CM 425

Concrete Technology

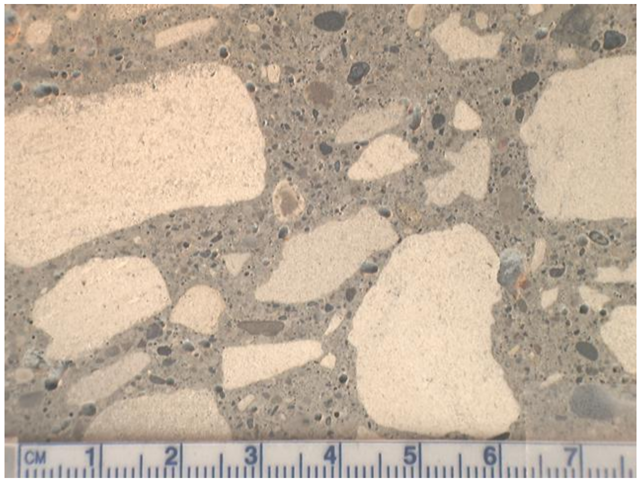
Durability of Concrete

Structure of "un-damaged" Concrete

- **Macrostructure**
  - **Aggregates (CA, FA)**
  - **Hydrated cement paste (hcp)**
  - **Entrapped air voids**
- **Microstructure**
  - **Hydrated cement paste**
    - **(Hydration products:C-S-H, ettriginite; monosulfate; porosity: gel, capillary pores entrained/ entrapped air voids)**
    - **Transition zone (TZ)**

2

Macrostructure of Concrete



3

Structure of "damaged" Concrete

- Macrostructure
  - Visible cracks in hcp and aggregates due to volume change

    (to understand cause of cracks, we need to look at microstructure)
- Microstructure
  - Alkali-silica reaction:
    - Reaction product forms at TZ and expands
  - Frost action:
    - Water freezes in capillary pores and expands
  - Sulfate attack:
    - reaction products form in hcp and expand

4

Alkali-Silica Reaction (ASR)

"The Cancer of Concrete"

- What causes ASR?
  - Chemical reactions involving:
    - alkali ions from portland cement
    - hydroxyl ions
    - siliceous constituents in aggregate

SiO_2 + 2NaOH + H ➔ $Na_2SiO_{32}H$

Silica alkali water alkali-silica gel

Alkalis + Reactive Silica + Moisture ⇨ ASR Gel which expands ⇨ Concrete cracking

5

Why is it Important to Study ASR

- Concrete quality
  - Loss of strength, stiffness, impermeability
  - Premature failure of concrete structures

- Economic/Environmental impacts
  - ASR lowers concrete lifetime
  - Less reactive aggregates often expensive or difficult to find
  - Cement production creates 7% of the world's CO_2 emissions (a greenhouse gas).

6

Alkali-Silica Reaction (ASR)

- Signs of ASR
  - Expansion and cracking
  - Loss of strength
  - Pop-outs and exudation of viscous alkali-silicate fluid
- Where?
  - Humid environments (dams, bridge piers, sea walls)
  - Exposed environments (roads, building exteriors)

7

ASR Expansion Mechanism

- Breakdown of silica structure in the aggregate by hydroxyl ions.
- Silica becomes available to form AS gel
- When the silica gel comes in contact with water is swells
- Reaction rate depends on:
  - Reactivity of silica in aggregate
  - alkali content of cement (reported as wt% Na_2O EQUIV.)

8

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ASR Expansion Mechanism

- AS gel is the source of expansion
  - Absorption swelling theory:
    - Expansive pressure and subsequent expansion of concrete are due to pore water inhibition and swelling of AS gel that forms around aggregate
  - Osmotic pressure theory:
    - AS gel that forms around aggregate acts like a semi-permeable membrane. The membrane allows only a one way diffusion: alkali-ions and OH-ions diffuse from the pore to the aggregate surface, but silicate ions do not diffuse out from aggregate.

