4098-01-P1

WORKSHOP ON DESIGN OF DURABLE CONCRETE

February 18-19, 2003
Lubbock, TX

AGENDA

Tuesday, February 18

1:00 p.m. - 1:15 p.m.:	Session 1 - Introduction and Workshop Objectives [Folliard, UT]
1:15 p.m. - 2:15 p.m.:	Session 2 - Fundamentals of Concrete [Folliard, UT]
2:15 p.m. - 2:30 p.m.:	Break
2:30 p.m. - 3:30 p.m.:	Session 3 - Alkali-Silica Reaction [Folliard, UT]
3:30 p.m. - 4:05 p.m.:	Session 4 - TxDOT Experience with ASR [Lankes, TxDOT]
4:05 p.m. - 4:15 p.m.:	Break
4:15 p.m. - 4:50 p.m.:	Session 5 - Freezing and Thawing [Folliard, UT]
4:50 p.m. - 5:10 p.m.:	Open Discussion

Wednesday, February 19

8:00 a.m. - 9:00 a.m.:	Session 6 - Sulfate Attack (including DEF) [Folliard, UT]
9:00 a.m. - 9:35 a.m.:	Session 7 - Premature Concrete Deterioration: Case Studies [Merrill, TxDOT]
9:35 a.m. - 9:50 a.m.:	Break
9:50 a.m. - 10:50 a.m.:	Session 8 - Corrosion [Folliard, UT]
10:50 a.m. - 11:15 a.m.:	Session 9 - High-Performance Concrete Specifications [Pruski, TxDOT]
11:15 a.m. - 11:30 a.m.:	Break
11:30 a.m. - Noon:	Open Discussion
Noon - 1:00 p.m.:	Lunch
1:00 p.m. - 2:00 p.m.:	Session 10 - Concrete Cracking and Effects on Durability [Folliard, UT]
2:00 p.m. - 2:30 p.m.:	Session 11 - Practical Aspects of Concrete Durability [Browne, TxDOT]
2:30 p.m. - 2:40 p.m.:	Break
2:40 p.m. - 3:15 p.m.:	Summary and Panel Discussion [Cox, TxDOT]

Evaluation of Workshop for Concrete Durability
February 18-19, 2003

1. Was the workshop beneficial? Yes ☐ No ☐
   Comments:

2. Were the presenters knowledgeable about their subject matter? Yes ☐ No ☐
   Comments:

3. Were the presentations easy to understand and follow? Yes ☐ No ☐
   Comments:

4. Do you understand the mechanisms that cause concrete deterioration? Yes ☐ No ☐
   Comments:

5. Do you understand the basics of HPC usage? Yes ☐ No ☐
   Comments:

6. Were the slide presentations well prepared and easy to follow? Yes ☐ No ☐
   Comments:

7. Were the handouts sufficient? Yes ☐ No ☐
   Comments:

8. Do you recommend this workshop for others? Yes ☐ No ☐
   Comments:

Name/Position (Optional): ______________________________________

TxDOT Workshop

Design of Durable Concrete

Session 1: Introduction and Workshop Objectives

CONCRETE DURABILITY CENTER (CDC)

Presentation Outline

- **Introduction**
- **Workshop Objectives**
- **Workshop Outline**

TxDOT Project 5-4098
"Workshop on Design of Durable Concrete"

Developed by:

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The University of Texas at Austin

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University of New Brunswick

In Cooperation with

Texas Department of Transportation

Workshop Objectives

- Provide a basic overview of cement chemistry and concrete microstructure.
- Discuss the most important durability-related issues affecting concrete structures.
- Provide some recommendations and guidance on achieving long-term durability.
- Discuss how TxDOT addresses durability in specifications, etc.
- Generate open discussion on durability issues.

Workshop Outline

Tuesday, February 18 (afternoon)

- ➢ **Session 1** - Introduction and Workshop Objectives (Folliard, UT)
- ➢ **Session 2** - Fundamentals of Concrete (Folliard, UT)
- ➢ **Session 3** - Alkali-Silica Reaction (Folliard, UT)
- ➢ **Session 4** - TxDOT Experience with ASR (Lankes, TxDOT)
- ➢ **Session 5** - Freezing and Thawing (Folliard, UT)

* Open Discussion after Session 5

Workshop Outline

Wednesday, February 19 (morning)

- ➢ **Session 6** - Sulfate Attack (including DEF) (Folliard, UT)
- ➢ **Session 7** - Premature Concrete Deterioration - Case Studies (Merrill, TxDOT)
- ➢ **Session 8** - Corrosion of Reinforcing Steel (Folliard, UT)
- ➢ **Session 9** - High-Performance Concrete Specifications (Pruski), TxDOT)

* Open Discussion after Session 9

Workshop Outline

Wednesday, February 19 (afternoon)

- **Session 10** - Concrete Cracking and Effects on Durability (Folliard, UT)
- **Session 11** - Practical Aspects of Concrete Durability (Merrill/Browne, TxDOT)
- **Summary and Panel Discussion (Cox, TxDOT)**

Thank you for your participation.

Your input and feedback on this workshop are greatly appreciated!!!

TxDOT Workshop

Design of Durable Concrete

Session 2: Fundamentals of Concrete

CONCRETE DURABILITY CENTER (CDC)

Presentation Outline

- Basics of Concrete
- Constituent Materials
- Important Concrete Properties
- Some Durability Aspects

What is Concrete?

The Food Chain…

<u>Portland cement</u> = fine powder
<u>Paste</u> = Portland cement + water
<u>Grout</u> or <u>Mortar</u> = Portland cement + water + fine aggregate
<u>Concrete</u> = Portland cement + water + fine aggregate + coarse aggregate

ADMIXTURES!!!

Bulk Phases in Hardened Concrete

- Highly inhomogeneous inside concrete
- Composed of following phases:
  - Paste (hydration products + unhydrated cement)
  - Aggregates
  - Transition zone (between paste and aggregates)
  - Pore solution (solution within paste and transition zone)

Let's look at the hydration of cement paste first...

Cement is to Concrete as Flour is to Cake...

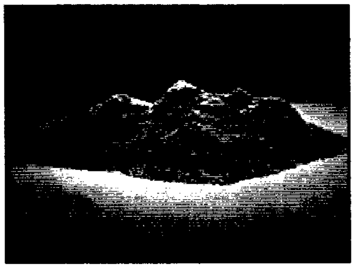


Photo: PCA

History of Cement

- 2000 B.C.: Egyptians used cement in mortar when making Pyramids
- 27 B.C.: Roman cement made of lime and volcanic ash
- 1824: Joseph Aspdin discovered and patented "portland" cement

Photo: PCA

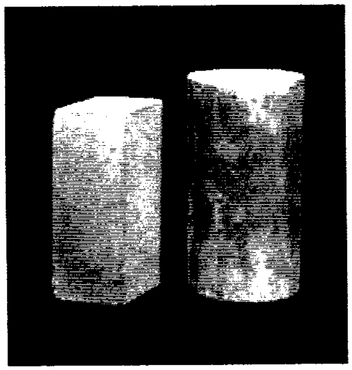


Photo: PCA

Isle of Portland Quarry Stone next to a Cylinder of Modern Concrete

Today's Cement

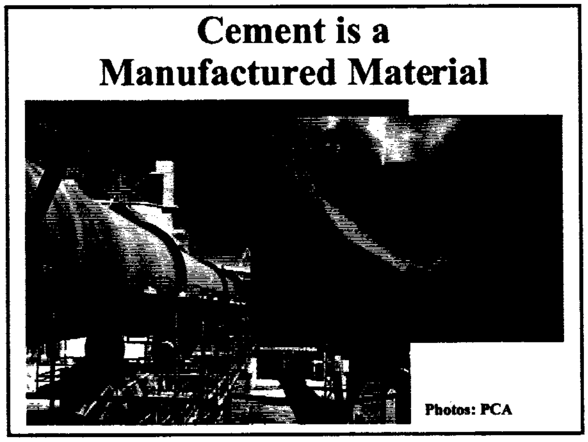
- Still relies on Aspdin's raw materials of:

Calcium
Iron
Silica
Alumina

Plus:
Gypsum

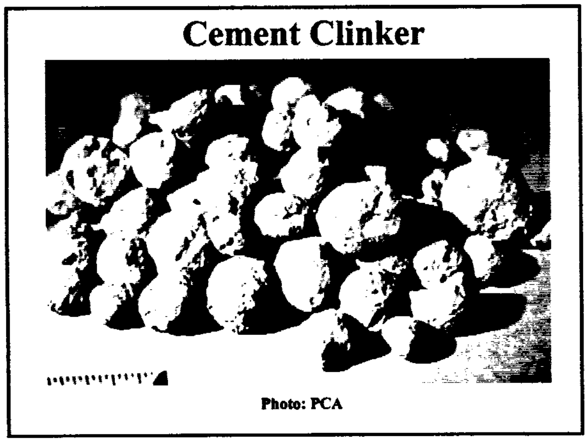
Common Sources for Raw Materials

- Calcium (CaO)
  - Limestone, shale
- Iron (Fe_2O_3)
  - Clay, iron ore
- Silica (SiO_2)
  - Clay, sand, shale
- Alumina (Al_2O_3)
  - Clay, fly ash, shale



