American Concrete Institute

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Concrete Cracking

Pittsburgh ACI Chapter
October 2, 2019

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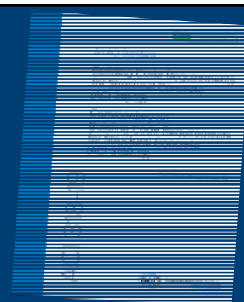

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Scope

- Introduction to Cracking
- Causes and control of cracking
  - Fresh concrete
  - Hardened concrete
- Evaluation of cracking
- Crack repair

(Photo credit: web)

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Introduction to Cracking

- Are cracks of concern?
- "It depends" (on location, extent, depth, and width of cracks)

Concerns

- Structural performance
- Aesthetic
- Durability

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Introduction to Cracking

- Reasons for Concrete Cracking

Concrete volume change

- Temperature
- Moisture loss/gain

Restraint conditions

Load induced

Tensile strength of concrete

Photo credit: PCA

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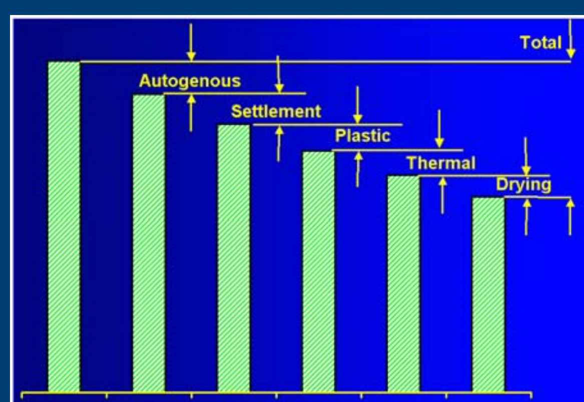
Introduction to Cracking

Two things to remember:

- Shrinkage effects are additive
- NEVER A SINGLE MECHANISM!!



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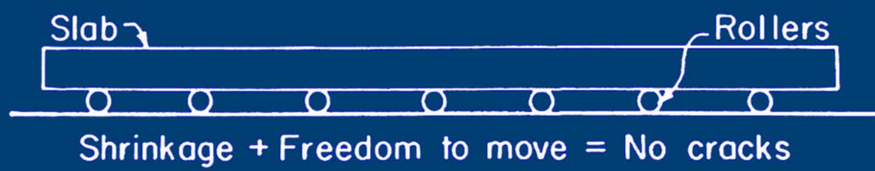
Introduction to Cracking



(Source: PCA, EB001)

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Introduction to Cracking

- How much movement can we expect?

  Assumptions (shrinkage):

- Shrinkage = 600 × 10^{-6} in./in.
- Concrete section length = 100 ft [30 m]

ΔL: ~ ¾ in. (19 mm)
(0.016 in. crack @ 2 ft)
[0.41 mm @ 60 cm]

  Assumptions (thermal):

- Coef. of thermal expansion = 6 × 10^{-6} in./in./ºF [3 × 10^{-6}/ºC]
- Temp. differential = 70ºF [39ºC]
- Concrete section length = 100 ft [30 m]

ΔL: ~ ½ in. [13 mm]
(0.016 in. crack @ 3 ft)
[0.41 mm @ 90 cm]

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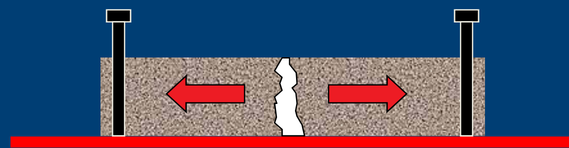
Introduction to Cracking

Restraint



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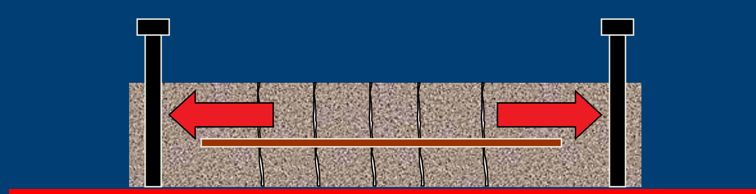
Introduction to Cracking

