mix them with water to a state approaching impalpability, either by manuel labour or machinery. After this proceeding I put the above mixture into a slip pan for evaporation, either by the heat of the sun or by submitting it to the action of fire or steam conveyed in flues or pipes under or near the pan till the water is entirely evaporated. Then I break the said mixture into suitable lumps, and calcine them in a furnace similar to a lime kiln till the carbonic acid is entirely expelled. The mixture so calcined is to be ground, beat, or rolled to a fine powder, and is then in a fit state for making cement or artificial stone. This powder is to be mixed with a sufficient quantity of water to bring it into the consistency of mortar, and thus applied to the purposes wanted.

In witness whereof, I, the said Joseph Aspdin, have hereunto set my hand and seal, this Fifteenth day of December, in the year of our Lord One thousand eight hundred and twenty-four.

JOSEPH (L.S.) ASPDIN.

AND BE IT REMEMBERED, that on the Fifteenth day of December, in the year of our Lord 1824, the aforesaid Joseph Aspdin came before our said Lord the King in His Chancery, and acknowledged the Specification aforesaid, and all and every thing therein contained and specified, in form above written. And also the Specification aforesaid was stamped according to the tenor of the Statute made for that purpose.

Inrolled the Eighteenth day of December, in the year of our Lord One thousand eight hundred and twenty-four.

DUNNING, Extra.

LONDON:
Printed by GEORGE EDWARD EYRE and WILLIAM SPOTTISWOODE, Printers to the Queen's most Excellent Majesty. 1857.

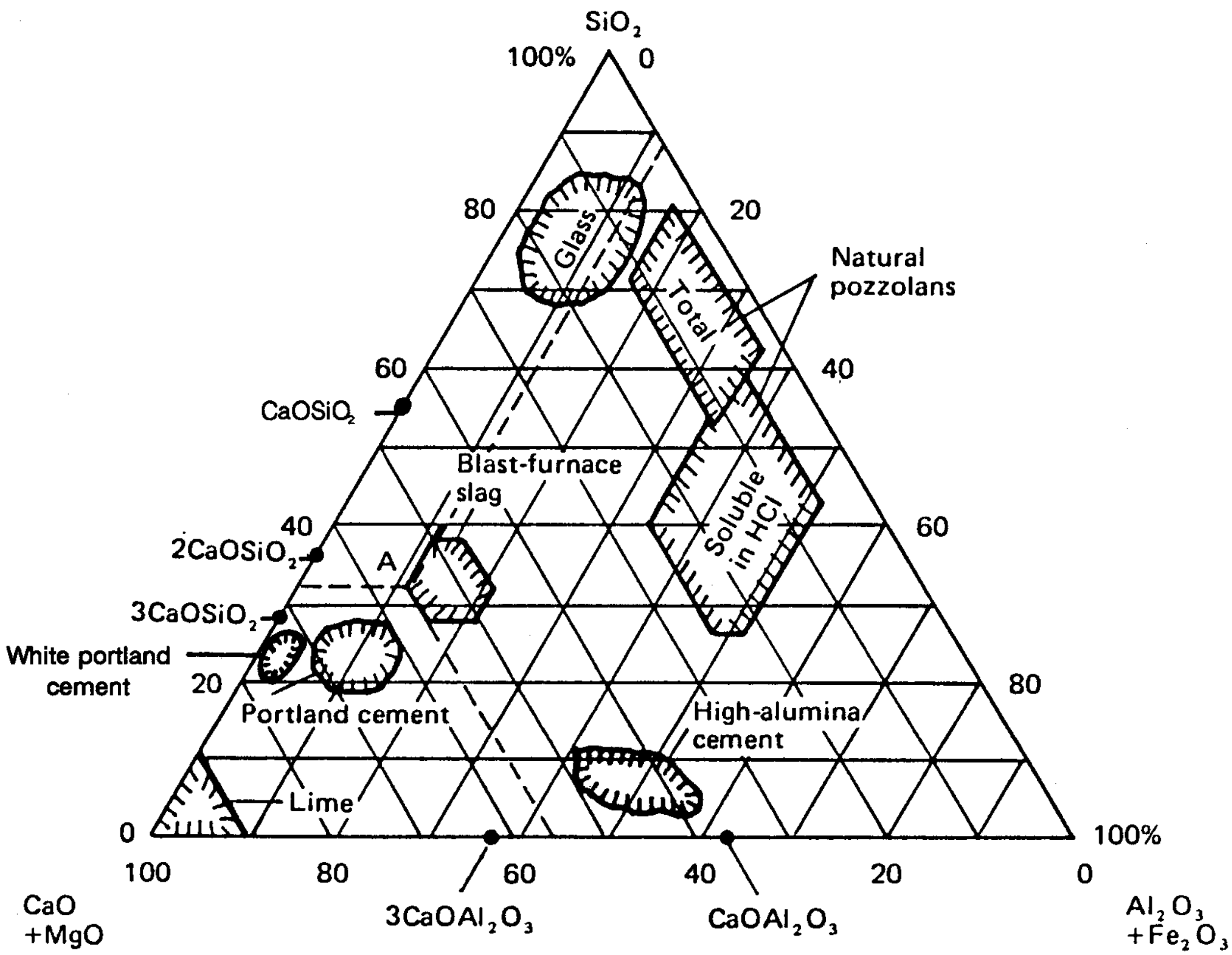
Joseph Aspdin's patent in 1824

Basics of Concrete

- Concrete is a cementitious composite typically made by Portland cement.
  - Cement + water = Cement paste
  - Cement + water + fine aggregate (e.g., sand) = Cement mortar
  - Cement + water + sand + fine aggregate + coarse aggregate (e.g., gravels) = Concrete (*mineral and chemical admixtures are used for improving workability and durability of the concrete*)
- Structural concrete is the concrete used for structural purposes such as providing mechanical bearing capacity.
- Major oxides of Portland cements:
  - Lime (CaO), Silica (SiO_2), Alumina (Al_2O_3), Iron oxide (Fe_2O_3)
- Minor oxides of Portland cements:
  - Magnesia (MgO), Alkali oxides (Na_2O and K_2O), Titania (TiO_2), Phosphorous pentoxide (P_2O_5), Gypsum ($CaSO_4 \cdot 2H_2O$)

Basics of Concrete

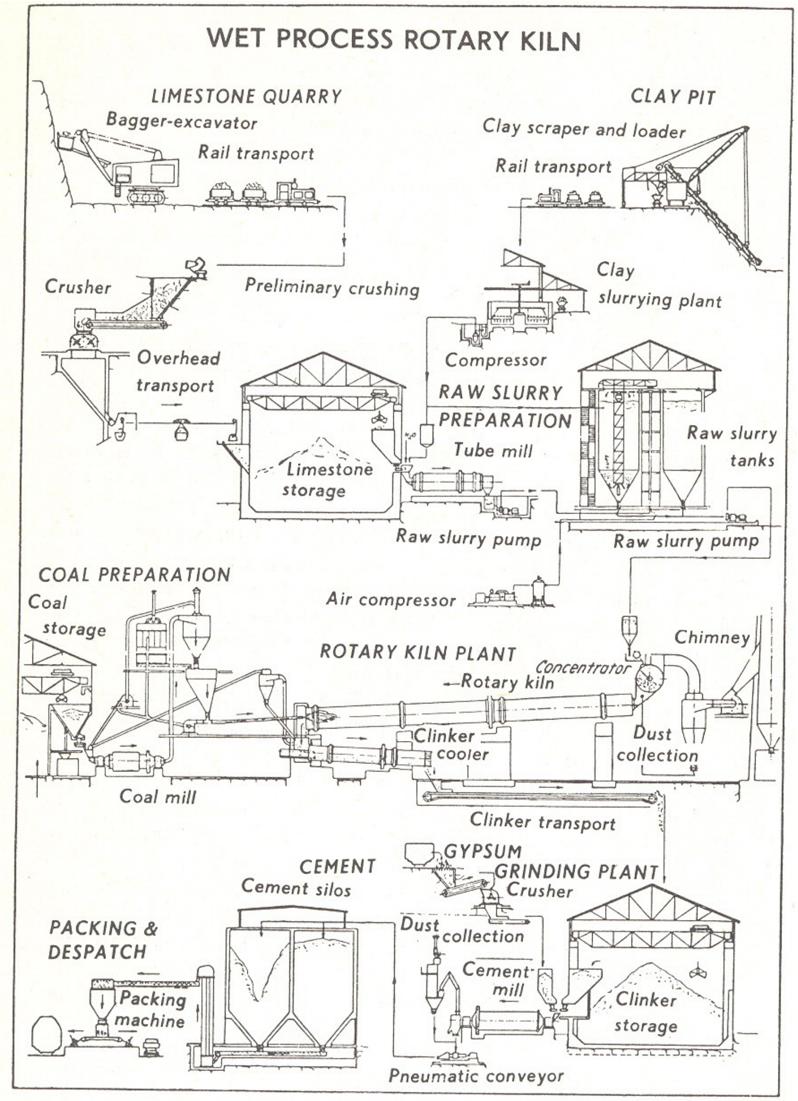
- Phase diagram of various substances consisting of the major oxides



(Popovics 1992)

Basics of Concrete

- Manufacturing of Portland Cement
  - Collection of the raw mineral materials
  - Grinding and blending of the raw materials
  - Storage and final blending of the raw materials
  - Burning (clinkering) process
  - Final process.