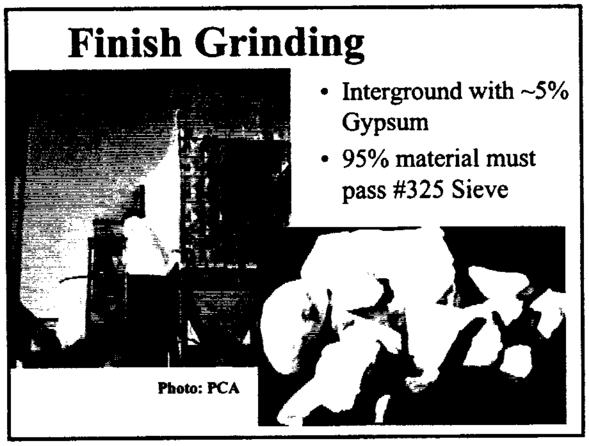
Cement is a Manufactured Material

Photos: PCA



Cement Clinker

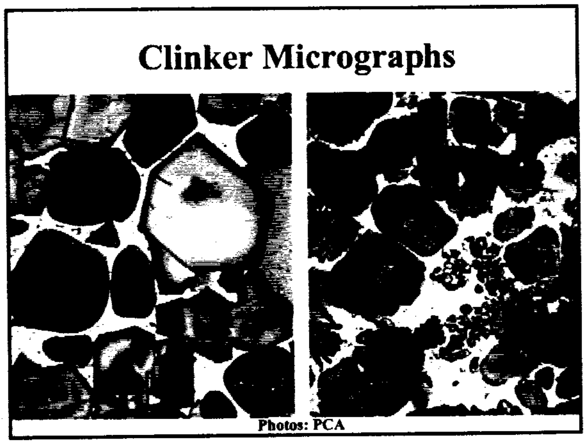
Photo: PCA



Finish Grinding

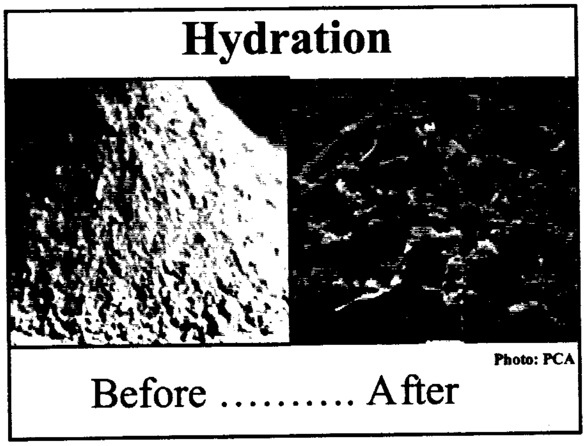
- Interground with ~5% Gypsum
- 95% material must pass #325 Sieve

Photo: PCA



Clinker Micrographs

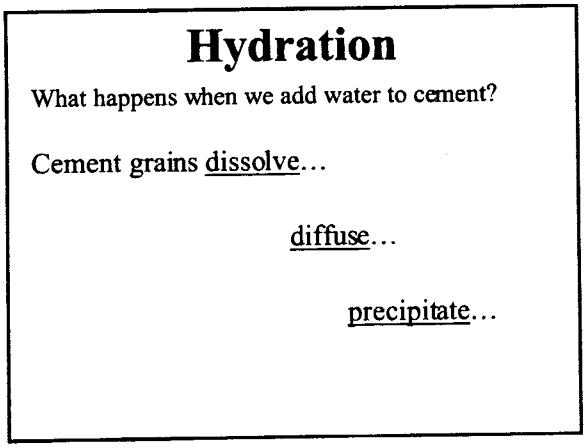
Photos: PCA



Hydration

Photo: PCA

Before .... After



Hydration

What happens when we add water to cement?

Cement grains dissolve...

diffuse...

precipitate...

Hydration

Let's first discuss cement chemistry terminology…

Cement Chemistry Abbreviations

Oxides

C = CaO
S = SiO_2
A = Al_2O_3
F = Fe_2O_3
H = H_2O
$\overline{S}$ = SO_3

4 main compounds in portland cement (+ gypsum)

Calcium aluminates
$C_3A = 3CaO \bullet Al_2O_3$
$C_4AF = 4CaO \bullet Al_2O_3 \bullet Fe_2O_3$
Calcium silicates
$C_3S = 3CaO \bullet SiO_2$
$C_2S = 2CaO \bullet SiO_2$

Let's discuss hydration of calcium aluminates and calcium silicates separately…

C_3A

- $3CaO.Al_2O_3$ -"Aluminate"
- **Provides early heat generated in hydration** (10° to 15° F per 100 lb. cement)
- Gypsum required to slow it down…
- High C_3A not as resistant to sulfate attack
- Little contribution to long-term strength

C_4AF

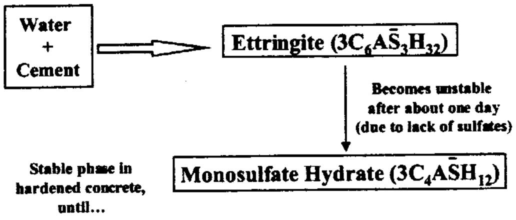
- $4CaO.Al_2O_3.Fe_2O_3$ -"Ferrite"
- Governs the color of the cement
- Present at 1-10%
- Little contribution to strength

Hydration of Calcium Aluminates (C_3A, C_4AF)

- Mainly affects setting and hardening
- Minimal effects on long-term strength
- Ettringite forms first, becomes unstable, then monosulfate forms as stable phase
- Some durability implications (C_3A)
- Set accelerators and retarders have impact

Hydration of Calcium Aluminates

First, consider early-age portland cement* hydration:



Water + Cement

Ettringite ($3C_6A\bar{S}_3H_{32}$)

Becomes unstable after about one day (due to lack of sulfates)

Monosulfate Hydrate ($3C_4A\bar{S}H_{12}$)

Stable phase in hardened concrete, until...

C_3S

- $3CaO.SiO_2$ -"Alite"
- **Provides early strength development**
- 70% reacts by 28 days
- Usually present at 40-70%

C_2S

- $2CaO.SiO_2$ -"Belite"
- **Provides late strength development**
- 30% reacts by 28 days
- Present at 20-40%

Hydration of calcium silicates (C_3S, C_2S)

- C_3S and C_2S = ~ 75% of the weight of Portland cement
- React with water to form two new compounds:
- Calcium Hydroxide (CH)
  - Relatively weak and can be attacked by acids
  - Plate-like crystals
- Calcium Silicate Hydrate (C-S-H)
  - Strong and durable
  - Amorphous, "tribble" structure

Ideally, we want to convert CH to C-S-H....

C-S-H

The tribbles of the concrete world...

Main Types of Cement (as per ASTM C 150)

- Type I - Normal
- Type II - Moderate Sulfate Resistance/Moderate Heat ($C_3A < 8\%$)
- Type III - High Early Strength (finer grind or higher Blaine)
- Type IV - Low Heat of Hydration
- Type V - High Sulfate Resistance ($C_3A < 5\%$)

* Note -- Type I and Type III are usually from same clinker, just different fineness

* Note -- Type IV rarely, if ever, available

Some others...

  - **Type IS, IP**
  - **Type I/II**
  - **White portland cement**
  - **Shrinkage-compensating cement**

Supplementary Cementing Materials

- DEFINITION: **Powdered or pulverized materials added before or during mixing to improve or change some of the plastic or hardened properties of concrete.**

- **Cementitious**
- **Pozzolanic**

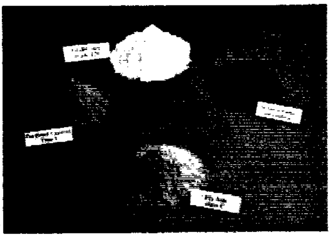


Photo: PCA

Cementitious Materials

- Possess hydraulic cementing properties
  - GGBF slag (by-product of steel industry)
  - Class C Fly Ash (high calcium)
  - Others
    - Natural cement- Cement Rock
    - Hydraulic hydrated lime

Pozzolans

- Possess no cemetitious value until finely divided and mixed with water and cement (or lime)
  - Class F Fly ash (low calcium)
  - Silica fume (silicon manufacture)
  - Calcined clay (metakaolin)
  - Rice husk ash

Fly Ash

- **<u>Class F</u> (low calcium) - from burning anthracite or bituminous coal, is pozzolanic**
- **<u>Class C (high calcium)</u> - from burning sub-bituminous or lignite coal, is somewhat cementitious**

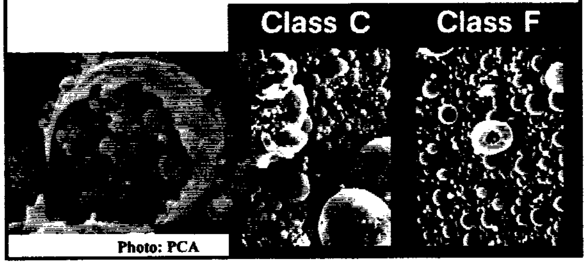


Photo: PCA

GGBFS (Slag)

