5 THINGS YOU CAN DO TO ENHANCE YOUR CONCRETE DURABILITY

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COURSE DESCRIPTION

The purpose of this course is to discuss what concrete durability means, the different forms of deterioration concrete may be subjected to, and how we can prevent from these types of attacks.

PREVIOUS KNOWLEDGE

It will be assumed that the participants of this courses should have some knowledge of the components and materials in used in modern concrete.

But please feel free to stop me at any point if something is not clear!!!
LEARNING OBJECTIVES

1. Identify conditions that can lead to concrete durability threats
2. Explain the mechanisms and the damage that can manifest from these durability threats
3. Identify accelerated test methods that can be used to evaluate performance from these threats in the lab.
4. Describe five principles or practices that can offer protection from these threats
TODAY’S CONCRETE MAKING MATERIALS

The Basics
- Portland Cement
- Water
- Aggregates (coarse and fine)

Supplementary Cementing Materials
- Fly ash
- Slag
- Silica Fume
- Natural Pozzolans

Chemical Admixtures
- Air entrainment
- Water reducers
- Set modifiers
- Many others

Fibers
- Steel
- Polypropylene
- Others
The same materials are used to make concrete with different strengths.

<table>
<thead>
<tr>
<th>Strength (PSI)</th>
<th>General Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 300</td>
<td>Controlled low-strength material</td>
</tr>
<tr>
<td>2000 - 4000</td>
<td>Residential concrete</td>
</tr>
<tr>
<td>3000 - 5000</td>
<td>Commercial buildings</td>
</tr>
<tr>
<td>3500 - 5000</td>
<td>Pavements</td>
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<tr>
<td>4000 - 9000</td>
<td>Bridges</td>
</tr>
<tr>
<td>&gt; 10000</td>
<td>High-rise buildings</td>
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<tr>
<td>&gt; 14000</td>
<td>Special applications</td>
</tr>
</tbody>
</table>

Precast product are generally in this range
Good & bad concrete are produced from the same materials.
MOST OF THE TIME WE GET IT RIGHT
...SOMETIMES WE DON’T
WHY DOES CONCRETE FAIL?

Durability

➢ Responsive to environment: Drying shrinkage, freeze/thaw, carbonation
➢ Permeable: Ingress of deleterious materials
➢ Chemical attacks: Corrosion of steel, acid attacks, salt scaling
➢ Material incompatibilities: pH, heat gains, AAR

Durability problems account for most cases of premature failure of the concrete

Image Source: www.fhwa.dot.gov
WHAT IS CONCRETE DURABILITY?

Durability – ability of the concrete to maintain strength and serviceability during its specified or expected service life. (Neville 2011)

Durability of concrete is determined by its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration, and will retain its original form, quality, and serviceability when exposed to its intended environment. Durable concrete is a result of proper design, proportioning, placement, finishing, testing, inspection, and curing. (ACI 201.2R)
# WHY ALL THE FOCUS ON DURABILITY?

## 2013
- Bridges = C+
- Dams = D
- Road = D
- Wastewater = D
- AVG GPA = D
- $3.6$ Trillion Estimated Investment (8 yr)

## 2017
- Bridges = C+
- Dams = D
- Road = D
- Wastewater = D+
- AVG GPA = D+
- $4.59$ Trillion Estimated Investment (10 yr)

And it’s only getting worse…

**WE CAN DO BETTER!!!**

WHY ALL THE FOCUS ON DURABILITY?

Overall GPA: **D+**

*(American Society of Civil Engineers, 2017)*

Bridges: Repair / Rehabilitation = US$123 billion

For developed countries, 40-50%++ of annual construction budget is for repair/rehabilitation
WHY ALL THE FOCUS ON DURABILITY?