Basics of Concrete

- Chemicals formed by oxides in the clinkering/burning process:

Chemical	Formula	Abbr. notation	Weight (%)
Tricalcium silicate	$3CaO \cdot SiO_2$	C_3S	55
Dicalcium silicate	$2CaO \cdot SiO_2$	C_2S	18
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A	10
Tetracalcium aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF	8
Calcium sulfate dihydrate	$CaSO_4 \cdot 2H_2O$	CSH_2	6

- Types of Portland cement:
  - **Type I:** For use when the special properties specified for any other type are not required.
  - **Type II:** For general use, more especially when moderate sulfate resistance or moderate heat of hydration is desired.
  - **Type III:** For use when high early strength is desired.
  - **Type IV:** For use when a low heat of hydration is desired.
  - **Type V:** For use when high sulfate resistance is desired.

Formation of Structural Concrete

- Portland cement is the chief ingredient in cement paste and the most widely used building material in the world. In the presence of water, the chemical compounds within Portland cement hydrate causing hardening and strength gain. → Hydration process
- Hydrated cement forms the hydration products in concrete, which serves as the binding element in concrete.
- Chemistry of hydration:

  · **Tricalcium silicate:**

$$\boxed{2C_3S + 11H \rightarrow C_3S_2H_8 + 3CH} \qquad (1)$$

where $C_3S_2H_8$ is the C-S-H gel.

  · **Dicalcium silicate:**

$$\boxed{2C_2S + 9H \rightarrow C_3S_2H_8 + CH} \qquad (2)$$

Formation of Structural Concrete

- Chemistry of hydration:
  - **Tricalcium aluminate:**

    Primary:

$$\boxed{C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32}} \qquad (3)$$

where $3C\bar{S}H_2$ is gypsum and $C_6A\bar{S}_3H_{32}$ is ettringite.

Secondary:

$$\boxed{2C_3A + C_6A\bar{S}_3H_{32} + 4H \rightarrow 3C_4A\bar{S}H_{12}} \qquad (4)$$

where $3C_4A\bar{S}H_{12}$ is monosulfoaluminate.

  - **Tetracalcium aluminoferrite:**

$$\boxed{C_4AF + 3C\bar{S}H_2 + 21H \rightarrow C_6(A,F)\bar{S}_3H_{32} + (F,A)H_3} \quad (5)$$

$$\boxed{C_4AF + C_6(A,F)\bar{S}_3H_{32} + 7H \rightarrow 3C_4(A,F)\bar{S}H_{12} + (F,A)H_3} \quad (6)$$

Formation of Structural Concrete

- Kinetics of hydration:

$$\boxed{C_3A > C_3S > C_4AF > C_2S} \qquad (10)$$

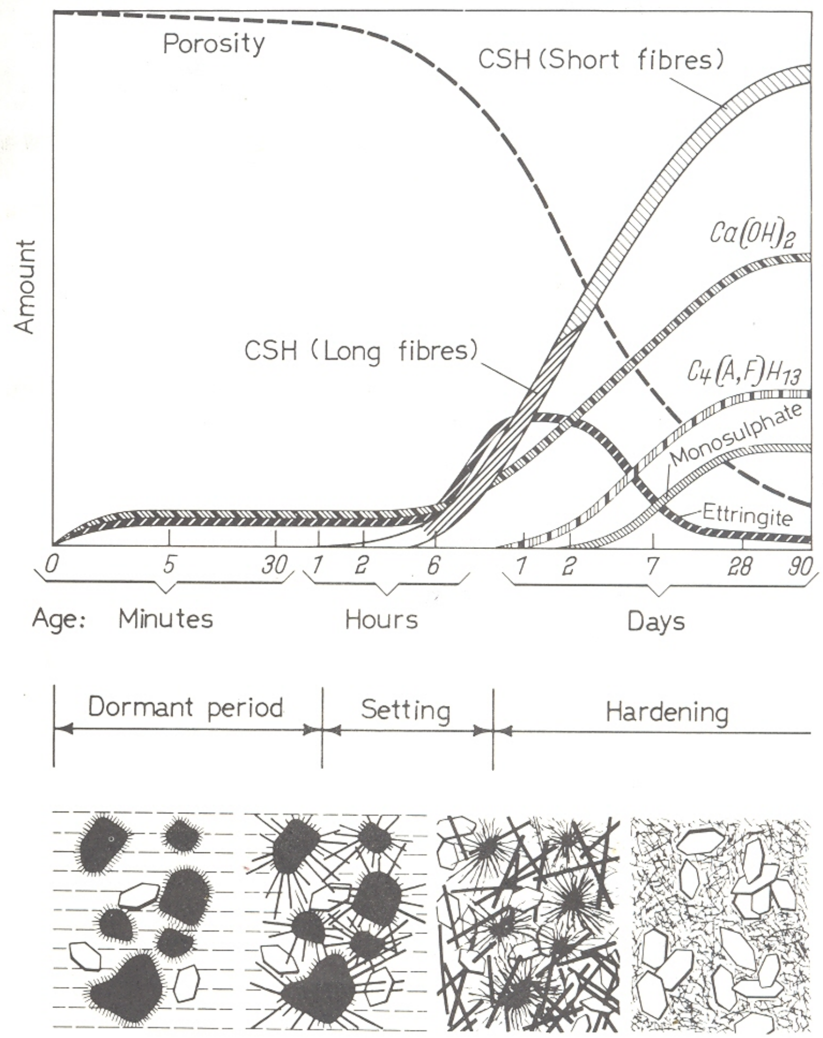
→ Impure C_3S is known as **alite** and impure C_2S as **belite**; alite and belite hydrate faster than pure C_3S and C_2S.

- Role of gypsum:
  - Too much gypsum can lead to excessive amounts of ettringite, causing unrestrained expansion and disruption of the paste microstructure.
  - Too little gypsum can lead to the formation of monosulfoaluminatesolid solution after the hydration of C_3S, resulting in the consumption of lime and preventing the nucleation of C_3S.
  - Gypsum accelerates C_3S hydration but lowers the of C-S-H due to the presence of sulfate ions.