Reinforcing Steel as Crack Control



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Scope

- Introduction to cracking
- **Causes and control of cracking**
  - Fresh concrete
  - Hardened concrete
- Evaluation of cracking
- Crack repair

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Causes and Control of Cracking

- Fresh concrete
  - Plastic shrinkage
  - Settlement
- Hardened concrete
  - Drying / autogenous shrinkage
  - Thermal
  - Chemical
    - AAR
    - Sulfate attack, DEF
  - Freezing and thawing
  - Corrosion
  - Construction / design / detailing

- Mechanism
- Damage
- Prevention

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Plastic Shrinkage - Mechanism

- Moisture evaporation
- Surface concrete shrinkage
- Restraint by underlying concrete
- Tensile stresses
- Cracks formation

Photo credit: CTLGroup

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Plastic Shrinkage – Mechanism

- Factors affecting plastic shrinkage cracking formation:

  Rapid loss of moisture
  - high air and concrete temperatures
  - low relative humidity
  - high wind velocity at concrete surface

  Concrete mixture composition
  - Concrete with mineral admixtures (especially silica fume) lead to less bleed water

Photo credit: CTLGroup

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Plastic Shrinkage - Damage

- Plastic shrinkage cracking characteristics:
  - Shallow cracks
  - Random pattern
  - Typically parallel to one another
  - Width: up to about 1/8 in. [3 mm] at the surface
  - Length: typically from few inches to many feet
  - Spacing: from few inches to as much as 10 ft [3 m] apart

Photo credit: Virginia Tech and CTLGroup

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Plastic Shrinkage - Damage

Slab-on-Ground

Photo credit: CTLGroup

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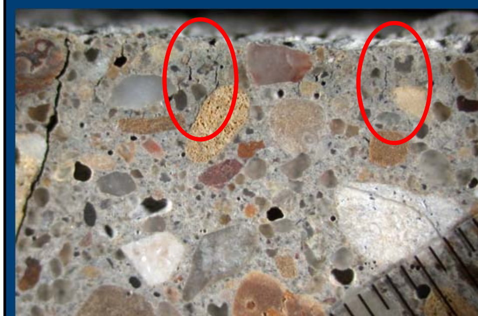
Plastic Shrinkage - Damage

Slab-on-Ground – Near Surface Regions



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Plastic Shrinkage – Damage

Bridge Deck

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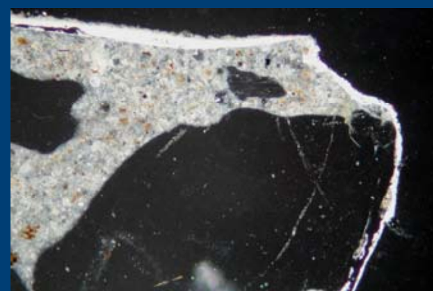
Plastic Shrinkage – Damage

Bridge Deck



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Plastic Shrinkage - Prevention

- Steps to prevent rapid moisture loss due to hot weather and dry winds
  - Use fog nozzles
  - Use plastic sheeting
  - Install windbreaks
  - Reschedule concrete placement / initiate operations at night

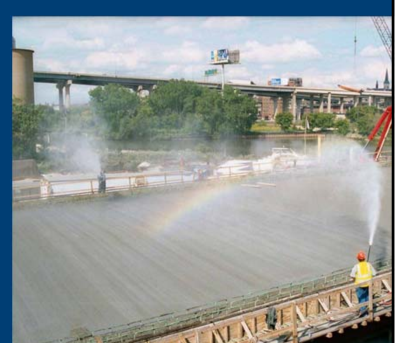

Photo credit: Associated Engineering, BC

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Photo credit: Associated Engineering, BC

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Photo credit: Associated Engineering, BC