- Structural concrete materials, quality control measures, and construction methods are continually evolving.
- Moreover, the industry has been exploring newer/innovative and alternative materials in recent years to improve concrete’s sustainability.
- Consequently, a number of new materials are now on the market
  - e.g., portland limestone cements (PLCs), alkali-activated cements, calcium aluminate cements (CACs), calcium sulfoaluminate cements (CSAs), magnesia cements, carbon dioxide-cured cement and many more.
- Keeping pace with changes to material characteristics is a must to ensure adequate performance and long-term durability.
CURRENT CONCRETE DURABILITY SPECIFICATIONS

- Obsessed with strength
  - Codes/specifications – f’c
  - Strength is important but **NOT** everything
  - No correlation with durability

- Reliability/robustness
  - Rather overdesign than risk
  - Prescriptive versus performance

- Durability is key; however
  - Durable to what?
  - Poorly defined exposures
  - Lack of attention – ”Lowest bid”
  - Contracts focus on time, f’c, cost

We have to better ensure durability!!
## WHAT HAS CHANGED?

<table>
<thead>
<tr>
<th></th>
<th>1960s</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of ingredients</strong></td>
<td>Cement, water, rock, sand, AEA</td>
<td>SCMs, Non-portland cements, admixtures, intermediate aggregates, limestone,</td>
</tr>
<tr>
<td><strong>Schedule</strong></td>
<td>Weeks</td>
<td>Days (or hours)</td>
</tr>
<tr>
<td><strong>Curing</strong></td>
<td>Weeks</td>
<td>Days (or hours)</td>
</tr>
<tr>
<td><strong>De-icing</strong></td>
<td>Sand, NaCl</td>
<td>Other chlorides, formats, acetates</td>
</tr>
<tr>
<td><strong>Design life</strong></td>
<td>20-30 years</td>
<td>50-125 years!!!</td>
</tr>
<tr>
<td><strong>Knowledge base</strong></td>
<td>In house</td>
<td>Contracted out</td>
</tr>
</tbody>
</table>

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EXAMPLES OF DURABLE CONCRETE

The Romans (and other ancient civilizations) demonstrated that it is possible to build concrete structures to last for millennia!

Pantheon (c. 120 AD)
EXAMPLES OF DURABLE CONCRETE

With “modern-day” Portland cement concrete, there are some examples of structures in excellent condition after more than a century.

Glenfinnan Viaduct, Scotland, 1897

Note: Portland cement patented in 1824
DURABLE CONCRETE REQUIREMENTS TODAY

Today’s engineers are being required (by owners) to build structures with a 100+ year service life in aggressive environments.
DURABLE CONCRETE REQUIREMENTS TODAY

Today’s engineers are also being asked to make those systems more sustainable by using eco-friendly materials and methods.

“Green” Concrete
DURABLE CONCRETE REQUIREMENTS TODAY

Unfortunately, there are too many examples where the concrete infrastructure is suffering from premature deterioration after a few decades or so.

The Gardiner Expressway, Toronto, Built ~1960,
WHY ARE OUR STRUCTURES NOT DURABLE?

Engineers & architects are well trained in the design and analysis of concrete structures.
WHY ARE OUR STRUCTURES NOT DURABLE?

HOWEVER, most are not trained to understand how it deteriorates in aggressive environments!

\[
\text{Ca(OH)}_2 + \text{Na}_2\text{SO}_4\cdot10\text{H}_2\text{O} \rightarrow \text{CaSO}_4\cdot2\text{H}_2\text{O} + 2\text{NaOH} + 8\text{H}_2\text{O}
\]
FACTORS AFFECTING DURABILITY OF CONCRETE

Concrete durability primarily depends on two main factors:
   1. The service environment (exposure); and
   2. The concrete “Hardware”

A. The service environment affects concrete by way of
   - Physical actions; and
   - Chemical actions on concrete

B. The concrete system is based on
   - Quality and quantity of materials used; and
   - Process involved in manufacture of concrete
FACTORS AFFECTING DURABILITY OF CONCRETE

Influenced by concrete producer & contractor
EXPOSURE CONDITIONS

Assessing the environment to which the concrete will be exposed is a fundamental part of designing durable concrete.