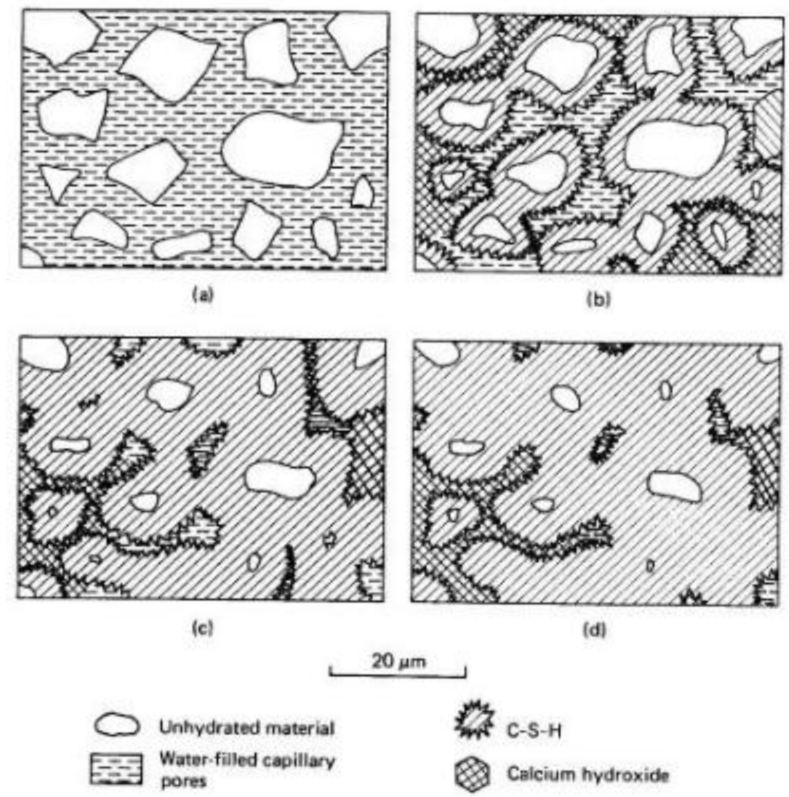
→ *Control of gypsum is important in the manufacturing of cement and curing of concrete.*

Formation of Structural Concrete

- Hydration and structure development in concrete:



(Locher and Richartz 1974)



(Mindess and Yooung 2003)

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Characteristics of Structural Concrete

- Advantages:
  - Workability (ability to be cast when in fresh)
  - Economy (cost; $100 cubic yard for 3000psi)
  - Durability (permeability, mass transport; ideally maintenance free; density = 2,300 kg/m^3 (145 pcf) for normal weight concrete and 1,800 kg/m^3 (110 pcf) for lightweight concrete)
  - Fire resistance (thermal conductivity = 1.53.5 Watts/m · K)
  - Energy efficiency (energy consumption; 3.4 GJ/m3)
  - On-site production (ease for material collection)
  - High compressive strength (compressive strength; 35MPa (5000 psi) for ordinary concrete and >150 MPa (22,000 psi) for high strength concrete)
  - Short-term dimensional stability (Poisson's ratio = 0.18; coefficient of thermal expansion=10^{-5} per C (5.5×10^{-6} per F))

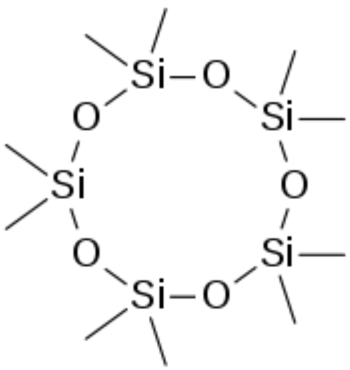
Characteristics of Structural Concrete

- Disadvantages:
  - Low tensile strength (tensile strength; 3MPa (400psi))
  - Low ductility (brittle in nature; less or no inelastic deformability; ultimate compressive strain = 0.003~0.004 and ultimate tensile strain = 0.001) → Fiber reinforced concrete (FRC) provides better ductility.
  - Low strength-to-weight ratio (for ordinary concrete, 0.015 MPa/kg in compression and 0.0026 MPa/kg in tension, both per cubic meter)
  - Long-term dimensional instability (porosity; shrinkage, creep)

Characteristics of Structural Concrete

- Types of water in hardened cement pastes
  - Chemically-bound water or combined water or non-evaporable water
  - Adsorbed water or gel water
  - Free water or capillary water

- Role of Water in Concrete:
  - Saturated concrete is about 20% weaker in compression than is dry concrete.
  - Possible reasons include:
    - The removal of water molecules makes C-S-H gel particles come closer to form a tighter system due to an increase in van der Waal's forces.
    - Water may attack Si-O-Si bonds (in C_3A and C_2A under stress.
    - Water may reduce mechanical interlock by acting as a lubricant.



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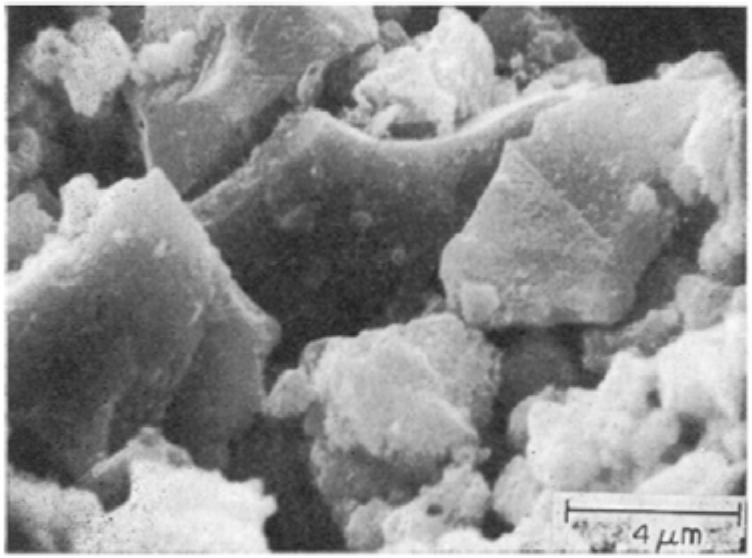
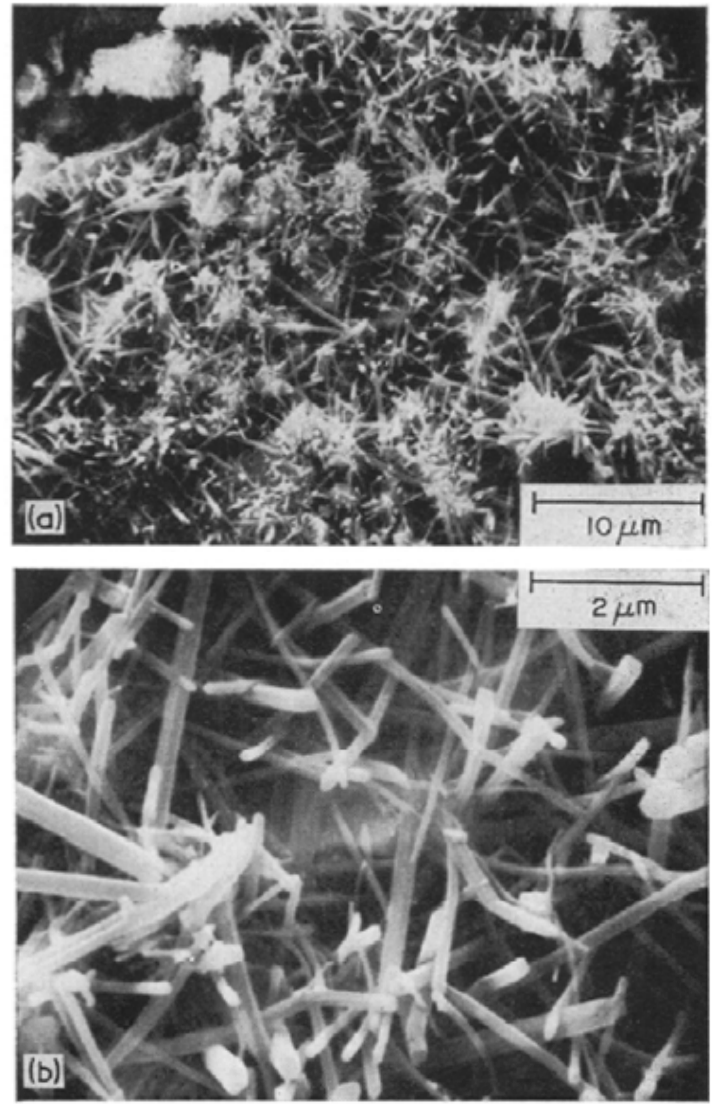
Microscopic Description of Concrete

- Scanning electron micrograph (SEM):



Fracture surface of a Portland cement paste after **1 hour** hydration



Fracture surface of a Portland cement paste after **24 hours** hydration
(Walsh et. al. 1974)

