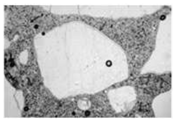
JENSEN HUGHES

Advancing the Science of Safety



Concrete Durability
Anthony F. Bentivegna, PhD, PE
May 9, 2018

References

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- ASTM C989 / C989M-18, Standard Specification for Slag Cement for Use in Concrete and Mortars, ASTM International, West Conshohocken, PA, 2018, www.astm.org
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- Portland Cement Association – 16th Edition, Design and Control of Concrete Mixtures
- Silica Fume Association – Presentation, “Silica Fume in Concrete”

Agenda

Concrete Durability

- **Introduction**
- Corrosion
- Alkali-silica Reaction
- External Sulfate Attack
- Delayed Ettringite Formation

  - Introduction to Mechanism
  - Relevant ASTM Test Methods
  - Field Studies

Concrete Service-life Challenges

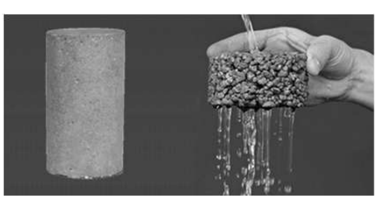
Concrete Durability

- Reinforcement Corrosion
- Alkali-silica Reaction (ASR)
- Sulfate Attack
- Freeze-thaw/scaling

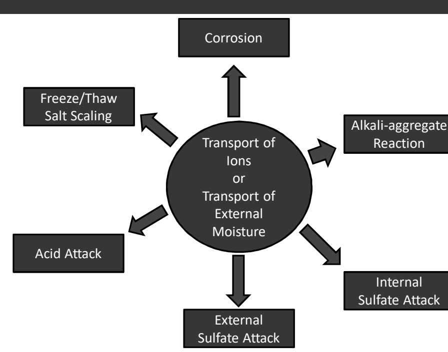
- And more…(Delayed ettringite formation, acid attack, etc.)

Transportation of Ions

Although concrete is perceived as a solid impermeable material at its microstructure it is porous and permits the movement of moisture and ions

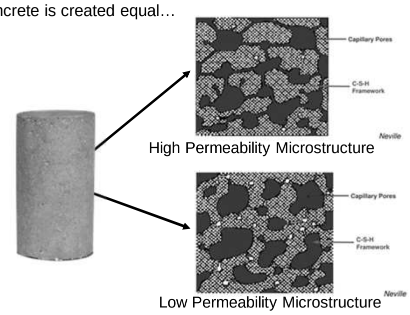


What's Affected by Transport Properties?



Transportation of Ions

Not all concrete is created equal…



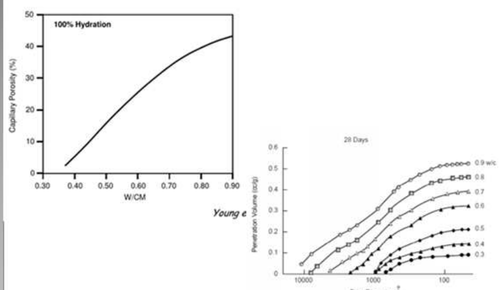
Factors Effecting Concrete Permeability

Transportation of Ions through concrete is effected by:

- w/c Ratio
- Time or Concrete Age
- Curing
- Exposure Conditions
  - Weather, Heating Drying
- Mixture Design
  - Cement Type and Quantity
  - Aggregate Type
  - Addition of SCMs
  - Admixtures

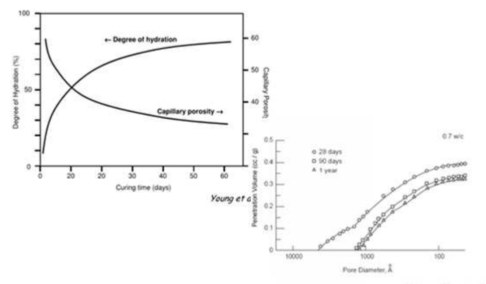
Factors Effecting Concrete Permeability

w/c Ratio More water more permeability



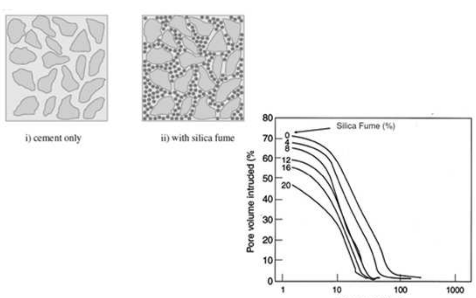
Factors Effecting Concrete Permeability

Time or Concrete Age



Factors Effecting Concrete Permeability

Addition of Silica Fume



Agenda

Concrete Durability

- Introduction
- **Corrosion**
- Alkali-silica Reaction
- External Sulfate Attack
- Delayed Ettringite Formation

Corrosion of Reinforcing Steel

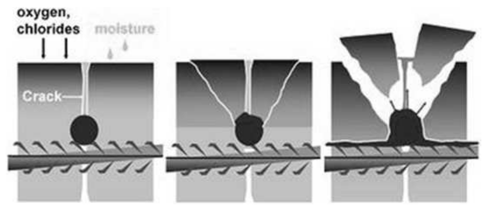
Chloride Induced Corrosion

Caused by penetration of Cl^- ions through permeable concrete.