Not perfect but it’s a start

Image Source: PCA
A COMMON THREAD...

Chemical
- Corrosion of Steel
- Alkali-aggregate reaction
- Sulfate attack
- Delayed-etrtringite formation
- Acid attack
- Leaching

Physical
- Freeze/thaw (scaling)

All of these mechanisms involve water... and the rate at which they proceed is somewhat dependent on the ease with which water (and any salts dissolved therein) can move through the concrete pore structure.
“IONS DO NOT FLY... THEY SWIM!”

-P.K. Mehta
CONCRETE VOID STRUCTURE – THE KEY TO LONG-TERM DURABILITY

- **Porosity**
  - Porosity in concrete is the total volume of capillary voids in the cement paste system.

- **Permeability**
  - Permeability is the rate of flow that a liquid or gas will move through the concrete.

- **Tortuosity (Real tongue twister right?!)**
  - Tortuosity is a measurement of the amount of turns and twists in a line.
CONCRETE VOID STRUCTURE

- Permeability/Watertightness
- Controlled by
  - pore network/connectivity
  - % porosity
- **Governs** movement of **fluids** and dissolved **ions** into, within, and out of concrete
  - Absorption/capillary action
  - Diffusion
- **Primary influence** on **durability** and **volume change** of hardened concrete
  - Can be measured! However, often indirectly as opposed to directly
WHY DO WE CARE SO MUCH ABOUT PERMEABILITY AND POROSITY?

Transport of water (and chemicals) in concrete is very important for understanding volume change, especially concrete durability

- Water can be lost from the system (drying/shrinkage)
- Aggressive elements can enter the system (chlorides, acids, sulfates)
- Water can move through the system causing damage (freezing)
ILLUSTRATION OF POROSITY AND PERMEABILITY

Porous & Impermeable

Porous & Permeable
ILLUSTRATION OF POROSITY AND PERMEABILITY

High Porosity, Low Permeability

Low Porosity, High Permeability
PORE STRUCTURE

Effect of Pore Size:

High flow through **large**, straight and well-connected pores

**Small** pores – low flow
PORE STRUCTURE

Effect of Pore **Tortuosity**:

High flow through large, **straight** and well-connected pores

High **tortuosity** – low flow
PORE STRUCTURE

Effect of Pore **Connectivity**:

High flow through large, straight and **well-connected** pores

---

**Poor connectivity** – low flow
**PHYSICAL TRANSPORT MECHANISM**

- Three Mechanisms:
  - **Permeation**: pressure gradient
  - **Absorption**: capillary suction
  - **Diffusion**: concentration gradient

Combined transportation of heat, moisture, and chemicals, both within the concrete mass and in exchange with the surroundings, and the parameters controlling the transport mechanisms, constitute the principals elements of durability.
CRACKING AND DURABILITY

- How does cracking impact permeability?
  - Shortcut to steel
  - Allows water and salt ingress
  - Low transport concrete between the cracks
- Concrete must have minimal cracking to maintain resistance to moisture
- Adversely affects durability regardless of concrete quality
WHY DO WE CURE CONCRETE?

- Reduce evaporation
- Minimize temperature gradients
- Promote hydration to form a dense microstructure
  - i.e., Decrease Permeability and Increase Durability

Frankly, most people don’t understand how important it is. Concrete **MUST** be properly cured for the optimum properties and performance to be achieved. **Regardless of design strength (or form removal) being reached**, continue to cure your concrete as long as possible.
EVALUATION OF TRANSPORT PROPERTIES – TEST METHODS

- Available Test Methods (common)
  - Chloride Ponding (AASHTO T259/ASTM C1543)
  - Rapid Penetrability (AASHTO T277/ASTM C1202)
  - Bulk Electrical Resistivity (ASTM C1876)