9

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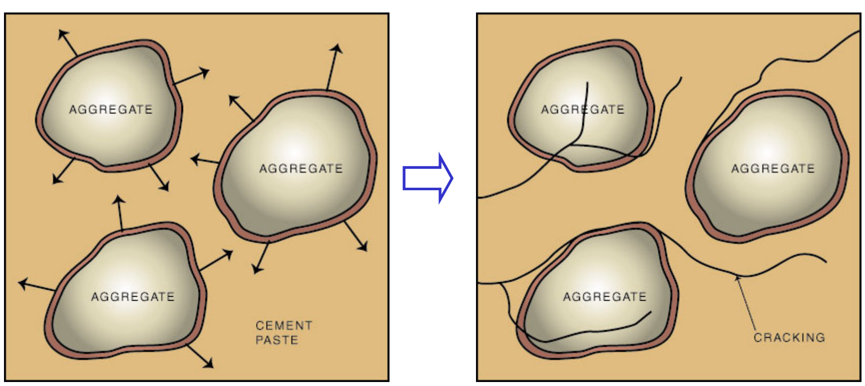
ASR Expansion Mechanism

- When the expansionary pressure exceeds the tensile strength of the concrete, the concrete cracks.



10

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ASR Expansion Mechanism

- When cracks reach the surface of the structure, "map cracking" results.

11

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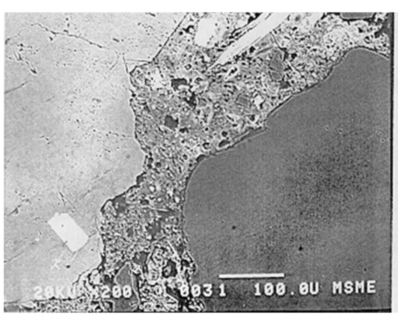
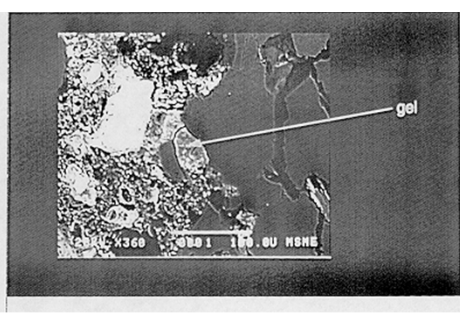
Transition Zone

Scanning Electron Microscopy (SEM) Images of:

un-damaged concrete



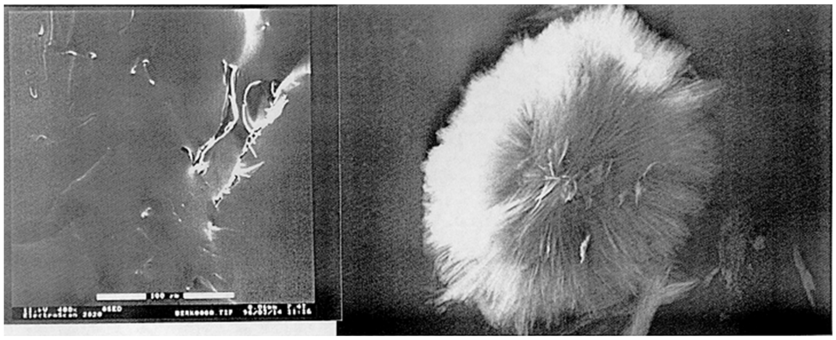
damaged concrete (ASR)



12

Alkali-Silica Gel

inside ESEM **inside SEM**



ESEM: Environmental Scanning Electron Microscope

13

ASR Damage

Concrete rail road tie disintegrated due to ASR

Gel filled cracks in pier deteriorating due to ASR

Fender disintegrated due to ASR and subsequently reinforcement corrosion

14

Methods to Prevent ASR

Alkalis + Reactive Silica + Moisture ⇨ ASR Gel

- Limit alkali presence
  - Low alkali cement
  - Limit other sources:
    - salt-contaminated aggregates
    - penetration of seawater
    - penetration of deicing solution
  - Cement content of the concrete
- Limit reactive aggregate
  - amount, size, reactivity
- Limit available moisture
  - RH of 75% required for reaction
  - Repair cracks, joints