- **Formed when molten iron blast furnace slag is rapidly chilled (quenched) by immersion in H_2O**
- **Grades 80, 100, 120**
- **Used as a cement replacement**

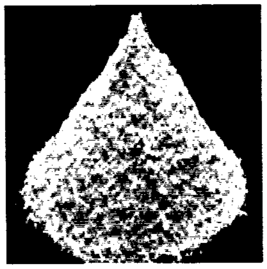


Photo: PCA

Silica Fume

- **Also known as microsilica**
- **By-product of the productio of silicon and ferrosilicon alloys.**
- **A small part of silica fume can be used to replace a larg part of cement**

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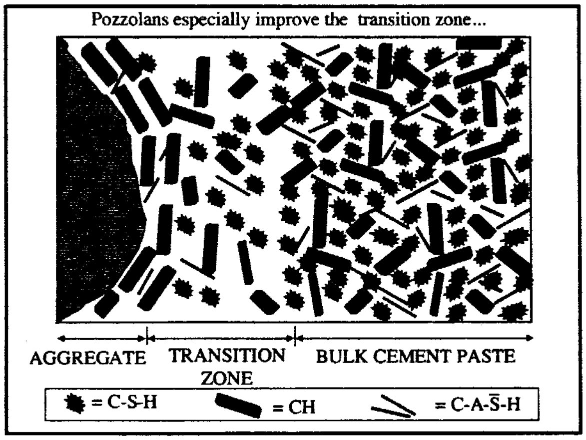
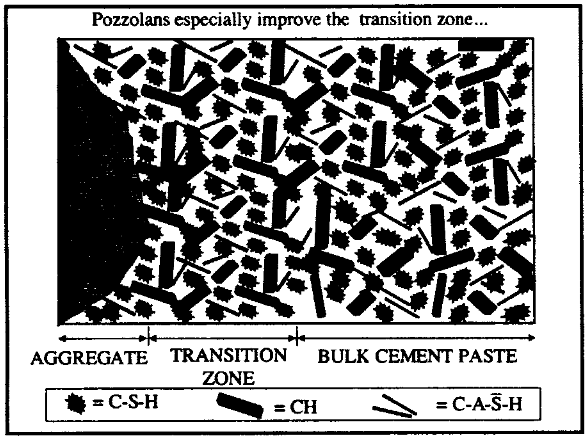
Benefits of SCMs

- **Durability** -- reduced permeability
- Reduced heat of hydration
- Strength development (age-dependent)
- Economics


Pozzolans especially improve the transition zone...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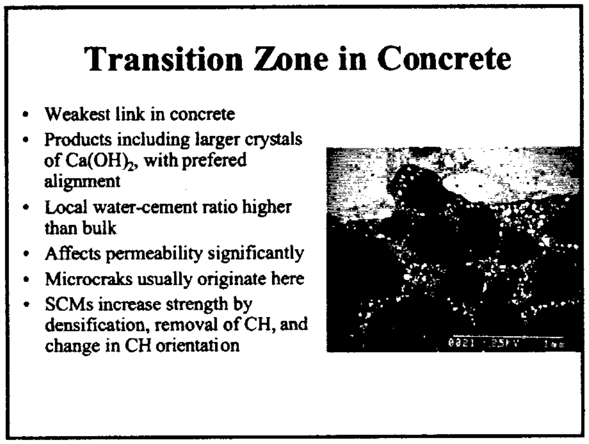
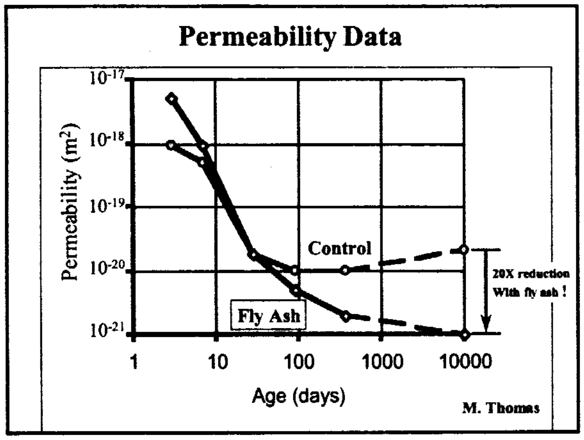
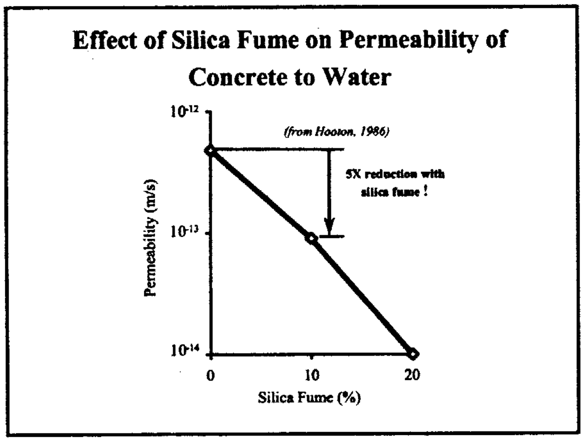

Transition Zone in Concrete

- Weakest link in concrete
- Products including larger crystals of $Ca(OH)_2$, with prefered alignment
- Local water-cement ratio higher than bulk
- Affects permeability significantly
- Microcraks usually originate here
- SCMs increase strength by densification, removal of CH, and change in CH orientation



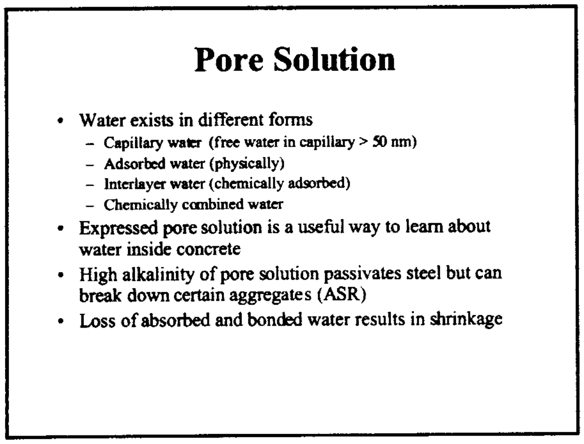
Permeability Data

M. Thomas



Effect of Silica Fume on Permeability of Concrete to Water

(from Hooton, 1986)

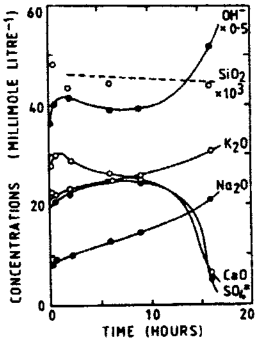


Pore Solution

- Water exists in different forms
  - Capillary water (free water in capillary > 50 nm)
  - Adsorbed water (physically)
  - Interlayer water (chemically adsorbed)
  - Chemically combined water
- Expressed pore solution is a useful way to learn about water inside concrete
- High alkalinity of pore solution passivates steel but can break down certain aggregates (ASR)
- Loss of absorbed and bonded water results in shrinkage

Expressed Pore Solution

- Only 10 to 20% of free water
- Calcium concentration decreases due to increase of pH
- Sulfate concentration decreases due to ettringite formation
- Crystalline $Ca(OH)_2$ is the buffer for the high pH of pore solution



Mixing Water

ΣMunicipal

ΣWell

ΣHeated

ΣSteam

ΣChilled

ΣIce

ΣRecycled

Photo: PCA

Questionable Water

- Water < 2000 ppm of total dissolved solids is satisfactory for making concrete.
- Water > 2000 ppm of dissolved solids should be tested for its effects on strength and time of set.

Photo: PCA

The Water - Cement Ratio Law

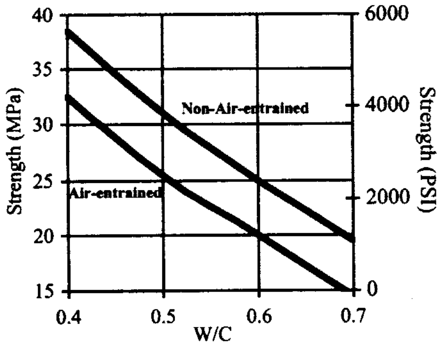
For given materials the strength of the concrete.... depends solely on the relative quantity of water as compared with the cement...

Duff A. Abrams
May, 1918

Why?

The Key to Strength is Porosity...