- Other Available Test Methods
  - Diffusion Coefficient
  - Surface resistivity
  - Ion Migration Testing
RAPID CHLORIDE PERMEABILITY TEST (ASTM C1202)
CHLORIDE RESISTANCE – BULK DIFFUSION TEST (ASTM C1556)

\[
\frac{C_x}{C_0} = 1 - erf\left(\frac{x}{2\sqrt{D_a \cdot t}}\right)
\]

\(C_0\) and \(D_a\) found by curve fitting
SURFACE RESISTIVITY TO ASSESS TRANSPORT PROPERTIES

Cement paste contains a dense network of interconnected pores through which the electrons will flow.

- Less interconnected, more tortuous porosity makes electron flow more difficult → higher resistivity
- Also more resistant to water flow → lower permeability
Electrical resistivity measurements can provide a good indicator of concrete’s permeability, since both properties are predominantly controlled by the interconnectivity and tortuosity of the pore network. However, saturation of concrete will influence results.
# FACTORS AFFECTING PERMEABILITY OF CONCRETE

## Principal Factors
- Water/cementitious material
- Water Content
- Curing
- Mineral admixtures
  - Silica fume
  - Fly ash
  - Slag
  - Other (e.g. metakaolin)

## Secondary Factors
- Cement Factor
- Chemical Admixtures
- Aggregate Type
- Air Content
# W/C VERSUS WATER CONTENT

<table>
<thead>
<tr>
<th>Cement content (kg/m³)</th>
<th>Water Content (kg/m³)</th>
<th>W/C =</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>250</td>
<td>-</td>
<td>113</td>
</tr>
<tr>
<td>300</td>
<td>-</td>
<td>135</td>
</tr>
<tr>
<td>350</td>
<td>-</td>
<td>158</td>
</tr>
<tr>
<td>400</td>
<td>140</td>
<td>180</td>
</tr>
</tbody>
</table>

- High water content means higher cement content.
- This means less aggregate content.
- Aggregates are generally considered impermeable.

**Graph:**

- Water Content (pcy)
- Gas Permeability (x 10^{-17} m²)

- W/C = 0.45

Increasing paste content
W/C ILLUSTRATION – FRESHLY MIXED PASTE

W/CM = 0.33 by mass

\[
\frac{\text{Volume of Water}}{\text{Volume of Cement}} = 1
\]

W/CM = 0.61 by mass

\[
\frac{\text{Volume of Water}}{\text{Volume of Cement}} = 2
\]
Low W/CM:
• Low capillary porosity
• Small pores poorly connected
• Low permeability
• High strength

High W/CM:
• High capillary porosity
• Large pores - well connected
• High permeability
• Low strength

Original water-filled spaces: “Capillary Porosity”
CAPILLARY POROSITY DECREASES WITH AGE (DEGREE OF CEMENT HYDRATION)

Degree of hydration
The amount of time given to cure your concrete (i.e. maturity)

Capillary porosity
The amount of empty space!

Curing time (days)
Degree of Hydration (%) Capillary Porosity (%)
EFFECT OF W/CM

Reducing the water content and W/CM of concrete leads to:

- Increased strength and stiffness
- Reduced shrinkage
- Better bond between concrete and reinforcement
- Lower permeability
- Increased resistance to weathering (i.e., durability)

Less Water  ▶️  Better Concrete

Provided the concrete can be consolidated properly!
EFFECT OF SUPPLEMENTARY CEMENTING MATERIALS

AKA SCMS

Fly Ash Spheres

Blended Cement with Silica Fume
HOW DO SCMS AFFECT CONCRETE?

- Improved **rheology/workability** – easier to pump, place and finish
- Increased **strength**
- Reduced **permeability** to water and other fluids
- Increased **resistance to chloride** ion penetration
- Decreased rate of **corrosion** of reinforcement
- Increased resistance to **chemical attack** (sulfates, acids, etc.)
- Reduced or suppressed expansion from **alkali-silica reaction** (ASR)
- Reduced risk of **delayed ettringite formation** (DEF)

But... not just any SCM will do. Appropriate use is the key!
HOW DO SCMS AFFECT CONCRETE?