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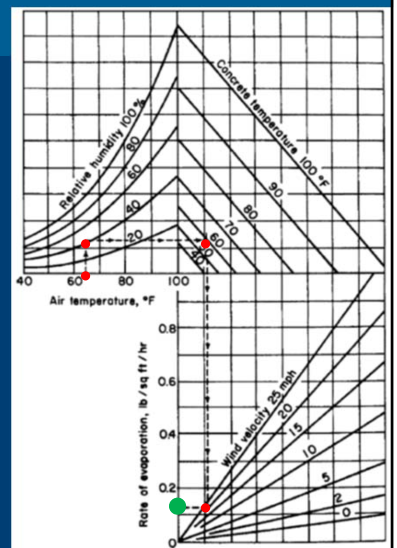
Plastic Shrinkage – Prevention

- Do I need any additional steps to prevent surface moisture loss?
- Use Menzel/NRMCA nomograph
  - Air temp. – 4-6 ft [1.2-1.8 m] above surface
  - RH – 4-6 ft [1.2-1.8 m] above surface, winward side
  - Concrete temperature
  - Wind speed – 20 in. [50 cm] above surface



Source: ACI 308R, Guide to Curing Concrete

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Settlement – Mechanism

- Inadequate vibration
- Leaking or flexible/loose forms
- Restraint by reinforcing steel

Photo credit: CTLGroup

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Settlement – Prevention

- Form design (in accordance with ACI 347)
- Concrete vibration (and revibration)
- Reduced slump
- Increased concrete cover

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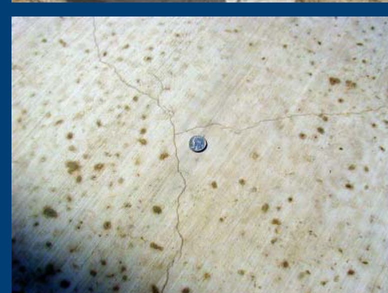
Drying Shrinkage – Mechanism

- Loss of moisture from cement paste
- Restraint (no restraint – no cracking)
- Tensile stresses



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Drying Shrinkage – Mechanism

- Drying shrinkage is influenced mainly by
  - Amount and type of aggregate

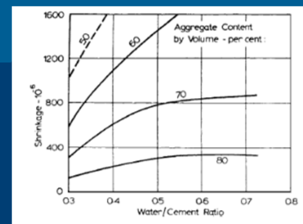

Fig. 3.7—Influence of w/c and aggregate content on shrinkage (Odman 1968).

Table 3.1—Effect of aggregate type on concrete shrinkage (after Carlson [1938])

Aggregate	Specific gravity	Absorption	1-year shrinkage, %
Sandstone	2.47	5.0	0.116
Slate	2.75	1.3	0.068
Granite	2.67	0.8	0.047
Limestone	2.74	0.2	0.041
Quartz	2.66	0.3	0.032

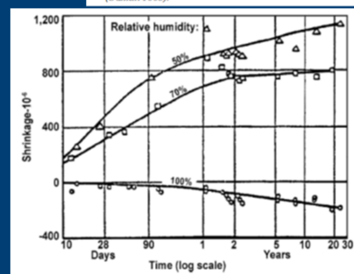

Fig. 3.3—Relations between shrinkage and time for concretes stored at different relative humidities. Time reckoned since end of wet curing at 28 days (Troxell, Raphael, and Davis 1958).