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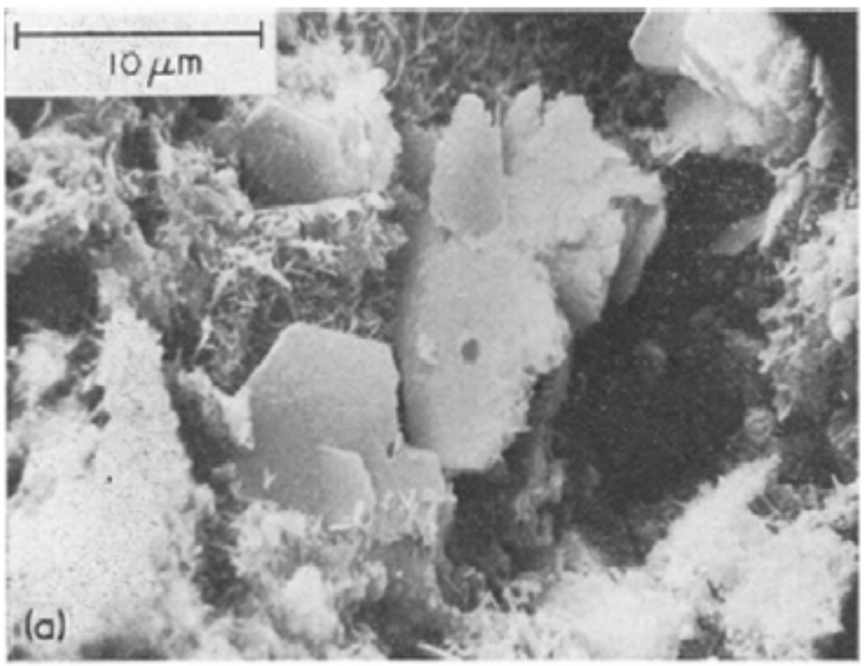
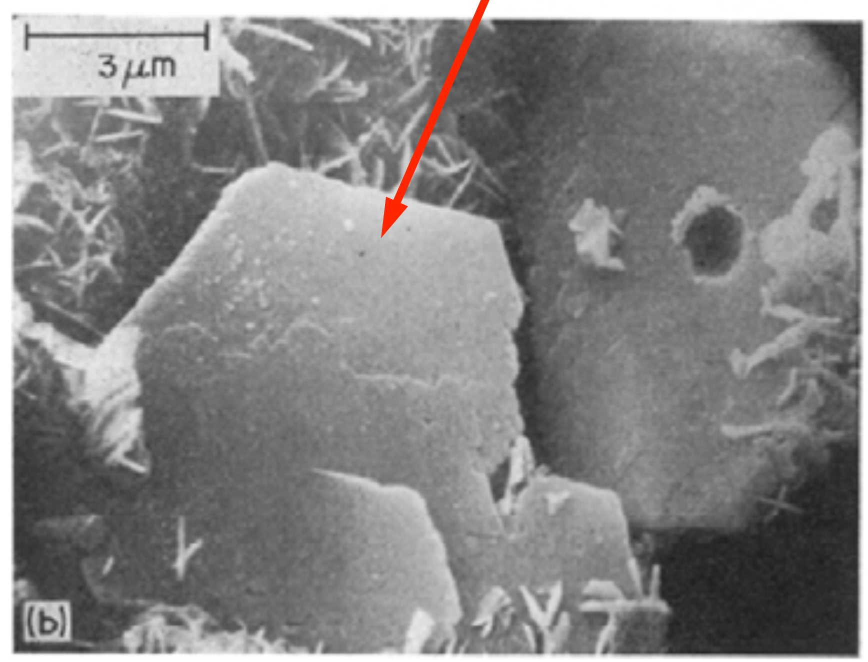
Microscopic Description of Concrete

- Scanning electron micrograph (SEM):



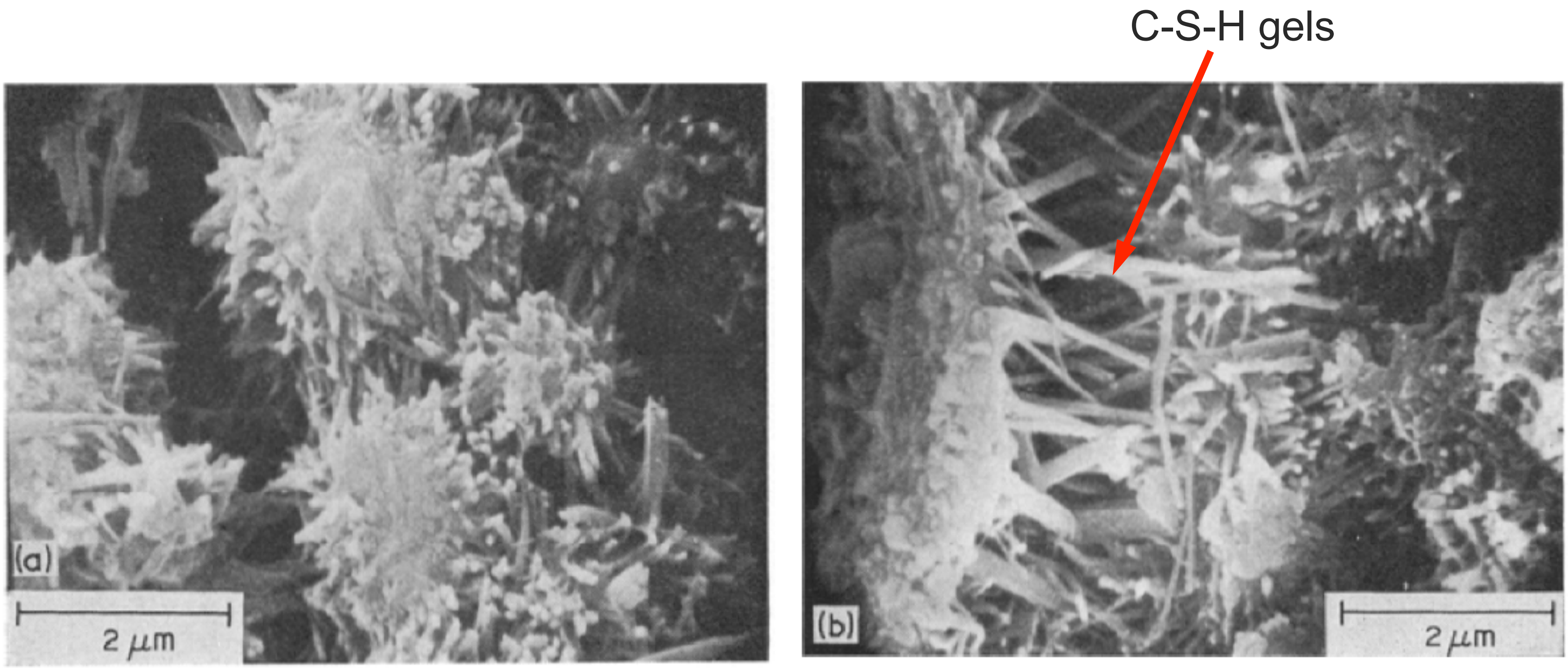


Fracture surface of a Portland cement paste after **21 days** hydration

(Walsh et. al. 1974)

Microscopic Description of Concrete

- Role of Water in Concrete:



Fracture surface of a Portland cement paste after **21 days** hydration

(Walsh et. al. 1974)

Microscopic Description of Concrete

- Pore sizes and their description:

Designation	Diameter	Description
Capillary pores	$10^4 \sim 50$ nm	large capillaries, macropores
	$50 \sim 10$ nm	medium capillaries, large meso-pores
Gel pores	$10 \sim 2.5$ nm	small isolated capillaries, small mesopores
	$2.5 \sim 0.5$ nm	micropores
	≤ 0.5 nm	interlayer spaces

Design of Concrete Materials

- Properties of concrete are determined by the mixing and proportioning of its ingredients (e.g., water, cement, aggregates, admixture). → Mix design

- Fundamentals of mix design:
  - Water to cement ratio → Abram's law
  - Aggregate grading → Fuller and Thompson's formula

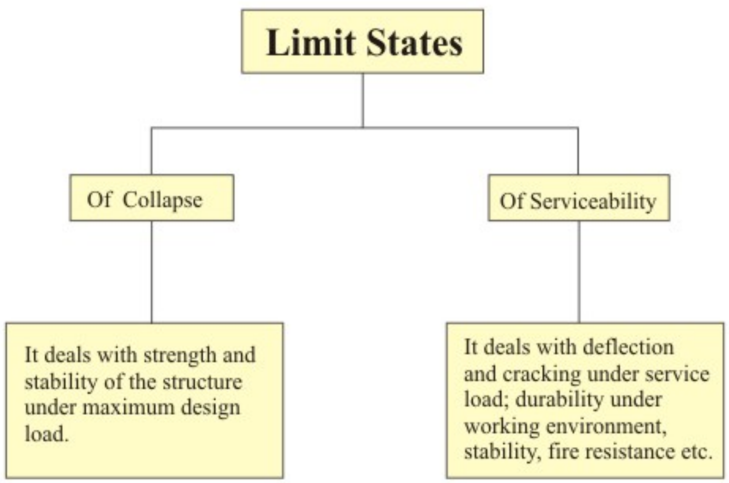
- ACI method of mix design

  → ACI 211.1-91 (1991), Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, ACI Committee 211, Farmington Hills, MI.