Carbonation Induced Corrosion

Caused by carbonation of concrete and depassivation of reinforcing steel.

Chloride-Induced Corrosion of Concrete

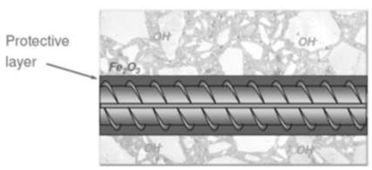


Chlorides from deicing salts or seawater penetrate and reach the steel

Chloride ions lead to corrosion if O_2 and H_2O are present

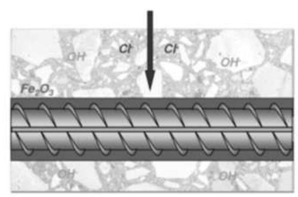
Chloride Induced Corrosion (1/4)

At high pH in concrete (above 13.0) a protective (or passive layer) of iron oxide forms on embedded steel protecting the steel from corrosion.



Chloride Induced Corrosion (2/4)

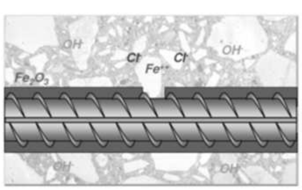
Chlorides penetrate concrete cover



Chloride Induced Corrosion (3/4)

Chlorides penetrate concrete cover

Destabilize passive layer locally



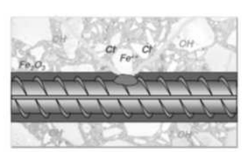
Chloride Induced Corrosion (4/4)

Chlorides penetrate concrete cover

Destabilize passive layer locally

Corrosion occurs

Cracking spalling and delamination occurs



External Sources of Chlorides

Chloride in seawater

- Affects marine structures, harbors, oil platforms, coastal bridges, and ships

Chloride in ground water

- Affects buried structures, piles, tunnels and foundations

Chloride from deicing chemicals

- Affects highway structures, bridges and parking structures.

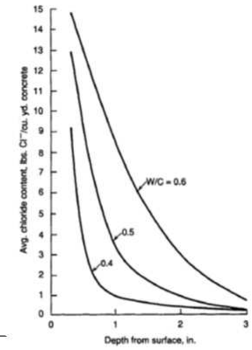
The Challenge Remains: to slow or prevent the ingress of chloride ions through the use of **SCMs**.

Effect of w/cm and Cover

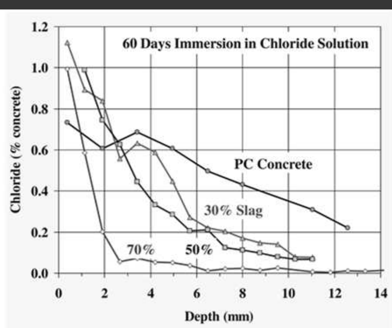
Concrete sprayed with salt spray for 830 days

Shows Advantages of:

- Increased Cover
- Decreased w/cm



Effect of Slag Cement on Chloride Diffusion

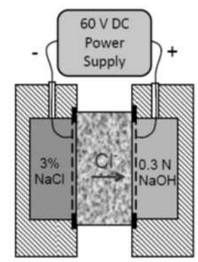


Source: Thomas

ASTM C1202 - Rapid Chloride Permeability Test

Scope:

- This test method covers the determination of the electrical conductance of concrete to provide a rapid indication of its resistance to the penetration of chloride ions. This test method is applicable to types of concrete where correlations have been established between this test procedure and long-term chloride ponding procedures such as those described in AASHTO T 259.



How and Why Was this Test Developed?

Developed for US FHWA in 1980s

Techniques to nondestructively measure chloride permeability

Prior: chloride ponding test used AASHTO T259

- Takes 90 days or longer
- Profile grinding, chemical analysis, and chloride profile

Good correlation to ponding tests

Electrical current used to accelerate the test

Description of Test

Overview:

- 100 mm diameter cores or cylinders cut to 50 mm length
- Vacuum specimens for 3 hrs and submerge for 18 hrs
- System is then connected in direct current with 3% NaCl and 0.3 N Na OH
- Apply 60-volts potential for 6 hours and measure current every 30 mins.

Factors that Influence Results

Age and curing (drastically affect results)

- Older specimens lower coulombs

Presence of admixtures with ionic salts

- Salts act as transport media
- Typ. Accelerators with Calcium Nitrite, Calcium Nitrate, and Calcium Chloride

Others:

- cement factor, air content, water/cement ratio, aggregate source/type

Curing Cylinders

Moist Curing – 28 days for *Only Portland Cement*

- Per ASTM C192 for laboratory cast specimens
- Per ASTM C31 for field cast specimens

Extended Moist Curing – 56 Days *for SCMs*

- Allows extra time for SCMs to hydrate

Accelerated Moist Curing – *for SCMs*

- 7 days Moist cured followed by 21 days in lime-saturated water at 38.0 ± 2.0 °C.