Source: ACI 224R, Control of Cracking of Concrete Structures

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Autogenous Shrinkage

- "special case of drying shrinkage"
  - results from self-desiccation (internal drying) in concretes with water-cementitious material ratios (w/cm) < 0.42
  - most often observed at w/cm < 0.30
- Occurs without loss of moisture (from bulk concrete)

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Drying Shrinkage – Damage

Bridge Deck

Photo credit: CTLGroup

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Drying Shrinkage – Prevention

- Shrinkage cracking can be controlled by
  - Using contraction joints, and
  - Proper detailing of the reinforcement
- Shrinkage cracking may also be reduced or even eliminated by using
  - Shrinkage-compensating cement
  - Shrinkage-reducing admixture
  - Lower amount of cement / lower amount of water
  - Greater amount of aggregate (and larger size)

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Thermal Deformation – Mechanism

- Temperature differences → differential volume changes
- Temperature differentials result from:
  - heat of hydration (mass concrete)
  - changes in the ambient temperature (affects any structure/member)

Photo credit: Virginia Tech and CTLGroup

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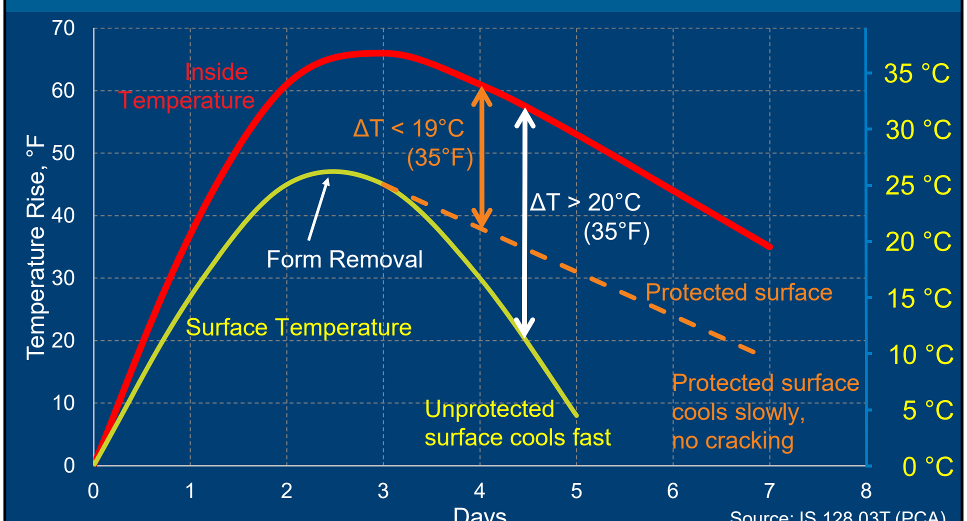
Thermal Deformation – Mechanism



Source: IS 128.03T (PCA)

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Thermal Deformation – Damage

Bridge Abutment

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Thermal Deformation – Damage

Slab-on-Ground

Sidewalk set above pavement

No. of Full Depth Isolation/ Expansion Joints = 0

Expansion of adjacent pavement

Photo credit: George Seegebrecht, Concrete Consulting Engineers LLC

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Thermal Deformation - Prevention

- Reduce maximum internal temperature
- Control rate of concrete cooling
  - Form removal timing
  - Insulation blankets
- Allow for movement
  - Proper design of contraction and isolation joints

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Alkali-Aggregate Reaction (AAR)

Photo credit: PCA

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AAR (ASR and ACR) – Mechanism

- Alkali-Silica Reaction (ASR) and Alkali-Carbonate Reaction (ACR):
  - Cement alkalis react with certain aggregates
- ASR only: silica gel forms and fills cracks and cavities

Photo credit: CTLGroup

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AAR (ASR and ACR) – Mechanism

- Conditions necessary to initiate and sustain AAR in concrete:
  - Reactive aggregate in concrete
  - High concentration of alkali hydroxides in pores
  - Supply of moisture

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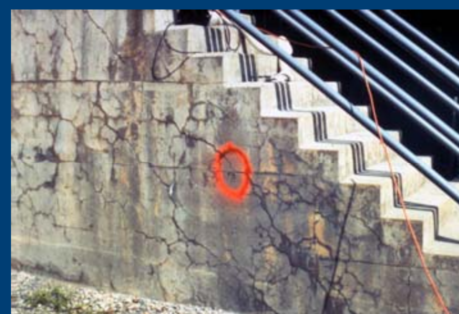
AAR (ASR and ACR) – Damage