Cement + Water
→ OK Concrete

Cement + Water + Low W/CM
→ Better concrete

Cement + Water + Low W/CM + SCM
→ SUPER Concrete

Maybe two SCMs??
APPROPRIATE USE OF SCMS

Concrete properties and performance will be affected by:

- Type of SCM (physical and chemical characteristics)
- Dosage level used (% replacement of cement)
- Chemistry of the cement (especially alkali content)
- Quality of the concrete
- But most importantly… Curing, curing, and plenty of MOIST CURING!

Adequate curing is essential for durable concrete, especially with SCMs

Image source: PCA
MANY OF THE BENEFICIAL EFFECTS OF USING A POZZOLANS OR SLAG ARE RELATED TO THE EFFECT IT HAS ON THE PORE STRUCTURE BY:

**Micro-Filler effect** – increased packing of cementitious particles (i.e., densification)

**Pozzolanic effect** – replacing porous CH with C-S-H (i.e., replacing OK with BETTER)

**Wall effect** – densifying the ITZ (interfacial transition zone) at the cement-aggregate interface

**Pore blocking** – occurs because of a combination of these factors

These effects refine the pore structure and reduce the permeability of concrete thereby making it more resistant to the penetration of deleterious agents.
INTERFACIAL TRANSITION ZONE - ITZ

AGGREGATE TRANSITION ZONE

BULK CEMENT PASTE

= C-S-H

= CH

= C-A-S-H
WHAT ABOUT AGGREGATES???

GRADING AND USE OF INTERMEDIATE SIZES → LESS PASTE

- Well-graded aggregate
- Low permeability
- Same w/c

- Poorly-graded aggregate
- High permeability
SOME LAST WORDS ON PERMEABILITY AND TRANSPORT MECHANISM IN CONCRETE

- Vital to most, if not all, durability issues
- Complex mechanisms, affected by specific environment and concrete microstructure.

**Reducing Permeability** to water (and other stuff in it) is a universal way of improving durability.
  - Reduce w/cm (as practical as possible)
  - Use of SCMs
  - Cure, cure, cure!!

- Measure permeability or performance whenever possible
# DURABILITY – TYPES OF DETERIORATION

## Physical
- Fire
- Freezing and thawing cycles
- Salt attack

## Chemical
- Alkali-Aggregate Reactions
- Carbonation
- Sulfate Attacks
- Corrosion
- Acid attacks
- Efflorescence

## Mechanical
- Impact
- Abrasion
- Erosion
- Cavitation

*Note: Can have multiple types of deterioration → leads to destructive synergies*
CORROSION OF THE REINFORCING STEEL
WHY IS CORROSION OF STEEL A CONCERN? – STRUCTURALLY

- The formation of rust leads to a loss of bond between the steel and the concrete and subsequent delamination and spalling.
- If left unchecked, the integrity of the structure can be affected. Reduction in the cross-sectional area of steel reduces its strength capacity. This is especially detrimental to the performance of tensioned strands in precast/pre-stressed concrete (i.e. rupture of strands → Big BOOM)

http://www.corrosion-club.com/concretecorrosion.htm
WHY IS CORROSION OF STEEL A CONCERN? – SEVERE EXPOSURE CONDITIONS

I-95 over in Georgia Turtle River

Image sources: R. Brett Holland

(Mehta, 1991)
“Chloride-induced corrosion is the leading cause of premature deterioration of concrete structures in North America”

(Portland Cement Association, 2010)
PASSIVATION OF STEEL

- **High pH** in most concrete (> 13.0) allows formation of passive layer of iron oxide on reinforcing steel

- **Passive layer** (in high pH environment)
  - Very thin film
  - **Corrosion** does not stop, but proceeds very slowly (~0.1 μm / year)
  - Loss of passive layer can **accelerate** corrosion rate 1000X.