- Trial batch adjustments are needed.

Design of Concrete Structures

- Design states:
  - Limit states:
    - **Ultimate limit state**: Structural collapse of all or part of the structure and loss of life can occur; Loss of equilibrium of a part or all of a structure as a rigid body; Rupture of critical components causing partial or complete collapse.
    - **Serviceability limit state**: Functional use of structure is disrupted, but collapse is not expected; Excessive crack width → corrosion of reinforcement → gradual deterioration
    - **Special limit state**: Damage/failure caused by abnormal conditions or loading (e.g., earthquakes, tornados, hurricanes, floods)



Design of Concrete Structures

Influences → **Structure** → **Response**

- **Loads (dead, live, environmental)**
- **Foundation settlements**
- **Time effects**
- **Temperature fluctuations**
- **Chemical effects**

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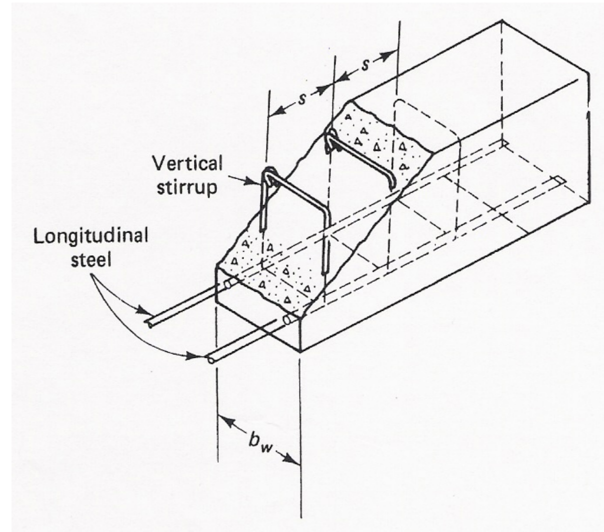
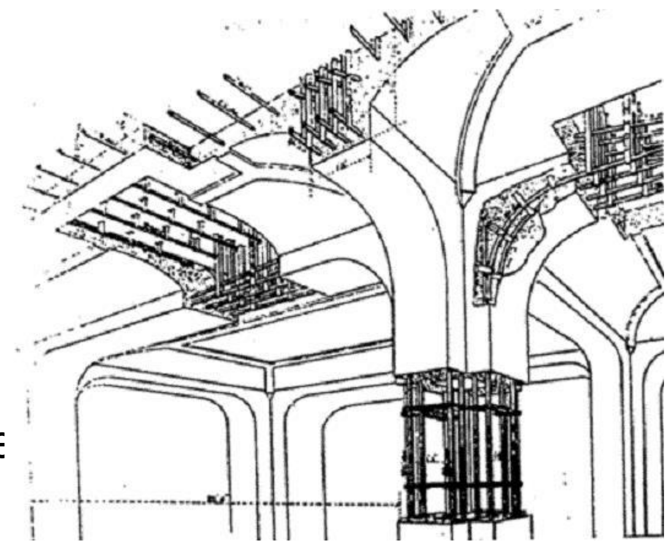
- **Failure (Strength)**
- **Failure mode**
- **Deformation**
- **Cracking**
- **Stress**
- **Motion**

- Design philosophies:
  - Emphasis on the reduction of structural capacity of concrete
  - Emphasis on the amplification of structural loading
  - Emphasis on both the reduction and the amplification

Design of Concrete Structures

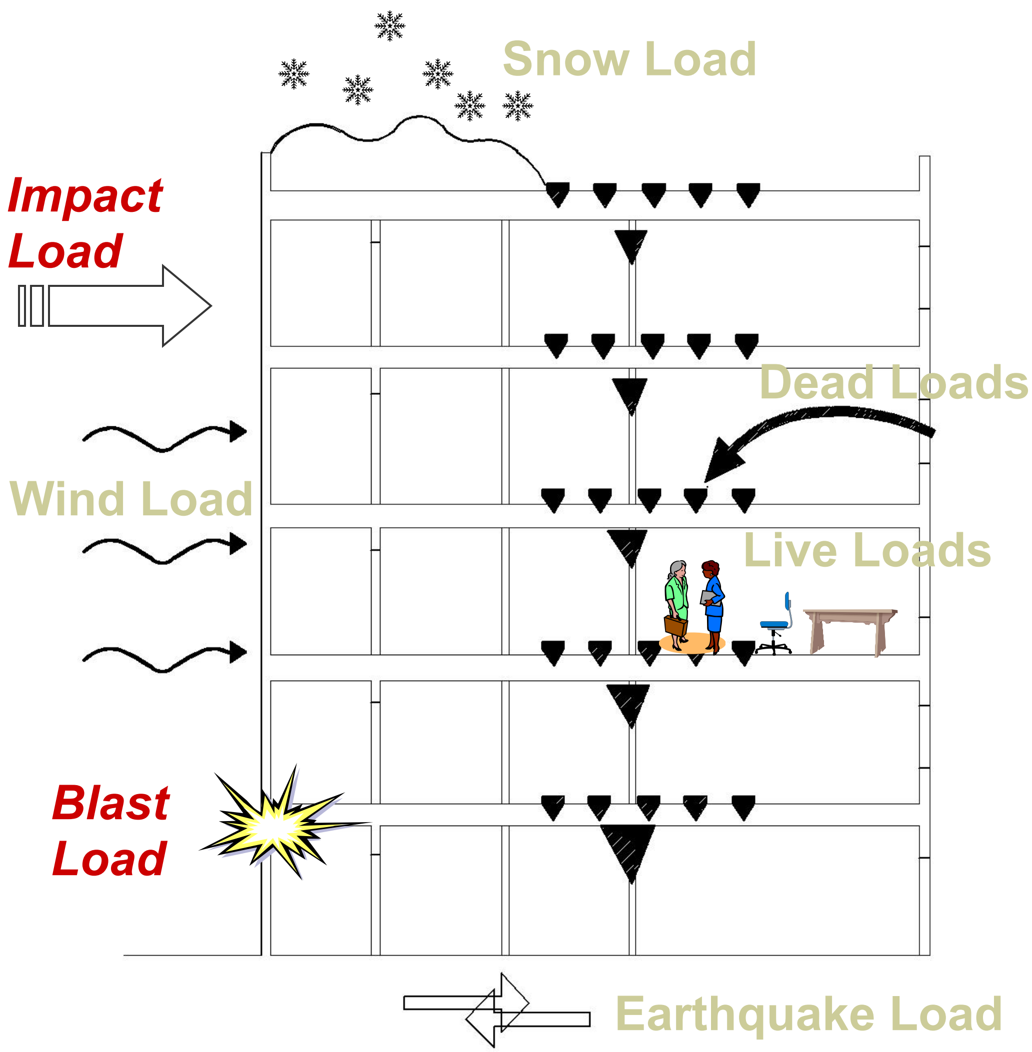
- Structural concrete is weak in tension, so reinforcements (steel or composites) are usually used to carry tensile stresses in concrete.
- Reinforcements can be introduced by
  - without being prestressed → Reinforced concrete (RC) structures
  - with being prestressed. → Prestressed concrete (PC) structures
- Design of concrete structures is basically about:
  - Material design (concrete and reinforcements) → Quality of materials affects the short-term performance of concrete structures
  - Structural design (configuration of concrete and reinforcements, cross-sectional design) → Quality of structural design affects both the short-term and the long-term performance of concrete structures