- Cracking (alligator pattern)
- White deposits (ASR) – gel (efflorescence like)
- Gross expansion of concrete
- Total disintegration of concrete



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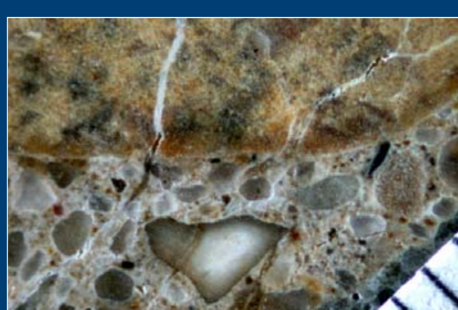
AAR (ASR and ACR) – Damage

ASR Petrography



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AAR (ASR and ACR) – Damage

- ACR Petrography

Photo credit: CTLGroup

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AAR (ASR and ACR) – Damage

Dam

Photo credit: www

Photo credit: PCA

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AAR (ASR and ACR) – Damage

Pavements

Photo credit: PCA

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AAR (ASR and ACR) – Damage

Bridges

Photo credit: Fred Strang, New Brunswick MoT

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AAR (ASR and ACR) – Prevention

- Aggregate selection
  Use non-reactive aggregate
  Mixing reactive w/ non-reactive aggregates
- Limiting the alkali content in concrete
  Low-alkali cements
- Supplementary cementitious materials
- Chemical additives (lithium-based) – ASR

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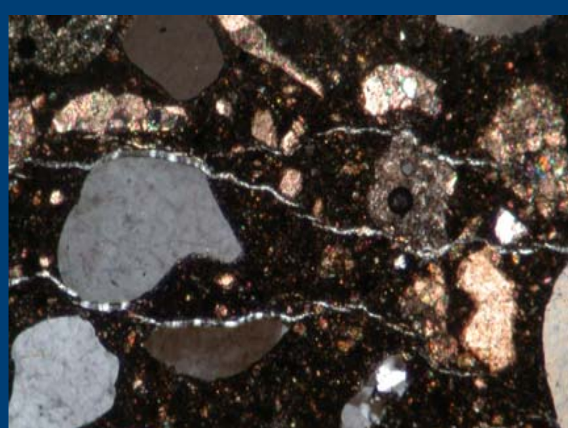
Sulfate Attack



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Sulfate Attack – Mechanism

- External sources of sulfates (soils, groundwater)
- Formation of ettringite and gypsum (and brucite)
- Chemical alteration that softens concrete matrix (gypsum)
- Mechanical expansive forces from expansive reaction products (ettringite, brucite)

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Sulfate Attack – Damage

- "Mush concrete"
- Cracking (expansive reactions)
- Complete disintegration (few years)

Type V cement, w/c = 0.65

Type V cement, w/c = 0.39

Photo credit: PCA

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Sulfate Attack – Prevention

- High quality, low permeability concrete (w/cm)
- Sulfate-resistant cements (low C_3A)
- Fly ash, slag, or silica fume

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Delayed Ettringite Formation (DEF)

- Form of sulfate attack
- Attributed to accelerated curing
- Critical temperature for DEF – between 140 and 195ºF (60 and 90ºC)
- Expansion and formation of gaps around aggregate particles

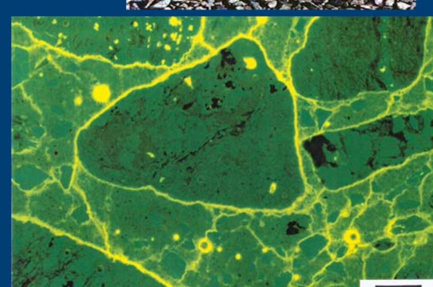

Photo credit: CTLGroup

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Weathering

- Freezing and thawing
- Alternate wetting and drying
- Heating and cooling

Photo credit: PCA

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Freezing & Thawing

Photo credit: www

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Freezing & Thawing – Mechanism