Calculation: Total Charge Passed (Conductance)

Plot amperes per time (sec)

Determine the area under the curve to get coulombs

- Using trapezoidal rule for determining area

$$Q = 900(I_0 + 2I_{30} + \cdots + 2I_{300} + 2I_{330} + 2I_{330})$$

Where:

Q = charge passed (coulombs),
I_0 = current (amperes) immediately after voltage is applied, and
I_t = current (amperes) at t_{min} after voltage is applied

Analysis of Results

Qualitative indication of the chloride ion penetrability is shown below:

Coulombs	Permeability Class	Typical of
>4000	High	$w/c^* > 0.5$
4000-2000	Moderate	w/c = 0.4 to 0.5
2000-1000	Low	$w/c < 0.4$
1000-100	Very Low	Latex-modified concrete
<100	Negligible	Polymer concrete

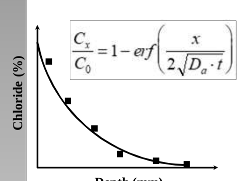
$^*w/c$ = water-cement ratio

Test is not accurate enough to clearly define permeability levels

Five categories were created.

ASTM C 1556 Test to Determine the Bulk Diffusion Coefficient of Concrete

Concrete sample is immersed in NaCl solution for time t (minimum 35 days)
Sample then ground in approx. 1-mm depth increments
Dust samples analyzed for chlorides →
To produce chloride profile ↓



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

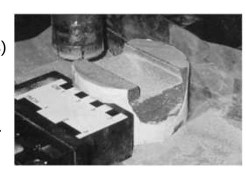
C_o and D_a found by fitting the equation shown to the measured profile.

Values of D_a typically in the range:
1 x 10^{-13} to 1 x 10^{-11} m^2/s

Bulk Diffusion Coefficient (ASTM C1556)

Overview

- Concrete sample is immersed in NaCl solution for time (minimum 35 days)
- Sample then ground in approx. 1-mm depth increments
- Dust samples analyzed for chlorides
- To produce chloride profile



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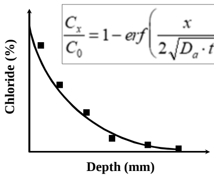
Bulk Diffusion Coefficient (ASTM C1556)

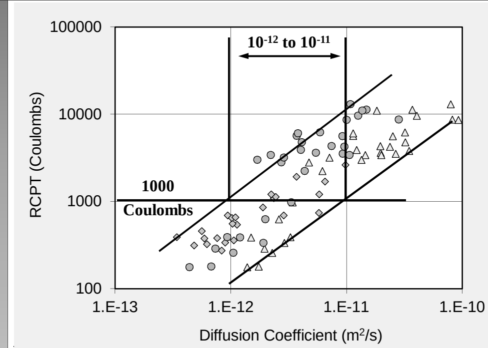


$$\frac{C_x}{C_0} = 1 - erf\left(\frac{x}{2\sqrt{D_a \cdot t}}\right)$$

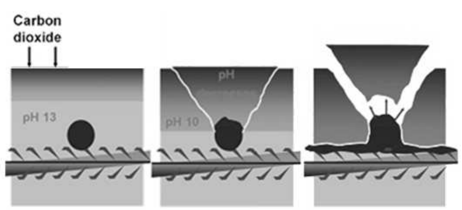
C_o and D_a found by fitting the equation shown to the measured profile.

Values of D_a typically in the range: 1×10^{-13} to 1×10^{-11} m²/s

RCPT (C1202) vs. Bulk Diffusion (C1556)



Carbonation-Induced Corrosion of Concrete



- CO_2 reacts with CH within concrete to form $CaCO_3$
- pH drops from 13 to <10
- Reinforcement becomes depassivated

Carbonation Testing

- Concrete has a pH < 9
- Phenolphthalein indicator solution highlights depth of carbonation from purple-to-colorless:

pH > 9 (purple)

pH < 9 (colorless)

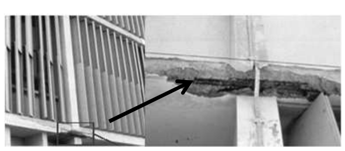
Physical Factors Affecting Carbonation

Relative CO_2 Concentration

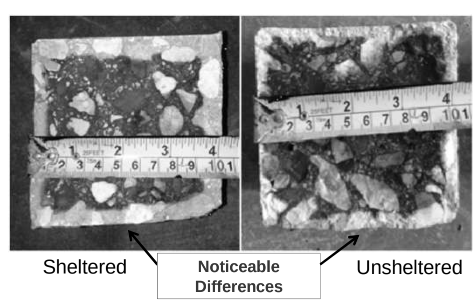
Shelter vs. Unsheltered

- 40% < RH < 90%

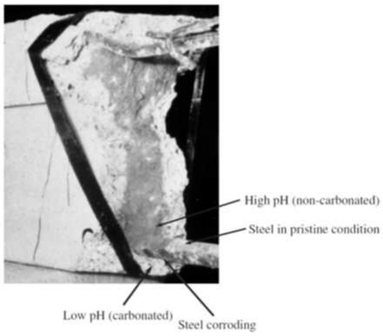
Low Concrete Cover



Carbonation Front



Example Damage from BRE



Example Damage from BRE

Courtesy of BRE

Carbonation Mechanism

Penetration of CO_2

- Penetrates slowly in saturated (or near saturated concrete) because pores are blocked by water
- Carbonation won't occur in dry concrete because CO_2 needs to dissolve in water before it reacts. Two Phases:

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad \text{(carbonic acid)}$$

$$H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$$

- Optimum humidity is between 45-65%
- Carbonation corrosion typical found on external elements that are protected from direct precipitation

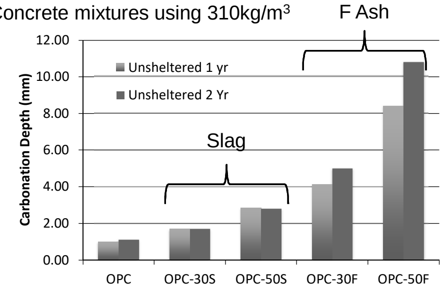
How do we test carbonation?