Effects of w/c on strength



Aggregates

Photo: PCA

Aggregates in Concrete

- Influence elastic modulus of concrete
- Influence coefficient of thermal expansion
- Affect drying shrinkage
- Determining ultimate strength of extremely high strength concrete
- Durability

Influence of Aggregates

- **STRENGTH**
  Shape
  Size
  Surface texture

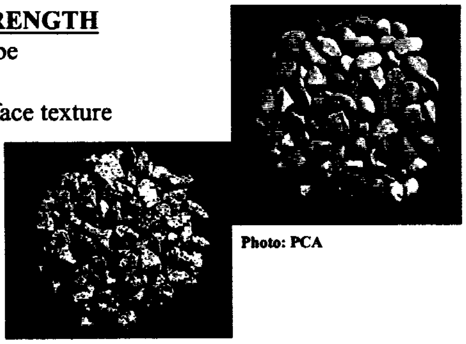
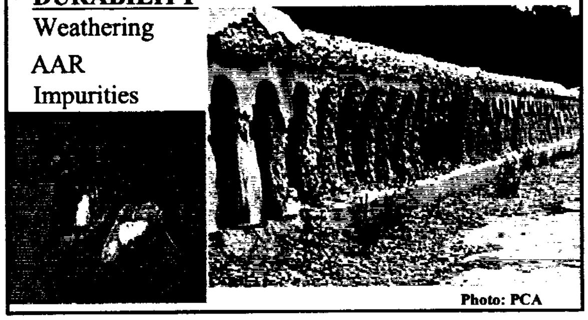


Photo: PCA

Influence of Aggregates

- **DURABILITY**
  Weathering
  AAR
  Impurities



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Aggregate Gradation

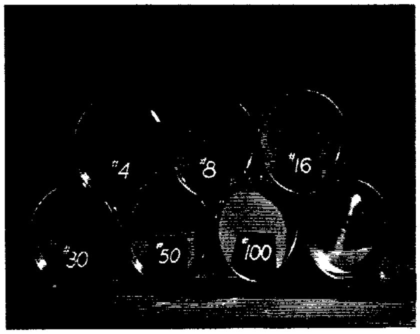


Photo: PCA

Maximum Size Aggregate

- 1/5 WALL THICKNESS (unreinforced)
- 3/4 MINIMUM CLEAR SPACE (rebar/forms)
- 1/3 SLAB THICKNESS

Gap Grading vs. Uniform Gradation

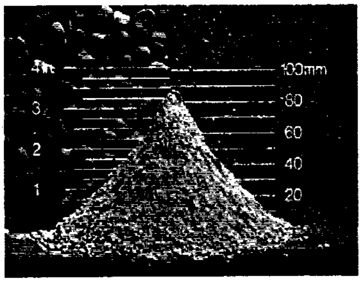


Photo: PCA

Chemical Admixtures

- **DEFINITION: Admixtures are any ingredients in concrete other than:**

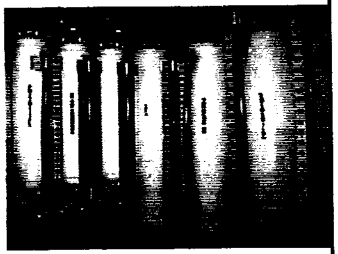
  Water
  Aggregates
  Cement &
  Fiber Reinforcement

- **Added to the batch immediately before or during mixing**

(ACI 116.R-2)

Chemical Admixtures

- **Dosed volumetrically**
- **What does oz/cwt mean?**
- **Storage and handling**
- **Quality control**



PCA photo

Why Use Admixtures?

To modify fresh concrete properties:

- decrease water content
- increase workability
- retard or accelerate setting time
- reduce segregation
- reduce the rate of slump loss
- improve pumpability, placeability, finishability
- modify the rate and/or capacity for bleeding

Why Use Admixtures?

To modify hardened concrete properties

- improve impact and abrasion resistance
- inhibit corrosion of embedded metals
- reduce plastic shrinkage cracking
- reduce long term drying shrinkage
- produce colored concrete
- produce cellular concrete

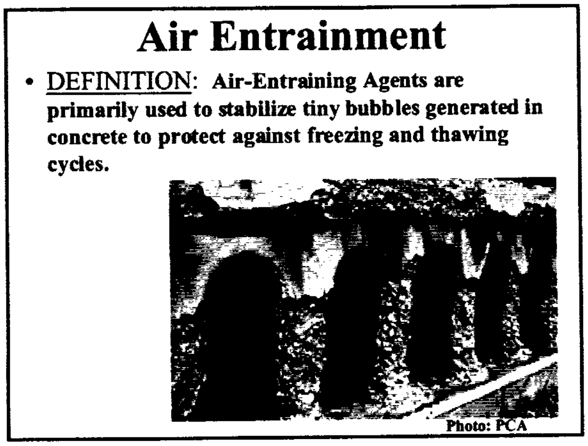
Current Admixture Standards

- **Air Entraining ASTM C 260**
- **Chemical ASTM C 494**
- Calcium chloride ASTM D 98
- Foaming agents ASTM C 869
- Admixtures for shotcrete ASTM C 1141
- Pigments ASTM C 979
- Others…

ASTM C 494 Chemical Admixtures

- Type A - Water-reducing admixtures
- Type B - Retarding admixtures
- Type C - Accelerating admixtures
- Type D - Water-reducing and retarding
- Type E - Water-reducing and accelerating
- Type F - High range water reducing
- Type G - HRWR and retarding

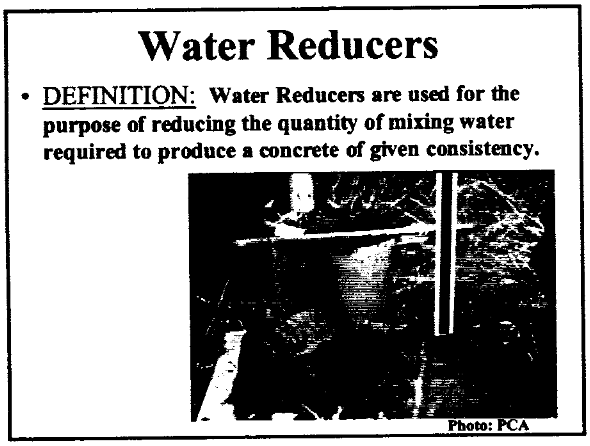
Note -- Mid-range water reducers (MRWR) not yet approved by ASTM, yet they're used more than any other water reducer!!



Air Entrainment

- DEFINITION: **Air-Entraining Agents are primarily used to stabilize tiny bubbles generated in concrete to protect against freezing and thawing cycles.**

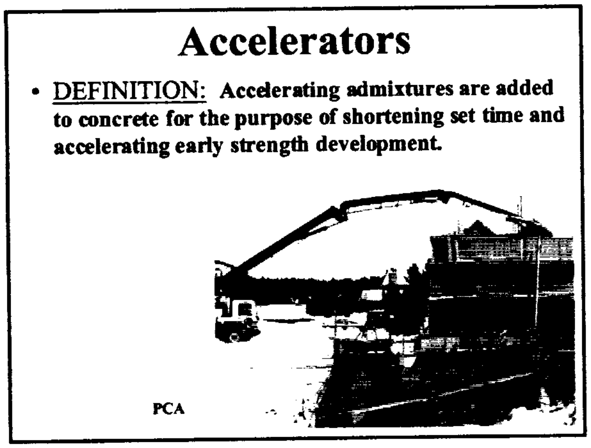
Photo: PCA



Water Reducers

- DEFINITION: **Water Reducers are used for the purpose of reducing the quantity of mixing water required to produce a concrete of given consistency.**

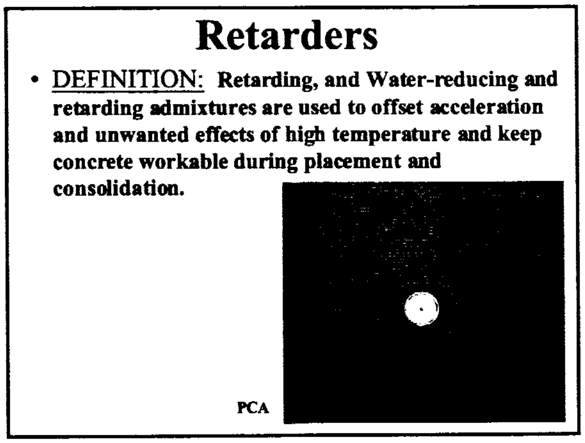
Photo: PCA



Accelerators

- DEFINITION: **Accelerating admixtures are added to concrete for the purpose of shortening set time and accelerating early strength development.**

PCA

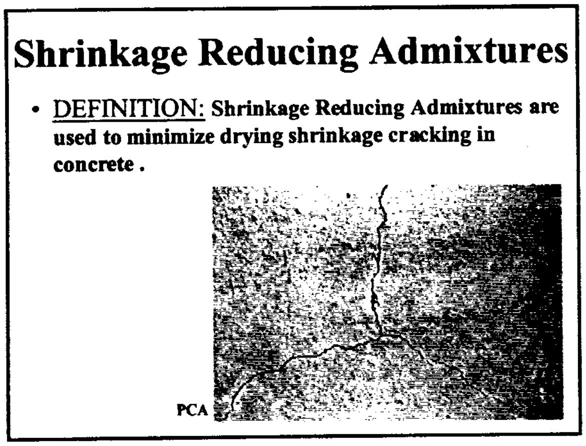


Retarders

- DEFINITION: **Retarding, and Water-reducing and retarding admixtures are used to offset acceleration and unwanted effects of high temperature and keep concrete workable during placement and consolidation.**

PCA

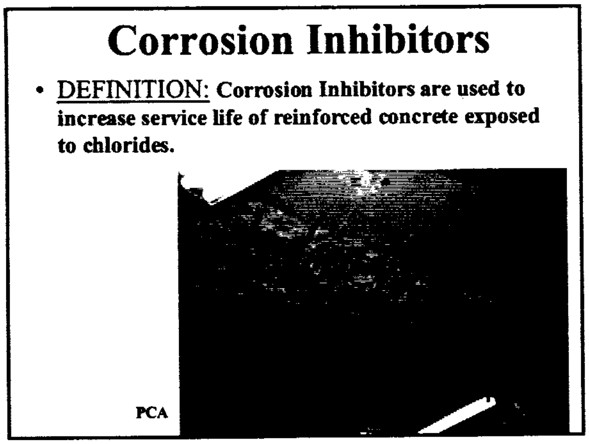
Let's look at some other admixtures that impact durability...