- Water (weak alkali solution) cooling
- Ice crystals formation
- Osmotic potential development – water movement within pores
- Continued ice formation
- Cracking occurs

Photo credit: CTLGroup

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Freezing & Thawing – Damage

- Cracking – parallel to the surface
- Failure w/o AEA
  - Critical saturation of paste
  - Critical saturation of aggregate
- Failure w/ AEA
  - Critical saturation of aggregate

Photo credit: CTLGroup

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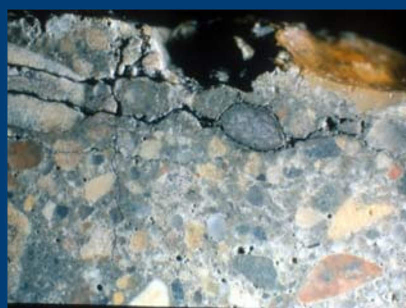
Freezing & Thawing – Damage

- Failure w/o AEA
  Critical saturation of paste
- Failure w/ AEA
  Critical saturation of aggregate



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Freezing & Thawing - Prevention

- Use lowest practical w/cm
- Use durable aggregate
- Specify adequate air entrainment
- Provide adequate curing (and drying) before 1st freezing cycle
- Design to minimize exposure to moisture (geometry, drainage, joints)

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Corrosion of Reinforcing Steel

Photo credit: Virginia Tech

Corrosion – Mechanism

- Electrochemical process
- Passive film - high pH
- Moisture and oxygen
- Causes
  - Galvanic coupling
  - Carbonation
  - Chloride ions

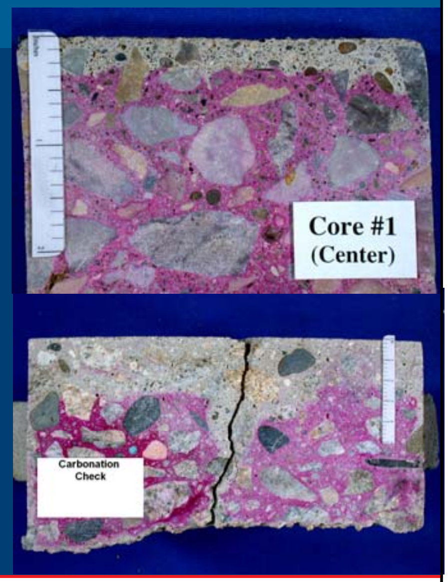
Photo credit: CTLGroup

Carbonation

- Carbonation check:

  Freshly exposed
  concrete surface

  Phenolphthalein solution
- Colorless – carbonated
- Pink/magenta - uncarbonated



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Corrosion – Damage

- Penetration of chlorides / Corrosion initiation
- Rust formation – voluminous corrosion products
- Cracking, delamination, spalling
- Accelerated corrosion

Photo credit: CTLGroup

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Corrosion Damage – Residential Building

Photo credit: CTLGroup

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Corrosion Damage – Residential Building

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Corrosion Damage – Parking Garage

Photo credit: CTLGroup

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Corrosion Damage – Bridge Deck

Photo credit: J. Zemajtis

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Corrosion - Prevention

- Concrete cover, concrete quality, proper curing, low w/c
- Mineral admixtures, corrosion inhibitors, stainless steel, galvanized steel, ECR
- Waterproofing, surface treatments
- Polymer impregnation, low permeability overlays
- Cathodic protection, chloride extraction

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Poor Construction Practices

- Construction practices' related cracking
  - Adding water to concrete (more water = more shrinkage)
  - Lack of curing / early termination of curing
  - Inadequate consolidation
  - Inadequate formwork supports
  - Poor surface preparation

Photo credit: CTLGroup

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Poor Construction Practices

- Construction practices' related cracking
  - Adding water to concrete (more water = more shrinkage)
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  - Inadequate formwork supports
  - Poor surface preparation

Photo credit: CTLGroup

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Errors in Design/Detailing or Poor Construction