15

Methods to Prevent ASR

- Use slag or pozzolanic admixtures
  - Insoluable alkalis
  - Blast furnace slag, volcanic glass, fly ash, silica fume
  - Iceland uses CFS (Condensed Silica Fume) in all cement
- Air entrainment may help
  - Provides pores; allows gel room to expand harmlessly
- Structural Design
  - Limit access to water
  - Avoid de-icing salt accumulation
  - Adequate compaction
  - Good finished surfaces

16

Frost Action

- What causes frost damage?
  - Freezing of pore water
  - Water undergoes a 9% volume expansion during freezing
- Frost damage affect both hcp and aggregates
- Signs of frost damage
  - Spalling
  - D-cracking and scaling

- Where?
  - Northern Climates
  - Concrete pavements, retaining walls, bridge decks

17

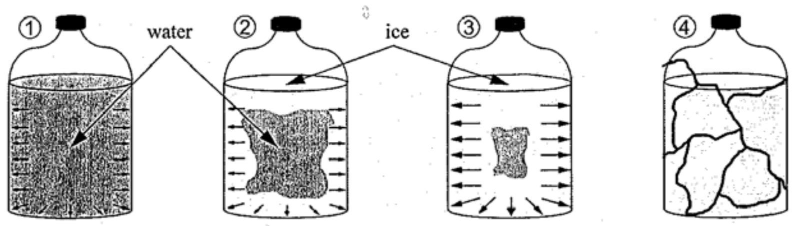
Frost Action

- Pore sizes and presence of water
  - Entrapped air: entrapped during mixing 10μm-1cm; usually empty of water
  - Entrained air: introduced by admixtures; 0.1-0.2 mm; usually dry
  - Capillary porosity: cavities of excessive, unreacted mixing water; 0.01-5μm; contain water; freezing point depends on pore solution chemistry, ranging from -1°C (30F) to -8°C (18F)
  - Gel pores: very fine internal C-S-H pores; 1-10nm; contain chemically bound water; resists freezing due to chemical bonding; typical freezing temperature: -78°C (-172F)

18

Freezing Water Damages Concrete

Consider the analogy of freezing water inside a glass jar:



① Water is free to flow; pressures on walls of the jar are small.

② Freezing begins, and expansion of ice exerts tensile stresses in the jar walls.

③ As freezing progresses, the jar restricts expansion of the ice resulting in accumulated strain energy which seeks to be released.

④ Internal pressure becomes too great and the jar fractures allowing ice to expand and release energy.

Damage Mechanism

- Hydraulic pressure*
- Osmotic Pressure
- Capillary Ice Growth

*Topic will be covered in next slides

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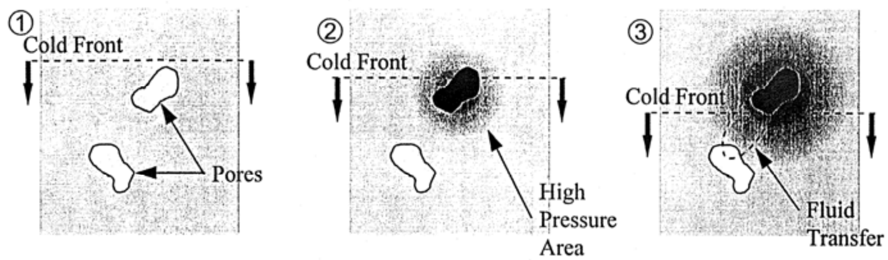
Hydraulic Pressure



① Prior to freezing, water in both pores are at low pressure

② Cold front enters upper pore, upper pore pressure increases. Surrounding concrete is exposed to high pressure water.

③ Cold front continues to cross upper pore. High pressure area reaches lower pore, causing fluid to enter lower pore. Hydraulic pressure and accelerated damage are caused by movement of fluid through highly restricted channels between capillary pores.