Laboratory

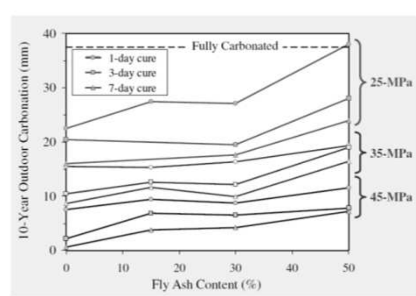
Exposure Site
(Covered and Uncovered)

Depth of Carbonation

Concrete mixtures using 310kg/m^3



Fly Ash Content in Outdoor Carbonation



Corrosion

Corrosion

- Most common and costly durability problem in world

Chloride Induced Corrosion

- Prevented with lower w/cm, SCMs, and increased cover
- ASTM test methods available for measuring concrete permeability

Carbonation Induced Corrosion

- High-volume SCM concrete prone to deterioration
- Curing and cover are important

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Agenda

Concrete Durability

- Introduction
- Corrosion
- **Alkali-silica Reaction**
- External Sulfate Attack
- Delayed Ettringite Formation

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What is Alkali-Silica Reaction (ASR)?

- alkali-silica reaction — the reaction between the **alkalies** (sodium and potassium) in portland cement and **certain siliceous rocks** or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates.

Source: American Concrete Institute Concrete Terminology 2013

What is Alkali-silica Reaction (ASR)?

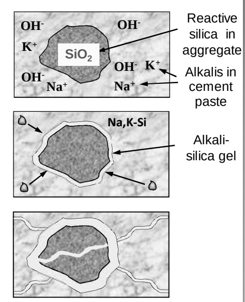
Reaction between the alkalis (Na^+& K^+) typically from the cement and unstable silica, SiO_2, in some types of aggregate

The reaction produces an alkali-silica gel

The gel absorbs water from the surrounding paste …

… and expands.

The internal expansion eventually leads to cracking of the surrounding concrete.



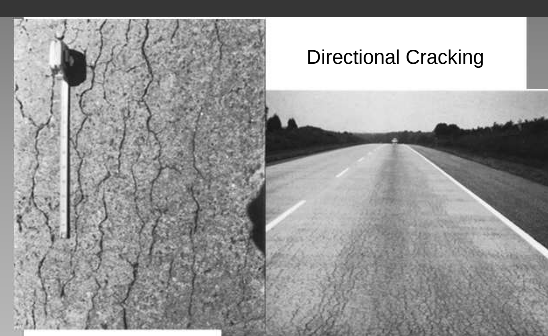
ASR Examples (1/4)

Map Cracking

Source: PCA

ASR Examples (2/4)

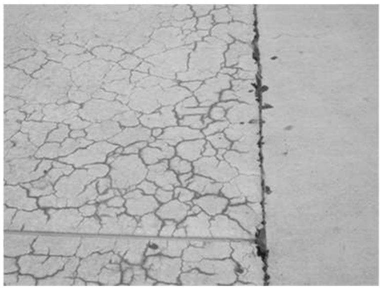
Directional Cracking



Source: PCA

ASR Examples (3/4)

Extrusion of joint-sealants



Source: PCA

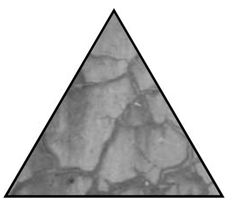
ASR Examples (4/4)

Concrete Crushing

Source: PCA

Alkali-silica Reaction (ASR)

Reactive Silica



Sufficient Alkali

Sufficient Moisture

Commonly Used ASR Test Methods

Aggregate Tests:

- **ASTM C 295** - Standard Guide for Petrographic Examination of Aggregates for Concrete
- ~~**ASTM C 289** - Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)~~

Mortar Tests:

- **ASTM C 227** - Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
- **ASTM C 441** - Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction
- **ASTM C 1260** - Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Accelerated Mortar-Bar Method)
- **ASTM C 1567** Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

Concrete Test:

- **ASTM C 1293** - Standard Test Method for Concrete Aggregates by Determination of Length Change of Concrete Due to Alkali-Silica Reaction (Concrete Prism Test)

ASTM C1260 – Mortar Bar Test

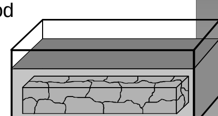
Description:

Accelerated Mortar Bar Test Method

1 x 1 x 11.25 in. Bars

Immersed in 1 N NaOH at 80°C

Specimens Monitored for 14 days after Immersion



Comment:

- Overly Severe (Temp. and NaOH)
- Should be used to accept aggregates (not reject)
- Aggregates Failing Test (should be confirmed by C1293)

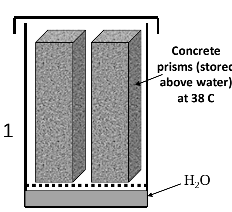
ASTM C1293 – Concrete Prism Test

Description:

Concrete Prism Test

3 x 3 x 11.25 in. Prism

Stored over-water at 38°C for 1 year (2 years for mitigation)



Comment:

- Most Reliable Test Method
- Best Correlation to Field Performance
- Does Not Test Job Mixtures
- Cannot Asses Alkali Loading of a Mixture (Specimen Size)
- Long Duration for Testing

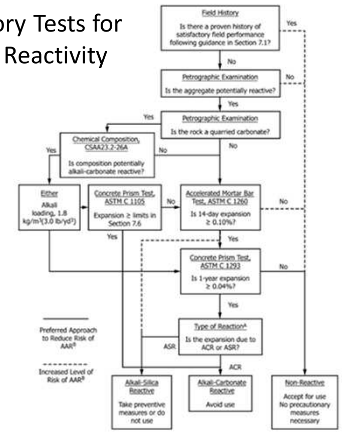
ASTM C1778 - Reducing the Risk of Deleterious Alkali-Aggregate Reaction

Guide for Identifying Reactive Aggregates

Approaches for Selecting Preventative Measures

- **Prescriptive Approach**
  - Select Appropriate Risk Levels
  - Limit Alkalis
  - Supplementary Cementitious Materials
- **Performance-based Approach**
  - ASTM C1567 – Mortar Bar Test Method
  - ASTM C1293 – Concrete Prism Test

Sequence of Laboratory Tests for Evaluating Aggregate Reactivity



Preventing ASR: Using SCMs

Fly Ash
Slag
Silica Fume
Natural Pozzolans

Almost all sources of these materials are effective in controlling ASR

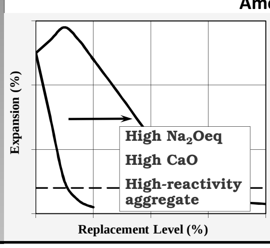
IF used in sufficient quantity

Amount of preventive required ...ends on:

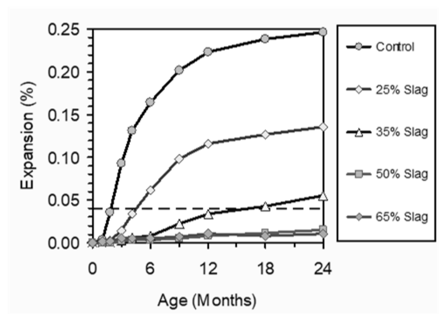
...omposition of material (esp. ...a_2Oeq, SiO_2, CaO)

...vailable alkali in the system

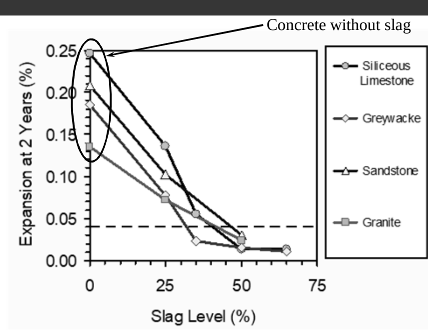
...ature of the reactive ...ggregate



Preventing ASR: Using Slag Cement



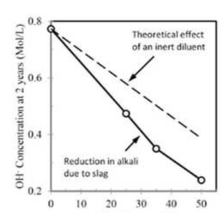
Slag Cement: Requirements by Aggregate Type



Thomas and Innis, 1998

How Slag Cement Prevents ASR?

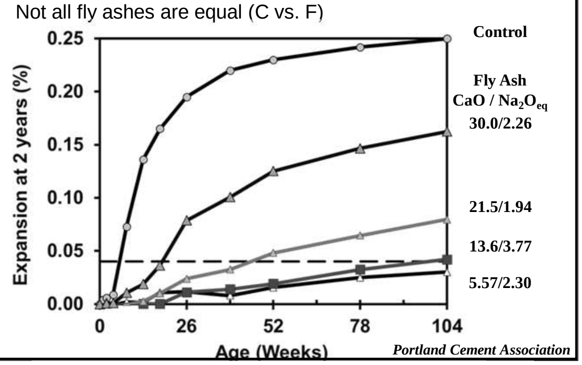
- Reducing permeability
- Change of the alkali-silica ratio
- **Dissolution and consumption of the alkali species**
- Reduce the calcium hydroxide needed to support the reaction



Slag Cement Association

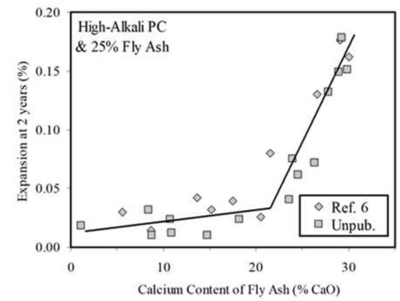
Effect of Fly Ash on ASR Expansion

Not all fly ashes are equal (C vs. F)