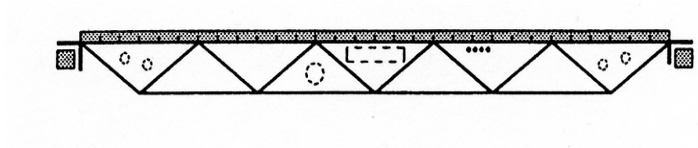
Design of Concrete Structures

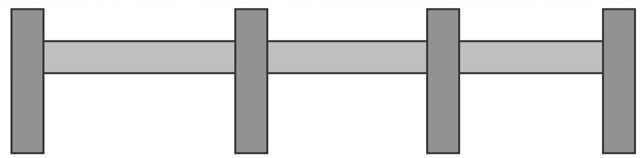
- Structural loads:
  - Gravity loads
    - Dead loads
    - Live loads
    - Snow loads
  - Lateral loads
    - Wind loads
    - Seismic loads
  - Special load cases
    - Impact loads
    - Blast loads



Design of Concrete Structures

- Gravity loads:
  - Floor systems account for a major portion of the gravity loads
  - Selection of the floor system may influence structural behavior and resistance
  - Structural use plays a major role in selection of the floor system
    - Office buildings
      - large simply supported spans
    - Residential and hotel buildings
      - short continuous spans

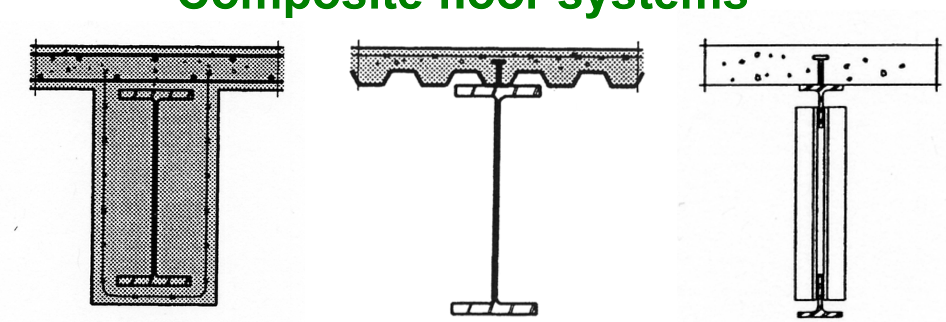




Types of floor systems

- Concrete
- Steel
- Composite
- Prestressed concrete

Composite floor systems



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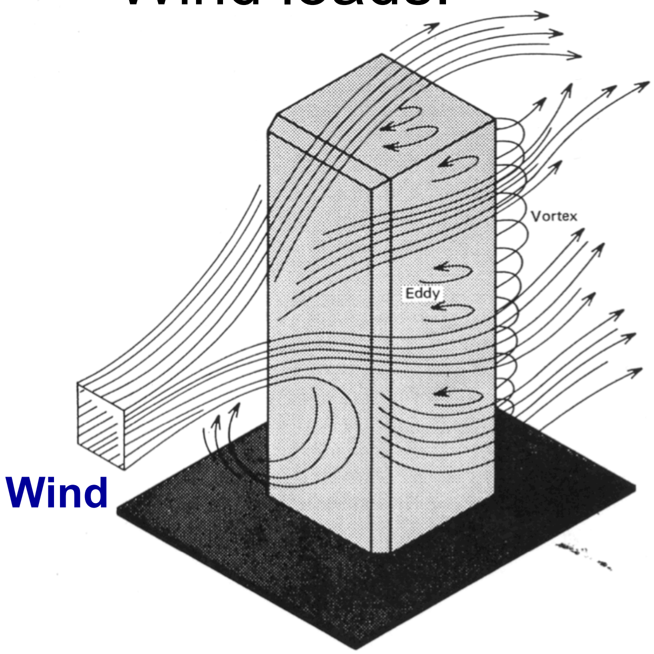
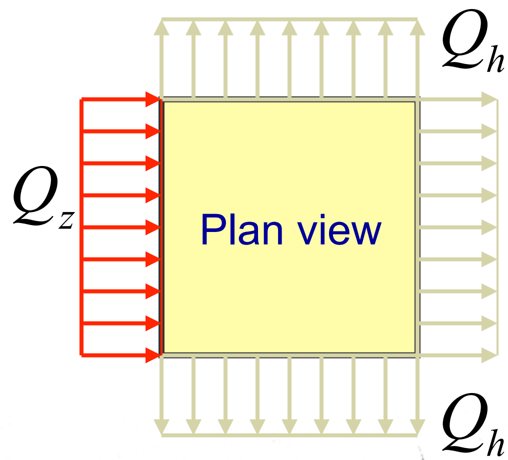
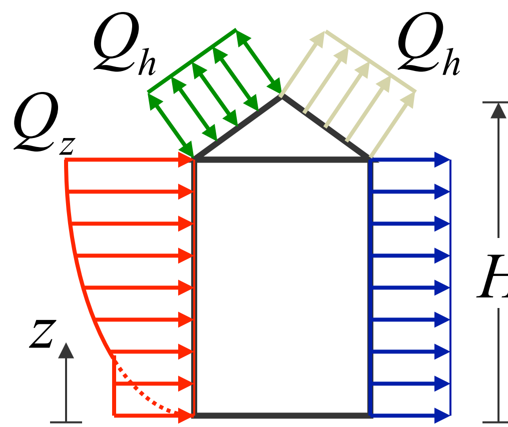
Design of Concrete Structures

- Wind loads:

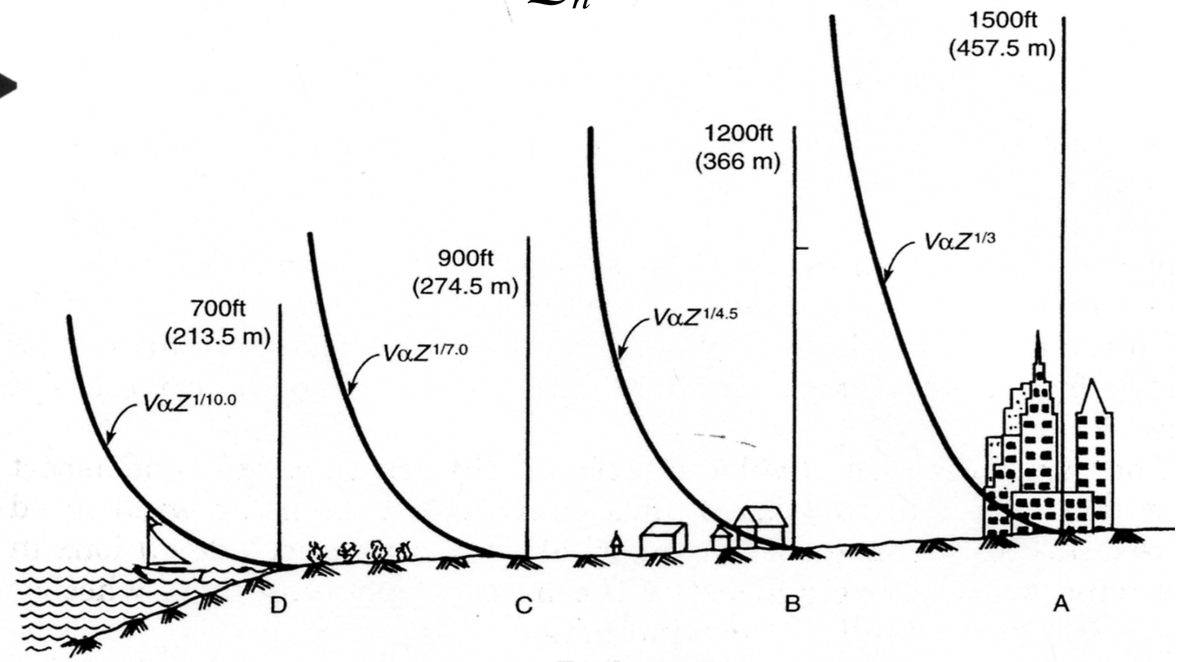






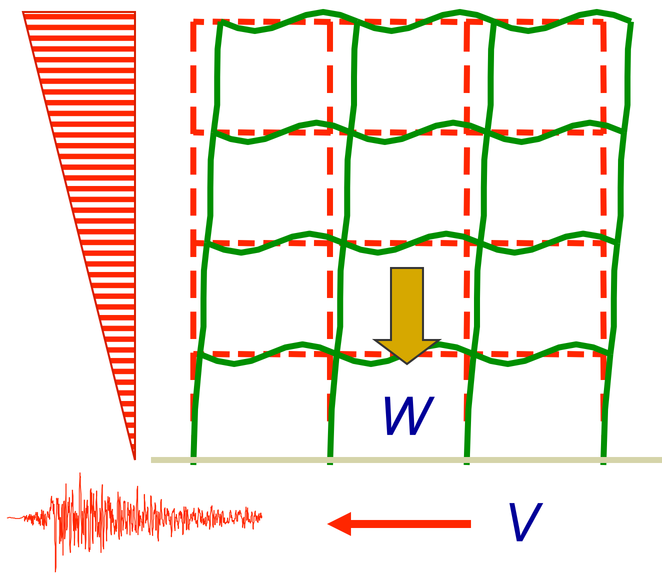
$$Q_z = KV^2 I$$

$$Q_h = Q_z\Big|_{z=H}$$

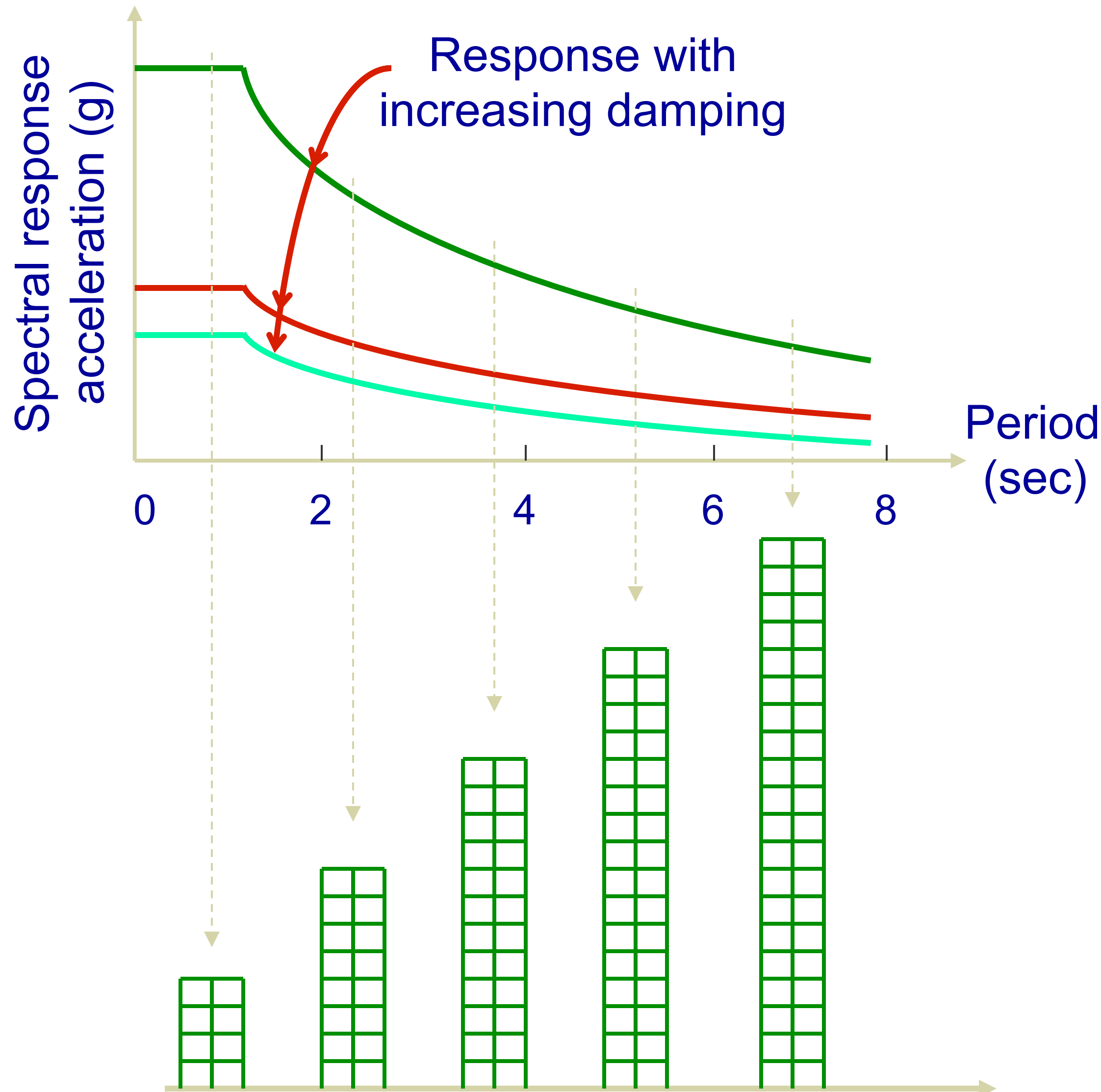


Design of Concrete Structures

- Earthquake/seismic loads:

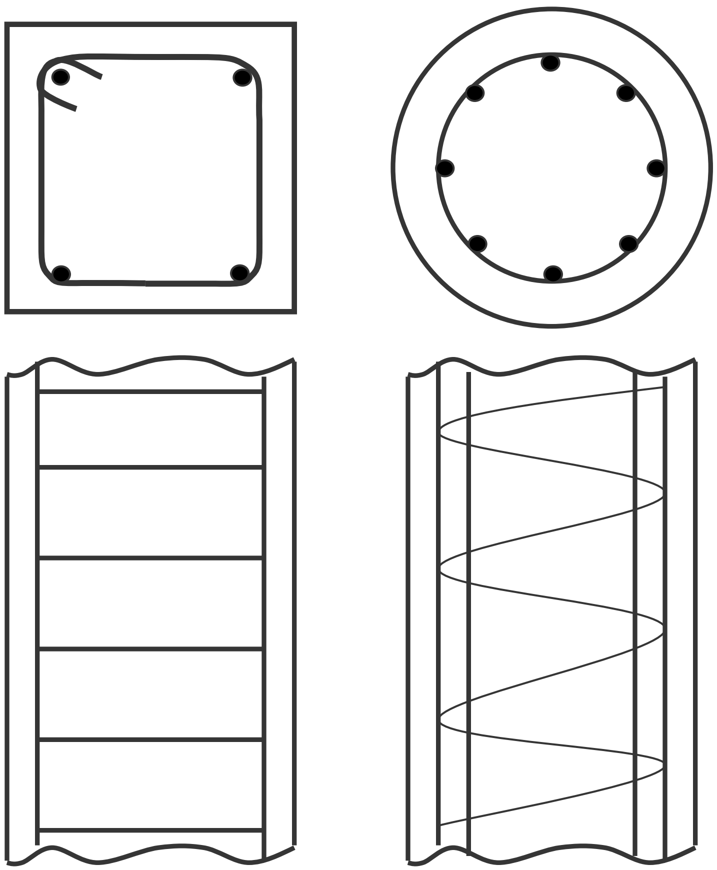


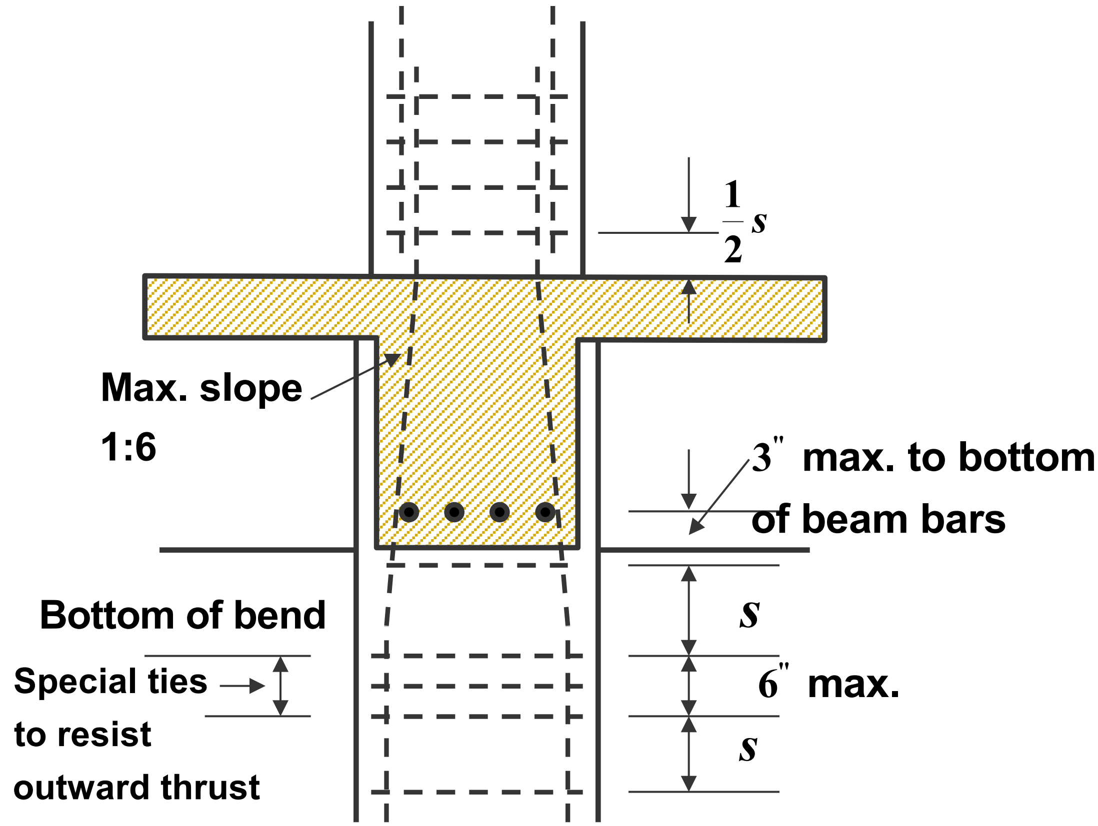
$$V = C_s ¥ W$$



Design of Concrete Structures

- Final design:





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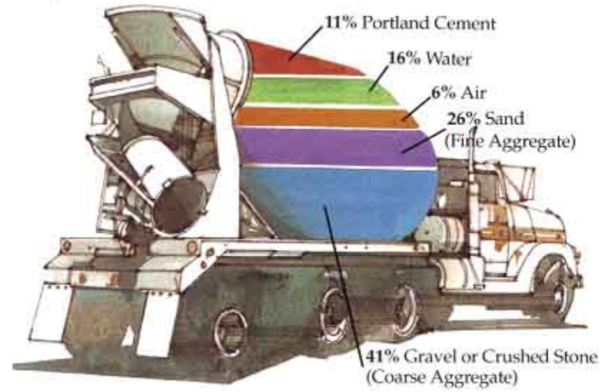
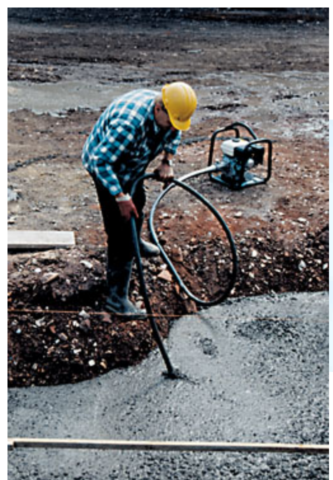
Manufacturing of Concrete

- Concrete construction include the following steps:
  - Batching
  - Mixing
  - Transportation
  - Placing
  - Consolidating
  - Finishing
  - Curing





Manufacturing of Concrete

- Typical construction site

→ Usually, different manufacturing steps are simultaneously ongoing on the site.

Manufacturing of Concrete

- Manufacturing of concrete bridges:




Lavant viaduct (Talubergang P19 Lavant), Austria (1985)

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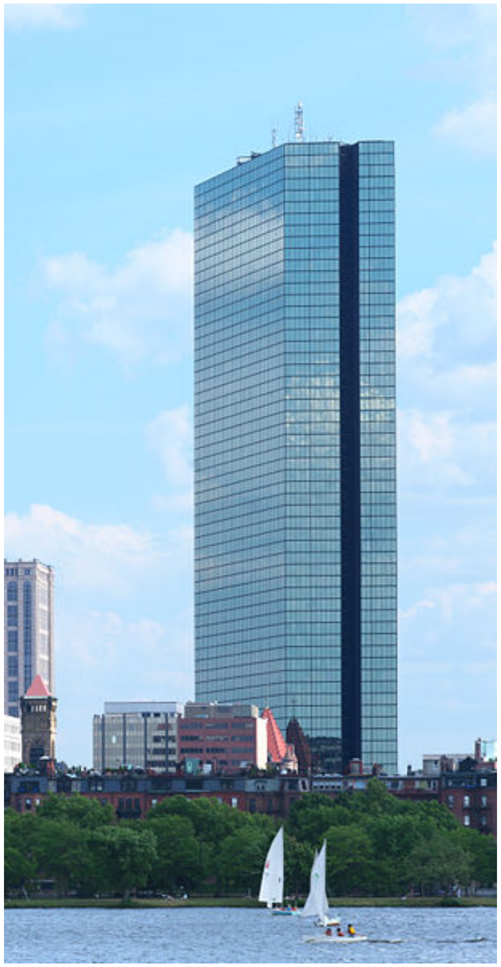
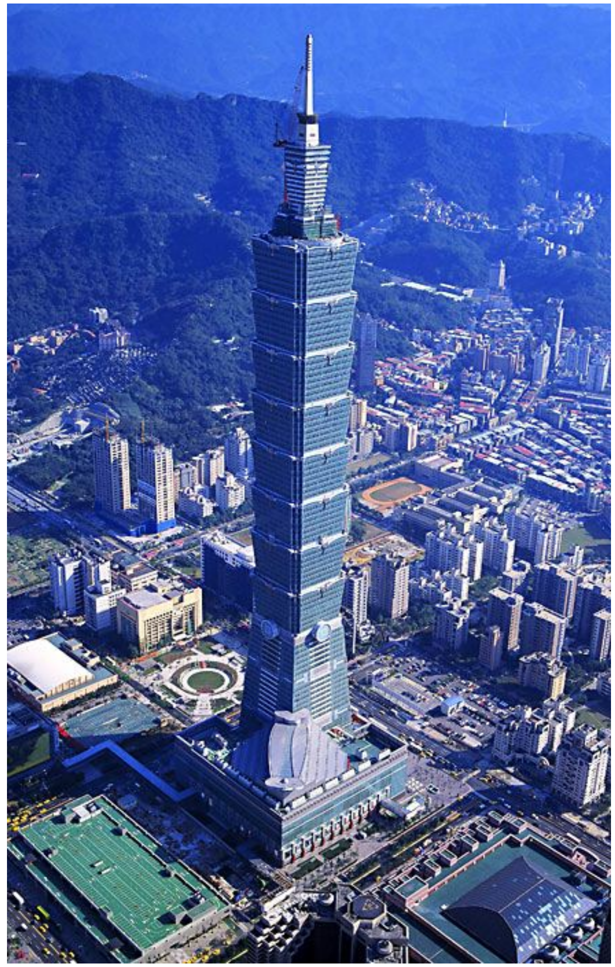
Application of Concrete

- Buildings:



John Hancock Tower, Boston (241 m)



Taipei 101, Taiwan (509m, No.2)

Burj Khalifa, Dubai (828 m, No.1)

Application of Concrete

- Bridges:

Zakim Bridge, Boston, U.S.A. (436 m)

Akashi Kaikyo Daibashi, Japan (1,991 m)

Millau Viaduct Bridge, France (2,460 m)

Queen Elizabeth Bridge, England (812 m)

Application of Concrete

- Nuclear power stations (NPS):

Maine Yankee NPS, ME
(Decommissioned in 1997)

Three Mile Island NPS, Harrisburg, PA
(TM-2 decommissioned in 1979;
TM-1 licensed to operate until 2034)

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Deterioration of Concrete

- Primary mechanisms of concrete deterioration:
  - Mechanical deterioration of the concrete surface
    - Abrasion
    - Erosion
    - Cavitation
  - Electrochemical deterioration of the steel reinforcement
    - Corrosion
  - Physical and chemical deteriorations of the aggregate
    - Freezing and thawing
    - Alkali-aggregate reactions (AAR)
  - Physical and chemical deteriorations of hydrated cement products
    - Freezing and thawing
    - Internal and external sulfate attacks
    - Seawater attack
    - Acid attack
    - Carbonation
    - Salty crystallization

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Summary

- Concrete is a reliable structural construction material, if designed correctly, manufactured properly, and maintained routinely.
- Concrete has its own characteristics as a construction material, but the performance of concrete structures depends on the design of structures, and their environment. → *How do we know the performance of each concrete structure?*
- Quality control is vital in the manufacturing of concrete.
- Deterioration of concrete structures can be attributed to a wide variety of causes.

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