Shrinkage Reducing Admixtures

- DEFINITION: **Shrinkage Reducing Admixtures are used to minimize drying shrinkage cracking in concrete .**

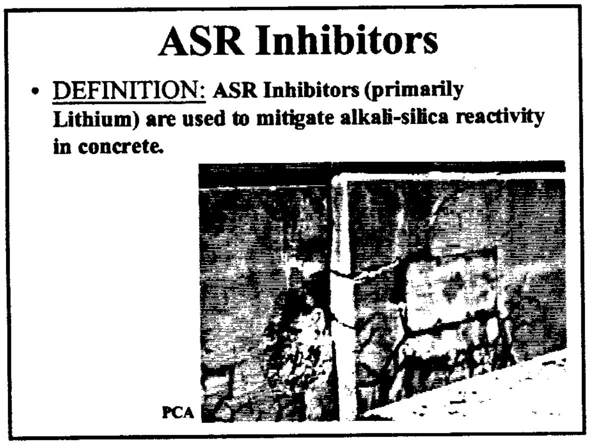
PCA



Corrosion Inhibitors

- DEFINITION: **Corrosion Inhibitors are used to increase service life of reinforced concrete exposed to chlorides.**

PCA



ASR Inhibitors

- DEFINITION: **ASR Inhibitors (primarily Lithium) are used to mitigate alkali-silica reactivity in concrete.**

PCA

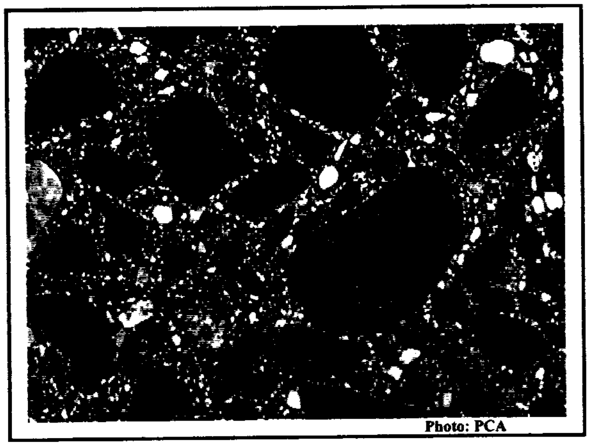


Photo: PCA

Desired Properties of Fresh Concrete

- Consistency
- Workability
- Slump life
- Uniformity
- Finishability
- Bleeding

Photo: PCA

Desired Properties of Hardened Concrete

- Strength
- Dimensional stability
- Appearance
- Economy
- **Durability (Permeability is the KEY!!!)**

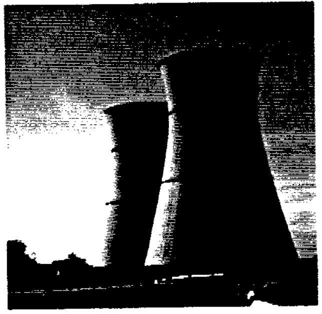
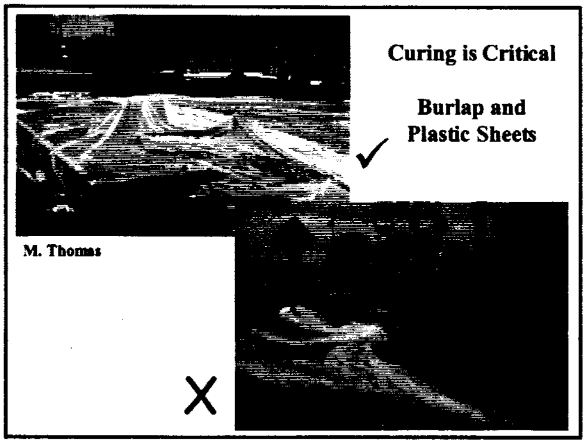


Photo: PCA

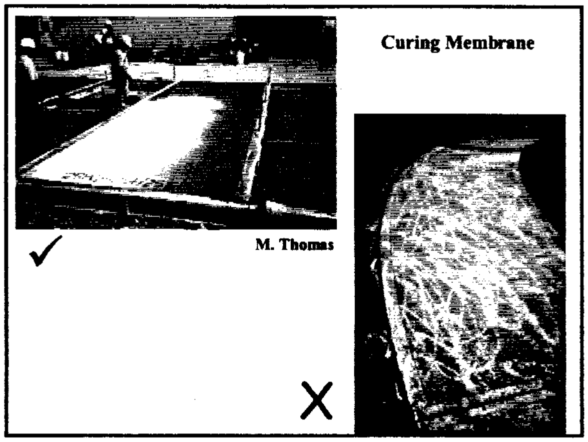
Understanding concrete doesn't mean things always get done right...



Curing is Critical

Burlap and Plastic Sheets

M. Thomas



Curing Membrane

M. Thomas

Conclusions

- Concrete is complex material – knowledge of its composition and properties is critical!!
- Understanding the fundamentals of concrete is essential to understanding how to ensure long-term durability.... Stay tuned for details.

TxDOT Workshop

Design of Durable Concrete

Session 3: Alkali-Silica Reaction

CONCRETE DURABILITY CENTER (CDC)

Presentation Outline

- **Definitions**
- **Background and History**
- **Mechanisms of ASR**
- **Contributing Factors**
- **Mitigating ASR**

Alkali-Aggregate Reaction - AAR

Alkali-Aggregate Reaction – AAR

… chemical reaction in either mortar or concrete between alkalies (sodium and potassium) from portland cement or other sources and certain constituents of some aggregates; under certain conditions, deleterious expansion of concrete may result

ACI 116

Alkali-Aggregate Reaction - AAR

Alkali-Aggregate Reaction (AAR)
- **Alkali-Carbonate Reaction (ACR)**
- **Alkali-Silica Reaction (ASR)**

Alkali-Carbonate Reaction - ACR

Alkali-Carbonate Reaction – ACR

… the reaction between the alkalies (sodium and potassium) in portland cement and certain carbonate rocks, particularly calcitic dolomite and dolomitic limestones, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

ACI 116

Alkali-Silica Reaction - ASR

Alkali-Silica Reaction – ASR

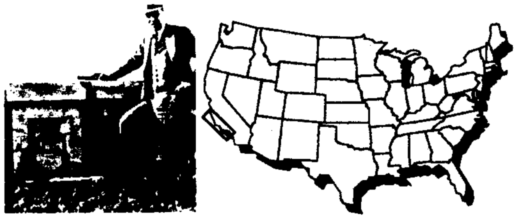
… the reaction between the alkalies (sodium and potassium) in portland cement and certain siliceous rocks or minerals such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service.

ACI 116

Alkali-Silica Reaction - ASR

- This workshop will only deal with ASR
- ACR occurs relatively infrequently and is restricted to a few isolated locations
- ACR can result in serious deterioration of the concrete
- Methods of mitigation for ASR generally **NOT** suitable for controlling ACR
- Must avoid the reactive phases – e.g. by selective quarrying

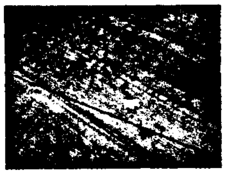
History of ASR

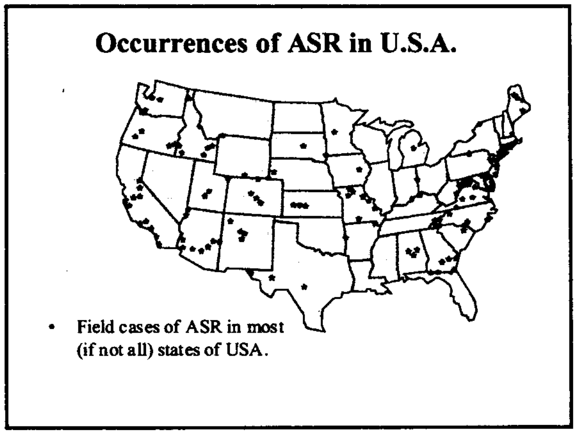


- First discovered in the late 1930s
- In Monterey County and Los Angeles County
- Thomas Stanton of California State Division of Highways

History of ASR

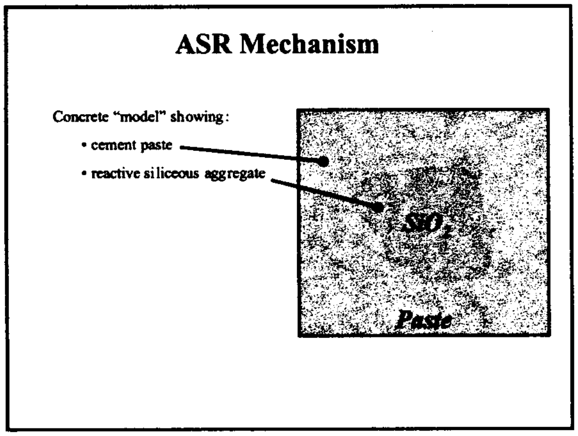
ASR affects all types of structures and has been implicated as a main or contributory cause of distress in thousands of concrete structures in North America.