21

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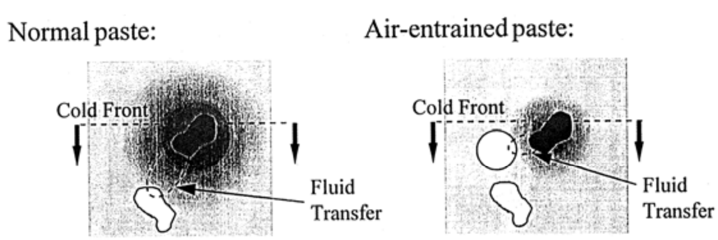
Air Entraining Agents



- Hydraulic pressures can become quite high and damage cement paste between capillary pores.
- Air voids allow hydraulic pressure to dissipate, avoiding damaging high pressures.
- A number of air voids decreases the average distance water must travel for pressure relief, but too many air voids decrease the overall strength of concrete. In general, each 1% air addition decreases concrete strength by 5%.

22

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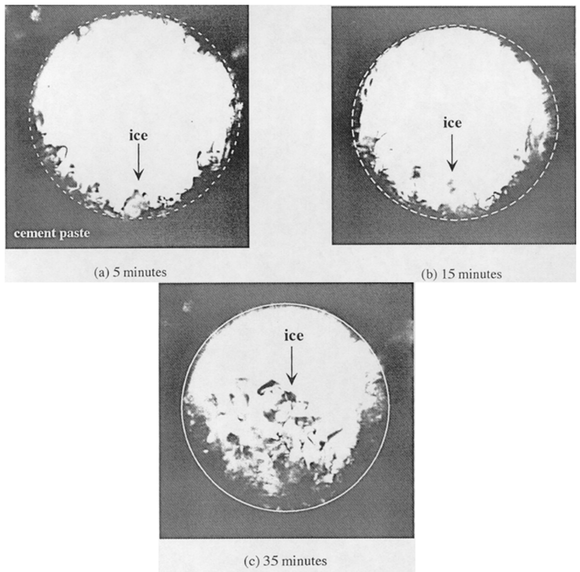
Ice Formation in Air Voids



23

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Freeze-Thaw Damage

Freeze-thaw scaling of a railroad bridge

Freeze-thaw scaling of a railroad bridge, detailed view

24

Methods to Prevent Frost Damage

- Paste Damage
  - low w/c ratio
  - Ensure proper curing of concrete
  - Air entraining agents
- Aggregate Damage
  - Frost-resistant aggregates

25

Sulfate Attack

- What causes sulfate attack?
  - Chemical reactions between sulfate ions and hydration products leading to ettringite and gypsum formation
- Sources of sulfate ions
  - Seawater
  - Organic-rich environments (sewage, stagnant water)
  - Industrial waste
  - Soils and groundwater
  - Clinker (delayed release)

26

Sulfate Attack

- Signs of sulfate attack
  - Extensive cracking and expansion (damage starts at edges and corners)
  - Deposition of ettringite crystals in internal cracks or internal voids
  - Characteristic whitish appearance on surface
- Where?
  - dams, bridge piers, hydraulic structures

27

Chemical Reactions

- Ettringite formation
  - Infusion of sulfate ions into hydrated cement paste
  - Monosulfate, CH and water combine to form ettringite

$$C_4AH_{18}+2CH+2\bar{S}+12H \rightarrow C_6A\bar{S}_3H_{32}$$

  - Expansive forces generate tensile stresses
  - Tensile stresses lead to severe damage and fracture