- Steel will typically remain passive if **pH > 11.5**
PASSIVATION OF STEEL

Concrete + Steel = a winning combination (usually)

Steel can become de-passivated in concrete if:
- Chlorides “destabilize” the passive layer
- pH is reduced (concentration of OH^- ions in the pore solution)
CHLORIDE-INDUCED CORROSION

Concrete

Chlorides

Steel

Passive film

$\gamma-Fe_2O_3$ ($\sim 10^{-2} \mu m$)

Pitting corrosion

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CARBONATION-INDUCED CORROSION

- Carbonation of CH leads to decrease in pH of concrete
- Carbonation “front” moves through concrete
  - Sharp change in pH from >13 to <9 over just a few mm of concrete
  - Rate depends on moisture conditions and permeability of concrete
  - When front reaches depth of the steel, passive layer is no longer stable → corrosion process becomes “active” and proceeds rapidly
Carbonation of Concrete
Carbonation-induced corrosion on underside of slab – **Low Reinforcement Cover!!! Check Spacing**
Carbonation of Fly Ash Concrete – Can (potentially) actually make things worse!!

Control (No SCMs)  50% Class F Fly Ash
HOW DO WE PREVENT STEEL CORROSION?

Corrosion Protection Strategies

- Non-chloride deicers
- Membranes and sealers
- Ultra/High-performance concrete (Precast)
- Sufficient cover
- Non-corrosive/ferrous metals
- Coatings on steel
- Corrosion inhibitors (Very Common in Precast/Prestressed)
CONTROLLING CORROSION – QUALITY PRACTICES

- Reduced permeability
  - w/cm of 0.4 or less
  - 7 days moist curing (or more!)
- Use of SCMs with extended curing
- Alumina-bearing cements – bind chlorides
- Low chloride content materials
- Sufficient, high-quality cover concrete
- Corrosion inhibitor (e.g., calcium nitrite)
- Water repellents
- Protective membranes cathodic protection, epoxy-coated reinforcing bars and concrete sealers (if reapplied every four to five years).
ALKALI SILICA REACTION (ASR)
WHAT IS ASR?

Reactive silica in aggregate

Alkalis in cement paste

ASR Gel + Sufficient Moisture → Expansive ASR

Expansion and micro-cracking

Surface macro-cracking

Gel will not swell if water is not available in concrete!!

Slide courtesy of Eric R. Giannini
CONTRIBUTING FACTORS TO ASR

Three conditions necessary for expansive ASR

- Reactive Silica
- Sufficient Alkalis
- Sufficient Moisture (External or internal)

All must be present!
MITIGATION/PREVENTION OF ASR

Three conditions necessary for expansive ASR

- Reactive Silica
- Sufficient Alkalis
- Sufficient Moisture (External or internal)

Remove any corner of the triangle will prevent/stop expansive ASR from occurring.

- Removing the supply of moisture should prevent/minimize deleterious expansion


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BUT KEEPING CONCRETE DRY IS EASIER SAID THAN DONE...
MITIGATION/PREVENTION OF ASR

Three conditions necessary for expansive ASR

- Reactive Silica
- Sufficient Alkalis
- Sufficient Moisture (External or internal)

Remove any corner of the triangle will prevent/stop expansive ASR from occurring.

• Can target both alkalis and reactive silica
• Test methods important to identify reactive aggregates and evaluate mitigation measures

METHODS FOR MINIMIZING THE RISK OF ASR IN FRESH CONCRETE

- Use a non-reactive aggregate *(whenever possible)*
- Limit the alkali loading \( (\text{Na}_2\text{O}_e) \) of the concrete (i.e., less cement), especially when SCMs are not available (or at least good quality ones)
- Use sufficient quantity of (SCM’s)
  - Fly Ash (15-40%)
    - Dependent on Type *(Class F vs. Class C)*
    - Beware of high-alkali fly ashes (>3% Alkali Content)
  - Slag (30-50+%)
  - Silica Fume (5-10%)
    - Typically not effective alone → However, much better when used in ternary blends (Fly ash + SF)
- Use of chemical admixtures
  - Lithium based compounds \( (\text{LiNO}_3) \) → Changes Gel to be non-expansive
- Combinations of the above

*How do we Evaluate Aggregate Reactivity and Preventive Measures??*
Most reliable way to determine the effectiveness of a preventive measure is to test it with the reactive aggregate in question.