Occurrences of ASR in U.S.A.

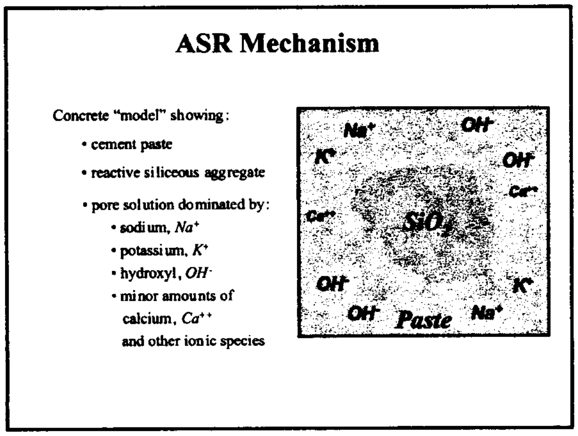
- Field cases of ASR in most (if not all) states of USA.



ASR Mechanism

Concrete "model" showing:

- cement paste
- reactive siliceous aggregate



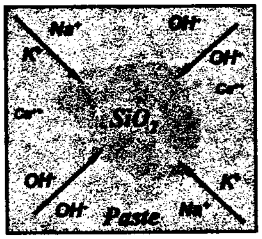
ASR Mechanism

Concrete "model" showing:

- cement paste
- reactive siliceous aggregate
- pore solution dominated by:
  - sodium, Na^+
  - potassium, K^+
  - hydroxyl, OH^-
  - minor amounts of calcium, Ca^{++} and other ionic species

ASR Mechanism

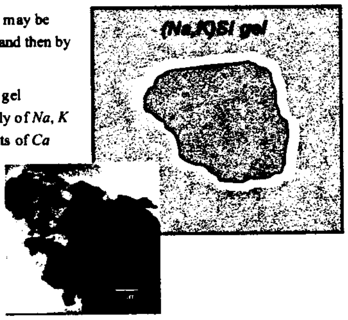
If the silica is reactive it may be "attacked" first by OH^- and then by Na^+ and K^+ ions



ASR Mechanism

If the silica is reactive it may be "attacked" first by OH^- and then by Na^+ and K^+ ions -

forming an alkali-silica gel composed predominantly of *Na*, *K* & *Si* with minor amounts of *Ca*



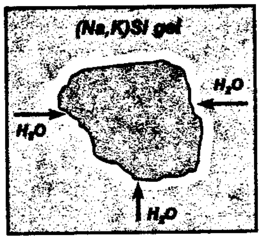
X-ray image showing ASR gel formation

ASR Mechanism

If the silica is reactive it may be "attacked" first by OH^- and then by Na^+ and K^+ ions -

forming an alkali-silica gel composed predominantly of *Na*, *K* & *Si* with minor amounts of *Ca*

The gel absorbs water from the surrounding cement paste and ...



ASR Mechanism

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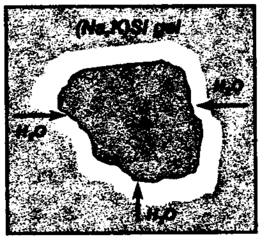
forming an alkali-silica gel composed predominantly of *Na*, *K* & *Si* with minor amounts of *Ca*

The gel absorbs water from the surrounding cement paste and expands ...



ASR Mechanism

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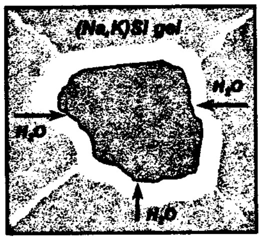
The gel absorbs water from the surrounding cement paste and expands – causing internal stresses and eventually leading to cracking



ASR Mechanism

If the silica is reactive it may be "attacked" first by OH^- and then by Na^+ and K^+ ions -

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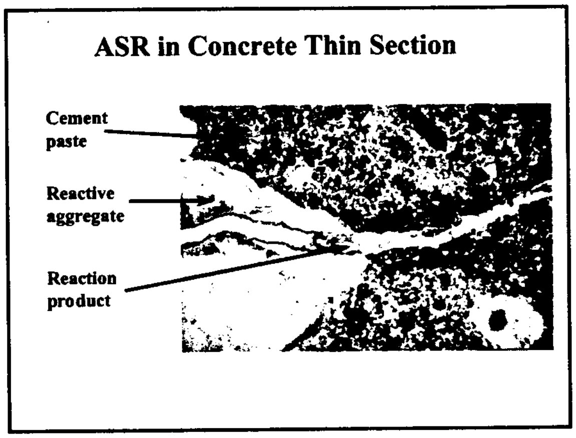
The gel absorbs water from the surrounding cement paste and expands – causing internal stresses and eventually leading to cracking

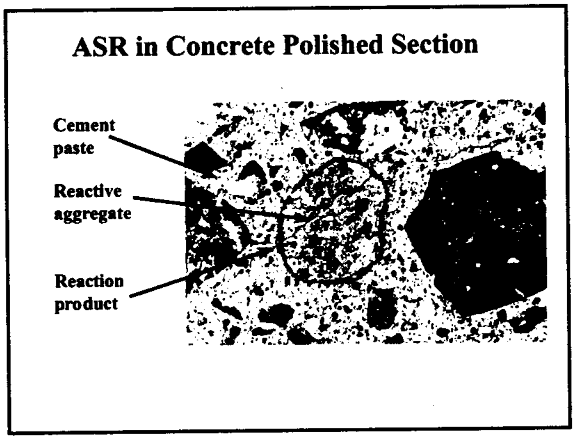


ASR in Concrete Thin Section

Cement paste

Reactive aggregate

Reaction product

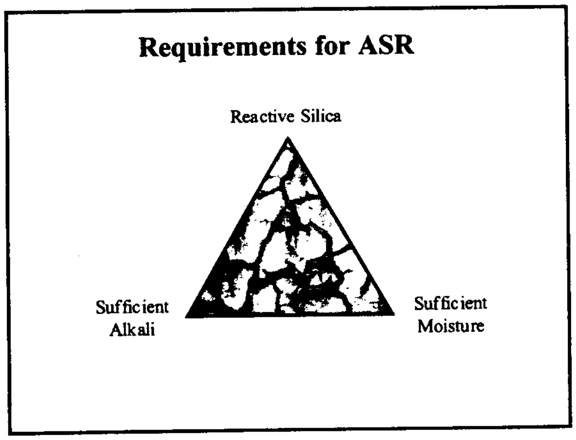


ASR in Concrete Polished Section

Cement paste

Reactive aggregate

Reaction product



Requirements for ASR

Reactive Silica

Sufficient Alkali

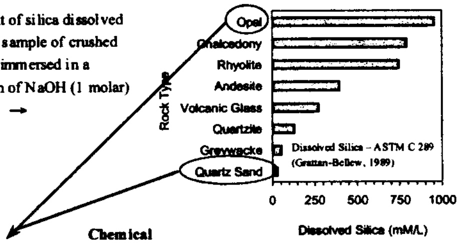
Sufficient Moisture

Rocks and Minerals

Rocks	**Reactive Minerals**
Shale	Opal
Sandstone	Tridymite
Limestone	Cristobalite
Chert	Volcanic glass
Flint	Cryptocrystalline (or microcrystalline) quartz
Quartzite	Strained quartz
Quartz-arenite	
Gneiss	
Argillite	
Granite	
Greywacke	
Siltstone	
Arenite	
Arkose	
Hornfels	

Rocks and Minerals

Amount of silica dissolved when a sample of crushed rock is immersed in a solution of NaOH (1 molar) at 80°C →



Dissolved Silica – ASTM C 289 (Grattan-Bellew, 1989)

Mineral		**Chemical composition**
Opal	→	SiO_2
Quartz		SiO_2

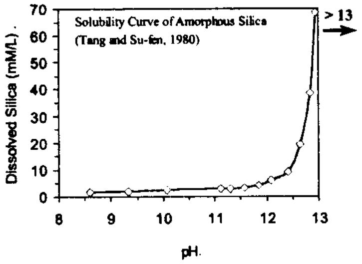
Not all siliceous minerals react to a significant degree in concrete.