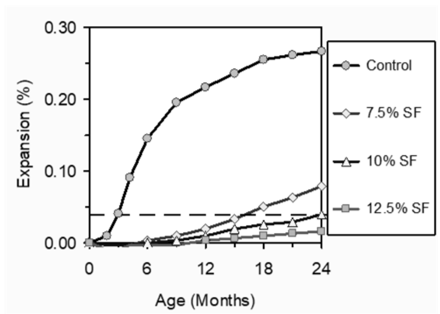


Portland Cement Association

Effect of Calcium Content of Fly Ash



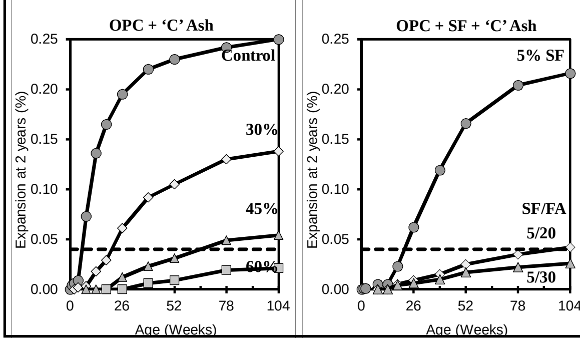
Silica Fume (Only)



Fournier et al. 1995

Effect of Silica Fume & Fly Ash
Concrete Prisms with 'C' Fly Ash

(27.7% CaO, 1.65% Na_2O_{eq})



Mitigation of ASR in New Concrete

Strategies:

- Avoiding reactive aggregates
- Controlling alkali content of the concrete
- Using suitable fly ash
- Using slag
- Using silica fume
- Using suitable natural pozzolans
- Using lithium compounds

Agenda

Concrete Durability

- Introduction
- Corrosion
- Alkali-silica Reaction
- **External Sulfate Attack**
- Delayed Ettringite Formation

External vs. Internal

External Sulfate Attack ("Classical")

- Caused by a **source external to concrete**, including sulfate from ground water, soil, solid industry waste, fertilizers, atmospheric SO_3 or liquid industry wastes.
- **ASTM C1012** - Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

Internal Sulfate Attack

- Source of sulfate is internal to concrete, including **excessive cement sulfate** and **delayed ettingite formation**.
- ASTM C1038 - Standard Test Method for Expansion of Hydraulic Cement Mortar Bars Stored in Water

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External or "Classical" Sulfate Attack

Various Sulfate Species

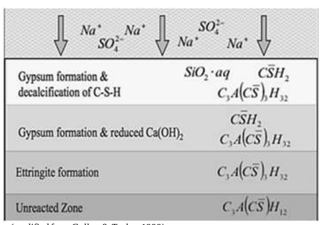
- Magnesium sulfate (Most Aggressive)
- Sodium Sulfate
- Calcium Sulfate (Least Aggressive)

Sulfate Compounds Can Attack:

- Calcium Hydroxide
- C-S-H
- Monosulfate hydrate
- Other hydrates

Sulfate Attack

When strictly speaking **chemical sulfate attack**, it is the chemical breakdown mechanism where sulfate ions (SO_4^{2-}) attack the components of the hydrated paste



(modified from Gollop & Taylor, 1999)

Mechanism of Sulfate Attack

- **Diffusion control** ingress of soluble sulfates (SO_4^{2-})
- Formation of several deleterious **expansive by-products**
- Paste micro-cracking encouraging further penetration and ultimately, reduce service life of the structures

Example: Sodium Sulfate

$$CH + N_2\bar{S}H_{10} \rightarrow C\bar{S}H_2 + 2NH + 8H$$

Calcium Hydroxide + Sodium Sulphate → Gypsum + Sodium Hydroxide + Water

$$C_3A(C\bar{S})H_{12} + 2C\bar{S}H_2 + 16H \rightarrow C_3A(C\bar{S})_3H_{32}$$

Calcium Monosulphoaluminate + Gypsum + Water → **Ettringite**

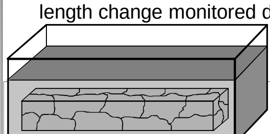
$$2C_3AH_{12} + 3N_2\bar{S}H_{10} \rightarrow C_3A(C\bar{S})_3H_{32} + 2AH_3 + 6NH + 17H$$

Tri-Calcium Aluminate Hydrate + Sodium Sulphate → **Ettringite** + Aluminum Hydroxide + Sodium Hydroxide + Water

How to Evaluate Sulfate Resistance?

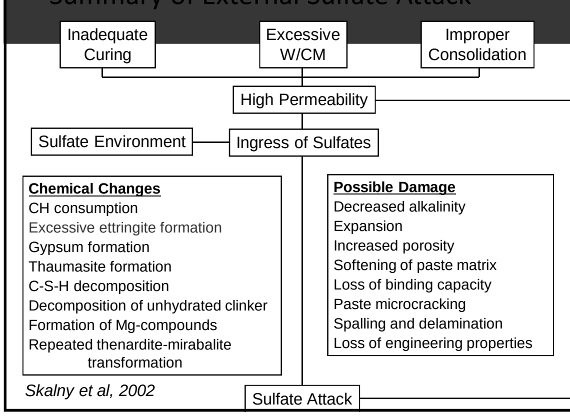
ASTM C1012

- Aggregate/cementitious material = 2.75 & W/CM = 0.485
- Heat cured at 38°C for 23.5 Hr
- **Mortars** stored in limewater until a strength of 20 MPa is attained
- Mortar bars **(25 x 25 x 250 mm)** then immersed in a 5% solution of sodium sulfate for **18 months** ~ length change monitored during storage