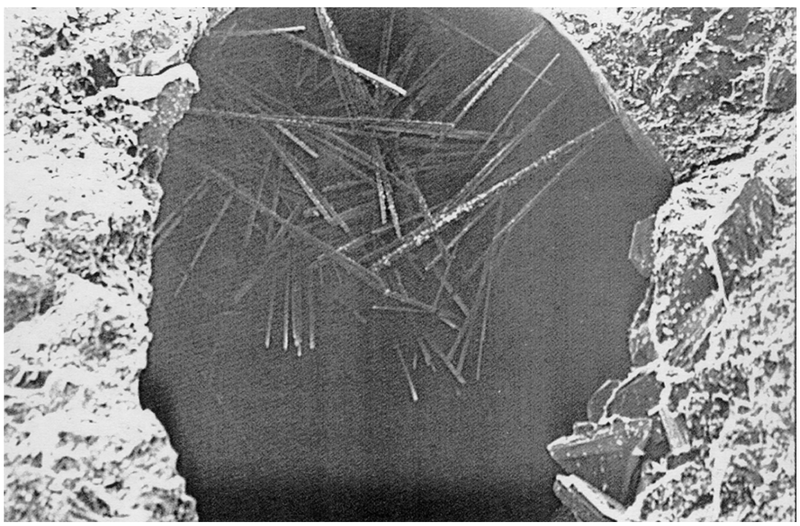
28

Chemical Reactions

- Expansion Mechanism
  - Crystallization Pressure theory:
    - Expansion is caused by the growth of ettringite crystals and their ability to induce crystallization pressure by pushing out the surrounding particles.
  - Swelling theory:
    - Expansion is caused by growth of ettringite crystals in solution. Crystals have high surface area and imbibe water and swell, leading to expansion.

29

Ettringite Formation



30

Chemical Reactions

- Gypsum formation
  - Infusion of sulfate ions into hydrated cement paste
  - CH reacts with sulfate ions to form gypsum

    $CH + \bar{S} + H \rightarrow CSH_2$
  - Gypsum formation leads to reduction in stiffness and strength, followed by expansion and cracking, transforming the material into a mushy or non-cohesive mass.
  - Depending on the cation type present in the sulfate solution (i.e. Na+ or Mg2+), both CH and C-S-H may be converted to gypsum by sulfate attack;

31

Chemical Reactions

- Sodium sulfate attack:
  - formation of sodium hydroxide as a by-product of the reaction ensures the continuation of high alkalinity in the system, essential for the stability of C-S-H.

  $Na_2SO_4+CH+2H \rightarrow CaSO_4.2H_2O+2NaOH$
- Magnesium-sulfate attack:
  - Formation of insoluble, poorly alkaline magnesium hydroxide reduces stability of C-S-H; hence C-S-H is attacked by the sulfate solution.

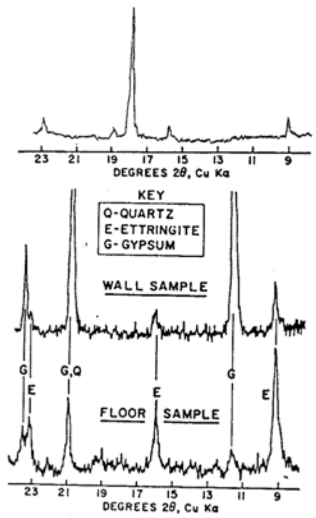
  $MgSO_4+CH+2H \Rightarrow CaSO_4.2H_20+Mg(OH)_2$

  $3MgSO_4+3C\text{-}S\text{-}H+|8H \rightarrow$
  $3(CaSO_4).2H_2O+3Mg(OH)_2+2SiO_2.H_2O$
  $+3Mg(OH)_2+2SiO_2.H_2O$

32

Sulfate attack

X-ray diffraction analysis of un-damaged and deteriorated concrete



33

Methods to Prevent Sulfate Attack

- Produce high quality, impermeable concrete
- Limit C_3A content
  - Type II Portland Cement
  - Type V Portland Cement
- For high sulfate concentrations (>1500 mg/liter): Addition of pozzolanic materials
- Coating of protective overlays

34

Structure of Damaged Concrete

- **Alkali-Silica Reaction:**
  Macrostructure:
  - **Cracking throughout the volume of concrete; pop-outs on surface of concrete; cracked aggregates.**

  Microstructure:
  - **ASR gel forms at TZ and expands**
- **Frost Action:**
  Macrostructure:
  - **Cracking of concrete; spalling, pop-outs**

  Microstructure:
  - **Water freezes in capillary pores and expands; water migrates to air voids**
- **Sulfate Attack:**
  Macrostructure:
  - **Cracking, characteristic whitish appearance.**

  Microstructure:
  - **Gypsum and ettringite form with hydration products in hcp and expand; ettringite crystals deposit in internal cracks and voids.**

35