- Low edge distances for embedments
- Inadequate amount of reinforcement
- Poorly detailed re-entrant corners in walls, precast members, and slabs
- Improper selection or detailing of reinforcement
- Restraint of members subjected to volume changes
- Lack of adequate isolation/expansion joints

Photo credit: www

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Errors in Design/Detailing or Poor Construction

- Restraint and lack of adequate isolation/expansion joints

Photo credit: PCA

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Errors in Design/Detailing

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Errors in Design/Detailing

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- **Evaluation of cracking**
- Crack repair

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Evaluation of Cracking

- Methods to determine location and **extent** of cracking:
  1. Direct and indirect observations
  2. Nondestructive testing
  3. Test cores from the structure

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Evaluation of Cracking: 1. Direct and indirect observations

- Crack comparator
- Mechanical movement indicators
- Transducers and data-acquisition systems

Fig. 2.1—Comparator for measuring crack widths (courtesy of Edmound Scientific Co.).

Photo credit: CTLGroup

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Evaluation of Cracking:
2. Nondestructive Testing (NDT)

- NDT can be used to:
  - Determine location and extent of internal cracks and voids
  - Determine depth of cracks visible at the surface

Photo credit: CTLGroup

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Evaluation of Cracking:
NDT Example

Nuclear power plant maintenance

Photo credit: CTLGroup

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Evaluation of Cracking: 3. Test Cores

- Accurate measurement of width and depth of cracks
- Petrographic examinations (ASTM C856)
  - Causes of cracking
- Chemical tests
  - Chlorides
- Petrographic examination / chemical tests
  - w/cm, cement content

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Crack Repair – Evaluation Data

- Time of occurrence
- Pattern of cracking or frequency
- Do cracks allow moisture passage?
- Width of cracks
- Passive or active (moving)

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Crack Repair – Tolerable Crack Widths

Table 4.1—Guide to reasonable* crack widths, reinforced concrete under service loads

Exposure condition	Crack width	
	in.	mm
Dry air or protective membrane	0.016	0.41
Humidity, moist air, soil	0.012	0.30
Deicing chemicals	0.007	0.18
Seawater and seawater spray, wetting and drying	0.006	0.15
Water-retaining structures†	0.004	0.10

*It should be expected that a portion of the cracks in the structure will exceed these values. With time, a significant portion can exceed these values. These are general guidelines for design to be used in conjunction with sound engineering judgement.
†Exclusing nonpressure pipes.

Source: ACI 224R, Control of Cracking

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Crack Repair – Material Choices

- Rigid Materials:
  - Portland cement grouts
  - Polymer-modified cement grouts
  - Polymer grouts
  - Epoxy resins
  - Methacrylates
- Flexible Materials:
  - Semi-rigid epoxies
- Elastomeric Materials:
  - Polyurethane grout
  - Polyureythane
  - Silicone
  - Strip-and-seal systems
  - Polyurea

Source: ACI 546.3R, Guide to Materials Selection for Concrete Repair

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Crack Repair – Material Considerations

- Bond strength / adhesive strength
- Elasticity and modulus of elasticity
- Tensile strength and elongation
- Flexural strength / modulus of rupture
- Compressive strength and hardness
- Coefficient of thermal expansion
- Volume stability / shrinkage
- Viscosity and pot-life
- Cyclic movement capability / fatigue
- Temperature and humidity
- Equal or similar to substrate
- Appearance
- Durability

Source: ACI 546.3R, Guide to Materials Selection for Concrete Repair

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Crack Repair

- Follow Application Requirements
  - Mixing sequence/ bonding agents / Curing method and duration
- Installation conditions:
  - Temperature, humidity, sun or shade
  - Moisture presence:
    - Surface
    - In-crack

Photo credit: www

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References

- ACI 201.2R, Guide to Durable Concrete
- ACI 224.1R, Causes, Evaluation, and Repair of Cracks in Concrete Structures
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