5%-Na_2SO_4 solution
Changed periodically

Summary of External Sulfate Attack

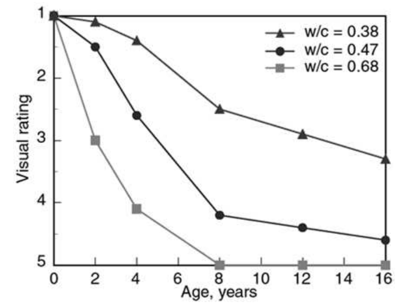


Skalny et al, 2002

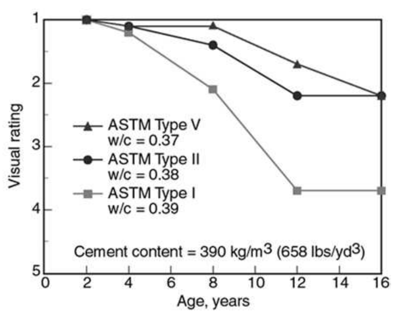
Approach to Mitigating Sulfate Attack

- Determine Susceptibility of Sulfate Attack
  - ASTM C1012
- Select Mitigation Strategies (if required)
  - Use of Sulfate-Resisting Cement
  - Use of SCMs
  - Combination of Sulfate-Resisting Cement and SCMs
- Control of w/cm

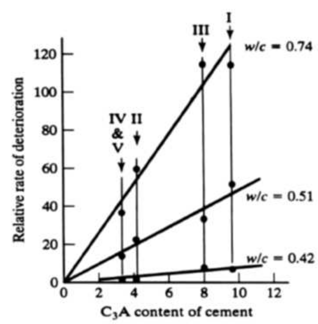
Performance of Concretes Made with Different W/C-Ratios in Sulfate Soil



Performance of Concretes Made with Different Cements in Sulfate Soil



Effect of w/cm



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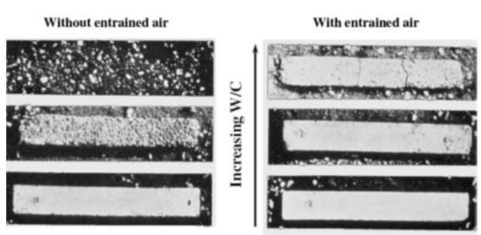
Effect of w/cm and Air Content

Type II cement after 5 years of sulfate exposure



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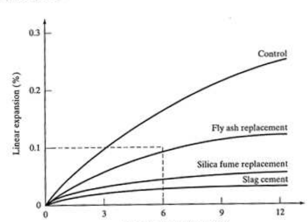
Effect of SCMs on Sulfate Attack

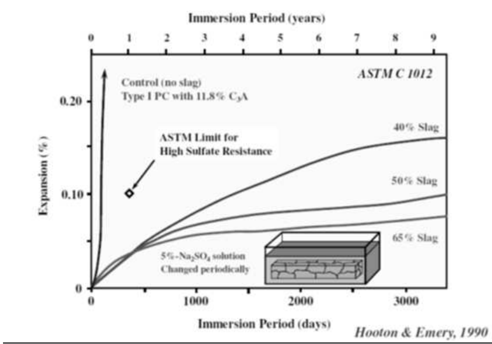
SCMs generally improve **sulfate resistance**

Slag > Class F fly ash **> Class C**

Can **equal** or **exceed** performance of **Type V** cement by using SCMs



Effect of Slag Cement on Sulfate Resistance



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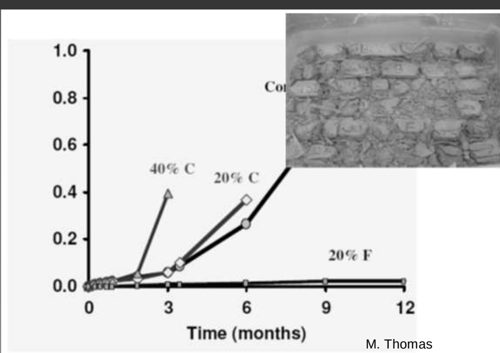
Why Slag Cement Prevents Sulfate Attack?

- Proportional Reduction in C_3A
- Reduction of Soluble Calcium Hydroxide (CH) through the Production of Calcium Silica Hydrates (C-S-H)
  - Reducing the Environment for Calcium Sulfoaluminate Formation
- Reduction in Permeability

Effect of Fly Ash on Sulfate Resistance



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Fly Ash Mineralogy - Matters

Fly Ash Mineralogy: (Most Ashes Contain)	Class C Fly Ash: (May Contain)
Mullite – $Al_6Si_2O_{13}$	**C_3A**
Magnetite – Fe_3O_4	**C_2S**
Hematite – Fe_2O_3	Lime – CaO
Quartz – SiO_2	**Anhydrite – $CaSO_4$**
These Phases are insoluble and do not participate in hydration reactions	Melilite – $Ca_2(Mg, Al)(Al,Si)_2O_7$
	Alkali sulfates – $(Na, K)_2SO_4$
	And others…..