In fact, most siliceous aggregates do NOT cause deleterious reaction.

Role of pH

Effect of the pH of the alkali solution on the solubility of amorphous silica →

pH of Concrete



Solubility Curve of Amorphous Silica (Tang and Su-fen, 1980)

Sources of Alkali in Concrete

- **Portland cement**
- Other cementing materials
  - Fly ash
  - Slag
  - Silica fume
- Chemical admixtures
- Wash water (if used)
- Aggregates
- External sources
  - Seawater
  - Deicing chemicals

Alkalies in Portland Cement

Typical Oxide Analysis

Oxide	%
SiO_2	20.55
Al_2O_3	5.07
Fe_2O_3	3.10
CaO	64.51
MgO	1.53
K_2O	0.73
Na_2O	0.15
SO_3	2.53
LOI	1.58

+ other trace elements

Alkalis (sodium & potassium) represent a small proportion of the cement

$$K_2O + H_2O \rightarrow 2K^+ + 2OH^-$$

$$Na_2O + H_2O \rightarrow 2Na^+ + 2OH^-$$

Most of the alkalies end up in the pore solution and the associated OH concentration is sufficient to produce a pH in the range of 13.2 to 14.0

Alkalies in Portland Cement

Typical Oxide Analysis

Oxide	%
SiO_2	20.55
Al_2O_3	5.07
Fe_2O_3	3.10
CaO	64.51
MgO	1.53
K_2O	0.73
Na_2O	0.15
SO_3	2.53
LOI	1.58

+ other trace elements

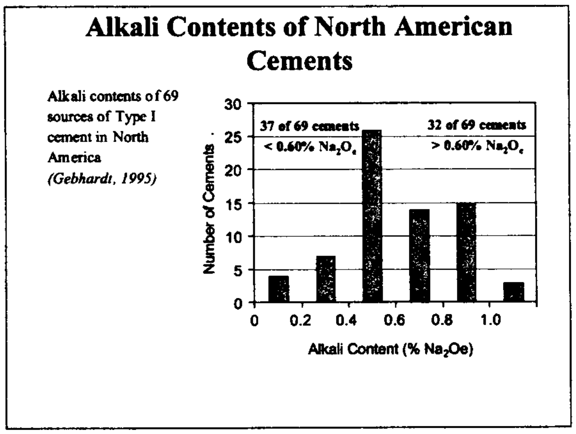
Alkali Equivalent or "Equivalent Soda"

- K_2O converted to an "equivalent" content of Na_2O
- Based on respective molecular weights of sodium and potassium oxide
- Total sodium oxide equivalent is often written as Na_2O_e
- Calculated as follows:

$$\boxed{Na_2O_e = Na_2O + 0.658\ K_2O}$$

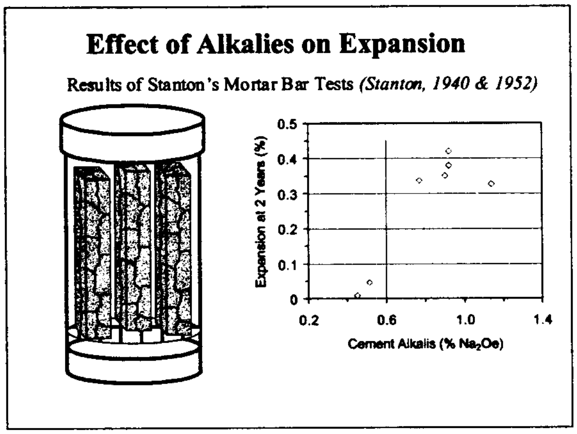
For the analysis shown the equivalent soda is:

$$\boxed{0.15 + 0.658 \times 0.73 = 0.63\ \%\ Na_2O_e}$$



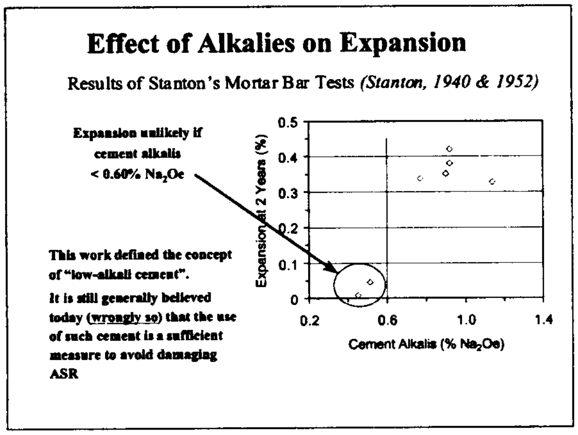
Alkali Contents of North American Cements

Alkali contents of 69 sources of Type I cement in North America *(Gebhardt, 1995)*



Effect of Alkalies on Expansion

Results of Stanton's Mortar Bar Tests *(Stanton, 1940 & 1952)*



Effect of Alkalies on Expansion

Results of Stanton's Mortar Bar Tests *(Stanton, 1940 & 1952)*

Expansion unlikely if cement alkalis < 0.60% Na_2Oe

This work defined the concept of "low-alkali cement".

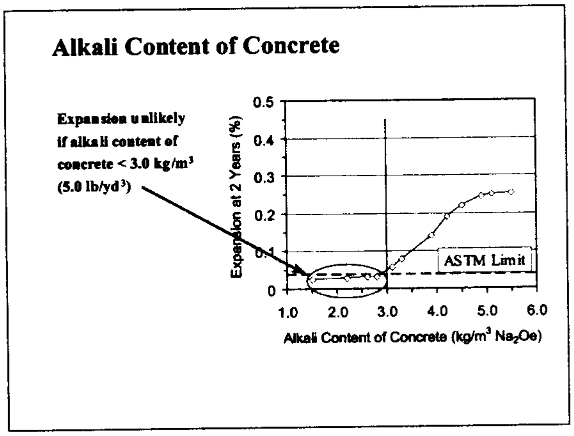
It is still generally believed today (wrongly so) that the use of such cement is a sufficient measure to avoid damaging ASR

Alkali Content of Concrete

It is now fairly well established that it is the alkali content in the concrete and not just the alkali content of the cement that influences the risk of damaging reaction for a particular aggregate. The concrete alkali content is calculated as follows:

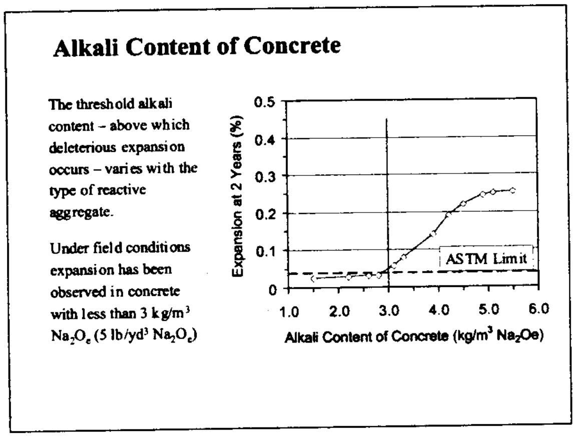
$$\underset{\text{kg/m}^3\ \text{Na}_2\text{Oe}}{\textbf{Concrete alkali content}} = \underset{\text{kg/m}^3}{\textbf{Cement content}} \times \underset{\%\ \text{Na}_2\text{Oe}}{\textbf{Cement alkalis}} \times \frac{1}{100}$$

$$\underset{\text{lb/yd}^3\ \text{Na}_2\text{Oe}}{\textbf{Concrete alkali content}} = \underset{\text{lb/yd}^3}{\textbf{Cement content}} \times \underset{\%\ \text{Na}_2\text{Oe}}{\textbf{Cement alkalis}} \times \frac{1}{100}$$



Alkali Content of Concrete

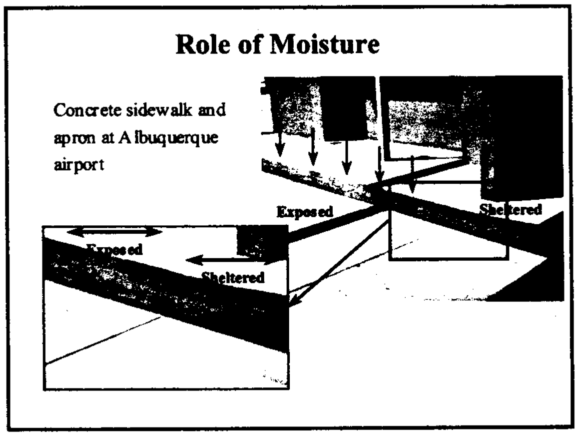
Expansion unlikely if alkali content of concrete < 3.0 kg/m³ (5.0 lb/yd³)



Alkali Content of Concrete

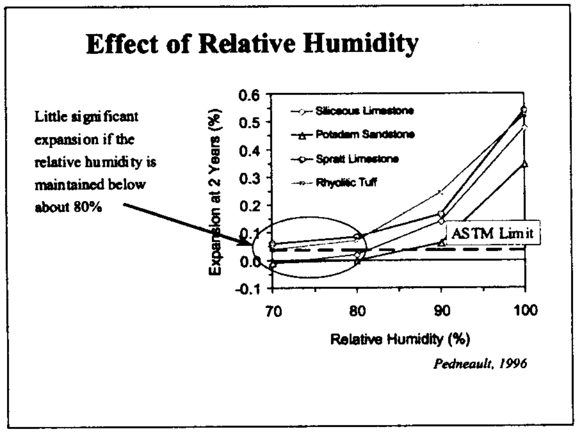
The threshold alkali content – above which deleterious expansion occurs – varies with the type of reactive aggregate.