- **ASTM C1260** – 14 days in 1N NaOH solution at 80°C
- **ASTM C1567** – 28 days, same conditions, evaluates mitigation measures
- **Expansion limit** of 0.10% (typ.)

- **ASTM C1293**
  - 1 year at 38°C and >95% RH
  - 420 kg/m³ (708 PCY) cementitious, 1.25% alkalis
  - Can test mitigation measures – extend to 2 years as “modified 1293 test”
  - **Expansion limit** of 0.04%
FIELD HISTORY

Reliability

14 - 28 days

Mortar Bars (ASTM C1260/1567)

Concrete Prism/Cylinder Test (ASTM C1293)

≥ 20 years ?

Large blocks stored outdoors

≥ 20 years

Field performance

Continuing to monitor long-term performance will increase reliability of lab test methods

Slide Courtesy of Michael D.A. Thomas
OTHER RECOMMENDED TEST METHODS

- ASTM C295 – Petrographic Examination of Aggregates
- ASTM C856 – Petrographic Examination of Concrete
- ASTM C1778 – Guidance on Risk Management for AAR

Designation: C1778 – 19a

Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete

This standard is issued under the fixed designation C1778; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of publication. The superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.
SULFATE ATTACK OF CONCRETE

- Internal Sulfate Attack
- External Sulfate Attack
- Chemical (Classical) Sulfate Attack
- Physical Sulfate Attack
WHAT IS CHEMICAL SULFATE ATTACK?

Chemical sulfate attack, it is the chemical breakdown mechanism where external sulfate ions ($\text{SO}_4^{2-}$) attack the components of the hydrated cement paste.

**Mechanism of Sulfate Attack**
- **Diffusion control** ingress of soluble sulfates ($\text{SO}_4^{2-}$)
- Formation of several deleterious expansive by-products
- Paste microcracking encouraging further penetration and ultimately, reduce service life of the structures

Typical sources of external sulfates:
- Soil
- Groundwater
- Seawater
HOW DO WE EVALUATE SULFATE RESISTANCE?

ASTM C1012 – Performance Test Method

1. Aggregate/cementitious material = 2.75 & W/CM = 0.485

2. Heat cured at 38°C for 23.5 Hr

3. Mortars stored in limewater until a strength of 20 MPa is attained

4. Mortar bars (25 x 25 x 250 mm) then immersed in a 5% solution of sodium sulfate for **6-18 months** ~ length change monitored during storage

![Diagram of mortar bar in 5% Na₂SO₄ solution](image)
EFFECT OF FLY ASH ON SULFATE RESISTANCE (ASTM C1012)

Figure Courtesy: T. Drimalas & K. Folliard
SOME CLASS C FLY ASHES MAKE THINGS WORSE...

Figure Courtesy: T. Drimalas & K. Folliard
"EQUIVALENT" SULFATE RESISTANCE BASED ON ASTM C1012 EXPANSION

<table>
<thead>
<tr>
<th>Exposure Class</th>
<th>Maximum expansion when tested using ASTM C1012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 6 months</td>
</tr>
<tr>
<td>S1</td>
<td>0.10 percent</td>
</tr>
<tr>
<td>S2</td>
<td>0.05 percent</td>
</tr>
<tr>
<td>S3</td>
<td></td>
</tr>
</tbody>
</table>

*The 12-month expansion limit applies only when the measured expansion exceeds the 6-month maximum expansion limit.