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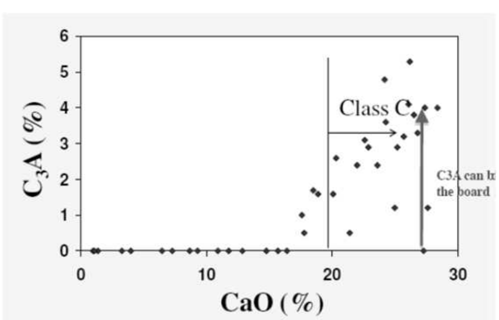
Relationship between C_3A and CaO



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Class C Fly Ash

Explanation of Reduced Sulfate Resistance

- Contributes C_3A and some CH
- Lower consumption of lime due to reduced pozzolanicity (hydraulic reaction)
- Presence of reactive calcium-aluminates in amorphous (glassy) phase
- Production of reactive aluminate hydrates

When to Protect External Sulfates?

ACI 201.2R – Guide to Durable Concrete

Severity of potential exposure	Water-soluble sulfate (SO_4) in soil, % by mass[*]	Sulfate (SO_4)[*] in water, ppm	w/cm by mass, max.[†‡]	Cementitious material requirements
Class 0 exposure	0.00 to 0.10	0 to 150	No special requirements for sulfate resistance	No special requirements for sulfate resistance
Class 1 exposure	> 0.10 and < 0.20	> 150 and < 1500	0.50[‡]	C150 Type II or equivalent[§]
Class 2 exposure	0.20 to < 2.0	1500 to < 10,000	0.45[‡]	C150 Type V or equivalent[§]
Class 3 exposure	2.0 or greater	10,000 or greater	0.40[‡]	C150 Type V plus pozzolan or slag[§]
Seawater exposure	—	—	See Section 6.4	See Section 6.4

- Measure water-soluble sulfate (SO_4) in soil, % by mass
- Use ASTM C1580 - Standard Test Method for Water-Soluble Sulfate in Soil

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Concrete Durability

- Introduction
- Corrosion
- Alkali-silica Reaction
- External Sulfate Attack
- **Delayed Ettringite Formation**

Delayed Ettringite Formation (DEF)

Rare form of sulfate attack by which hardened concrete is damaged by internal expansion caused by the late formation of ettringite in concretes cured at temperatures in excess of 158ºF

Types of Structures

Mass concrete

- Mass Concrete
- Bridge columns, foundations, etc.

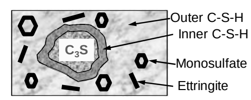
Precast Concrete

- Columns, beams, etc.

What is Delayed Ettringite Formation (DEF)?

Concrete cured at 20°C

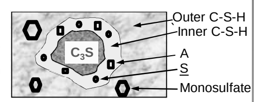
Ettringite and monosulfate form as part of the outer hydration products



Concrete cured at >70°C

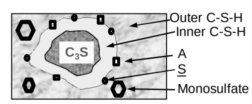
Incongruent of dissolution of ettringite.

Encapsulated sulfate and aluminate in rapidly forming inner C-S-H



Subsequent storage in water at 20°C

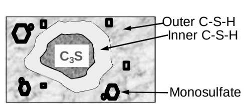
Sulfate and aluminate slowly released from inner C-S-H



What is Delayed Ettringite Formation (DEF)?

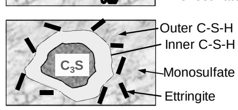
Continued storage in water at 20°C

Sulfate and aluminate slowly released from inner C-S-H



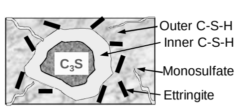
Continued storage in water at 20°C

Ettringite formed in fine pores of outer C-S-H



Under certain conditions this leads to expansion of paste

Leaves voids around aggregates and eventual cracking of paste and outer concrete



Prevention: Maximum Temperature Limit

Specifications Limit 70°C = 158°F(or 160°F)

Example Specifications:

Specification	Chapter	Requirement
ACI 301	Mass Concrete	158°F
	Precast	153+5°F
ACI 350.5	Mass Concrete	160°F
TxDOT	Mass Concrete	160°F
VDOT	Mass Concrete	(50-75 Slag Cement) 170°F
		(25-40% Class F Fly Ash) 160°F
FDOT	Mass Concrete	SCMs 180°F

Prevention: ACI 201.2R – Guide to Durable Concrete

Maximum Temp.	Level of Prevention Required
T ≤ 158°F	No Prevention Required
158°F ≤ T ≤ 185°F	1. Type II and V and low-alkali cement with fineness ≤ 430 m^2/kg 2. Use OPC with 1 Day Mortar Strength ≤ 2850 psi 3. ≥ 25% Class F Fly Ash ≥ 35% Class C Fy Ash ≥ 35% Slag Cement ≥ 5% Silica Fume + ≥ 25% Slag Cement ≥ 5% Silica Fume + ≥ 20% Class F Fly Ash ≥ 10% Metakaolin
T > 185°F	Concrete Should Not Exceed 185°F

Agenda

Concrete Durability

- Introduction
- Corrosion
- Alkali-silica Reaction
- External Sulfate Attack
- Delayed Ettringite Formation

Summary

- Mass Transport (Pore Solution and Moisture)
  - Affects almost every durability mechanism
  - Common “rules of thumb” apply:
    - Low w/cm, SCMs, Curing, Quality Construction
- Corrosion
- Alkali-silica Reaction
  - Sufficient Quantities of SCMs
  - ASTM C1778 – Good Guidance Document
- External Sulfate Attack
  - Type II/V Cements, Slag Cement Preferred,
  - Test per ASTM C1012
- Delayed Ettringite Formation
  - Temperatures during curing should be below 70°C

QUESTIONS?

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