**Drawbacks:**
- Length of test makes it difficult to assess preventive measures
- Very severe and unrealistic test (but necessary to accelerate)
WHY THE HATE – ON SULFATE?

Sulfate attack is the only durability mechanisms that does not include a standardized method evaluating the performance of concrete specimens.

ASTM methods for durability

- C1293/ASR
- C666/Freeze-thaw
- C672/Salt Scale
- G109/Corrosion
- C1012/Sulfate
RECENT ADVANCES ON TEST METHOD

- Vacuum Saturation Accelerated Method
RECENT ADVANCES ON TEST METHOD

• pH controlled chamber with cirulator
  – Sulfuric Acid (0.1M)
• Length change and compression strength monitor
CONCRETE ACC METHOD

- Type I/II control cement oven dried at 38°C
- Significant accelerated with higher w/cm (more porous)
HOW CAN WE IMPROVE SULFATE RESISTANCE?

**Sulfate Resistant Cement (SRC)**
- Type I Portland cement
- Type V Portland cement

**Low Permeability**

Concrete exposed to severe sulfate exposure

Concrete with Type II Cement after 5 years exposure in sulphate soil

*Figure Courtesy: K. Folliard; PCA*
HOW CAN WE IMPROVE SULFATE RESISTANCE?

- Determine the severity of exposure condition
  - The higher the sulfate concentration (in soils or groundwater), the more stringent requirements for protection

- Low permeability concrete
  - Low w/cm < 0.45
  - Proper compaction/consolidation/curing

- Sulfate-resistant cement (SRC) (ASTM C150)
  - Moderate sulfate resistance – ASTM C150 Type II C₃A ≤ 8%
  - High sulfate resistance – ASTM C150 Type V C₃A ≤ 5%

- Use of proper SCMs
  - Class C is should NEVER be allowed
  - Can decrease performance
DELAYED ETTRINGITE FORMATION (DEF)
WHAT IS DEF?

- Form of **INTERNAL** sulfate attack
- Primarily a result of high **early-age** curing temperatures (>158°F / 70°C) preventing the normal “early” formation of ettringite
  - Must happen within first 12-24 hrs after mixing
  - No DEF if temperature stays high for several days
  - Especially of concern in **mass concrete elements** often combined with high ambient temperatures as well
- **Cement chemistry** thought to be a contributing factor
  - Sulfate content
  - Sulfate/Alumina ratio

Image source: PCA
Often occurs in precast elements (e.g. heat-cured and Type III cements)
MITIGATION / PREVENTION OF DEF

**New construction**
- Limits on *maximum in-place temperature* (158°F / 70°C max)
- **Use of SCMs** can allow temperatures **up to** (185°F / 85°C → ACI 201.2R)
  - 25-35% Fly Ash
  - 35% slag
  - 5% Silica Fume + 25% slag
  - 5% Silica Fume + 20% Class F Fly Ash
  - 10% metakaolin

**Existing structures**
- **Dry out** structure if possible
- Provide **external confinement** (easier said than done)
FURTHER MOTIVATION FOR DURABILITY

- Last Week Tonight – John Oliver, “Infrastructure”

https://www.youtube.com/watch?v=Wpzvaqypav8
SUMMARY – 5 BIG INFLUENCES ON CONCRETE DURABILITY!!

1. Understand exposure condition and ask yourself - “Where will this concrete be placed and how severe is the condition?

2. Use low W/C or W/CM as practical as possible

3. Know your materials and how they will influence performance!! Use SCMs, especially for enhancing durability (assuming they will not make things worse)

4. Test for performance whenever possible or at least for transport properties, especially when new materials/sources are being included for your project.

5. Cute, Cure and Cure! And if possible, cure again!
THAT’S ALL FOLKS!

What did the beam say to the ASR gel?

You crack me up!
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5 THINGS YOU CAN DO TO ENHANCE YOUR CONCRETE DURABILITY

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