Under field conditions expansion has been observed in concrete with less than 3 kg/m³ Na_2O_e (5 lb/yd³ Na_2O_e)



Role of Moisture

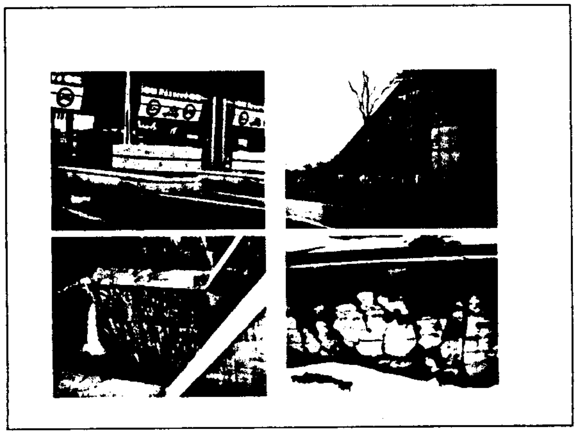
Concrete sidewalk and apron at Albuquerque airport

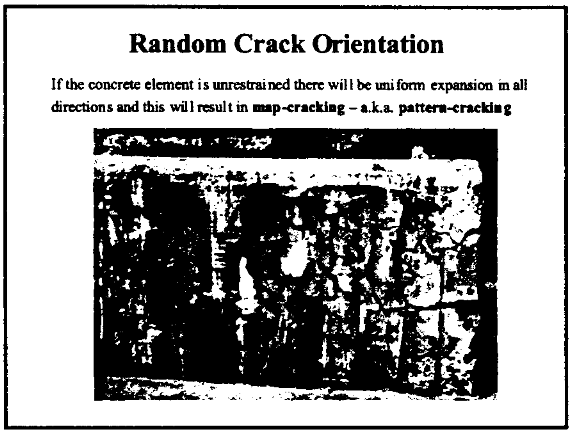


Effect of Relative Humidity

Little significant expansion if the relative humidity is maintained below about 80%

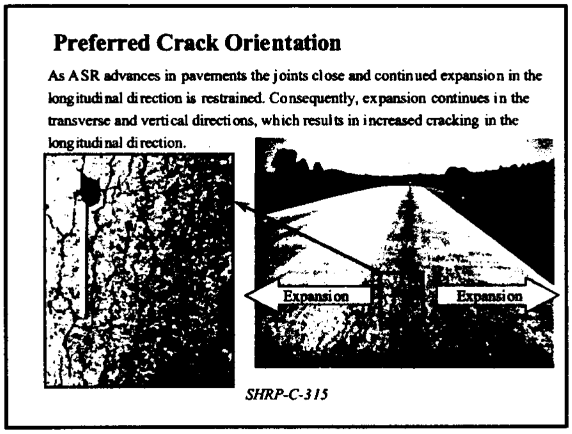
Pedneault, 1996





Random Crack Orientation

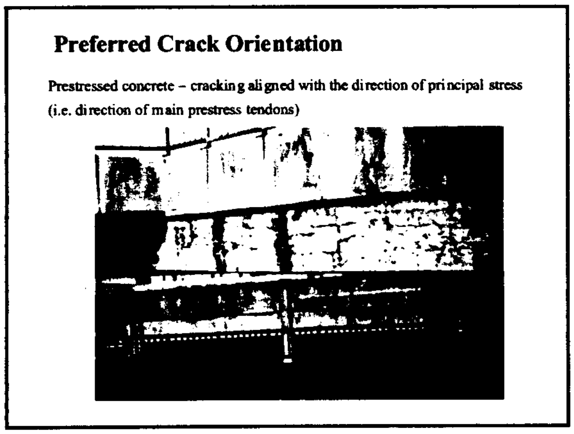
If the concrete element is unrestrained there will be uniform expansion in all directions and this will result in **map-cracking** – a.k.a. **pattern-cracking**



Preferred Crack Orientation

As ASR advances in pavements the joints close and continued expansion in the longitudinal direction is restrained. Consequently, expansion continues in the transverse and vertical directions, which results in increased cracking in the longitudinal direction.

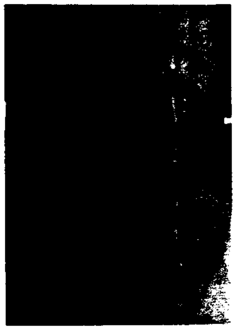
SHRP-C-315



Preferred Crack Orientation

Prestressed concrete – cracking aligned with the direction of principal stress (i.e. direction of main prestress tendons)

Preferred Crack Orientation



Prominent crack direction in reinforced columns is vertical

SHRP-C-315

Minimizing the Risk of ASR

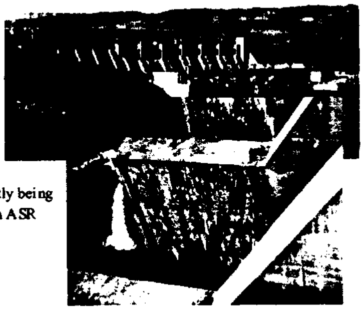
Methods for Minimizing the Risk of Expansion in Concrete Due to Alkali-Silica Reaction

- Use a non-reactive aggregate
- Limit the alkali content of the concrete
- Use supplementary cementing materials (SCM)
    - Fly Ash
    - Slag
    - Silica Fume
    - Natural Pozzolan
- Use chemical admixtures

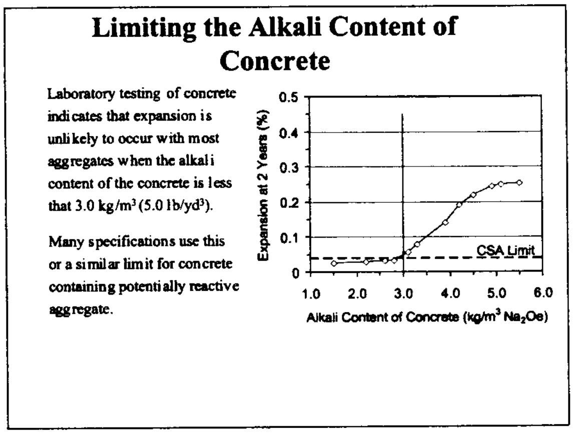
Using "Non-Reactive" Aggregate

Mactaquac Dam, NB

Aggregate passed criteria for "non-reactivity" that existed at the time of construction



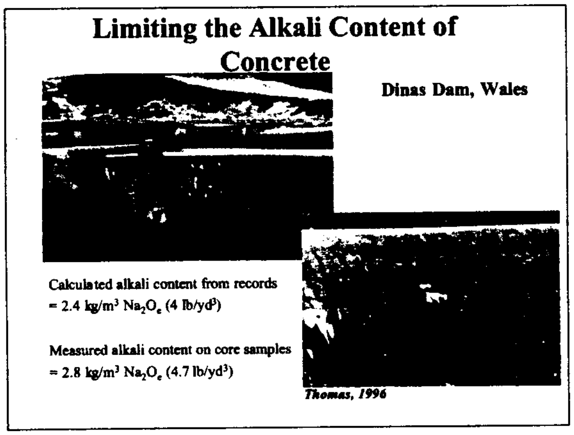
Millions of $$$s currently being spent trying to deal with ASR problems



Limiting the Alkali Content of Concrete

Laboratory testing of concrete indicates that expansion is unlikely to occur with most aggregates when the alkali content of the concrete is less that 3.0 kg/m^3 (5.0 lb/yd^3).

Many specifications use this or a similar limit for concrete containing potentially reactive aggregate.



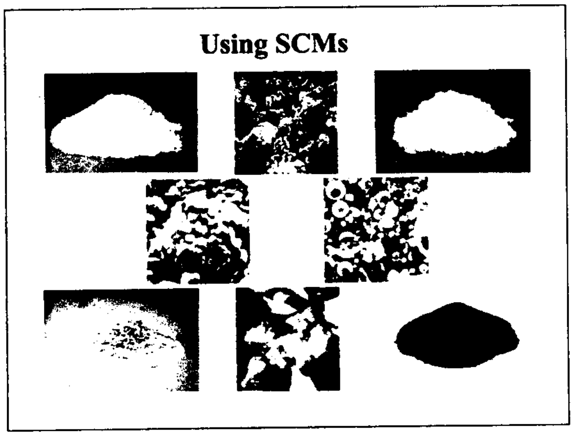
Limiting the Alkali Content of Concrete

Dinas Dam, Wales

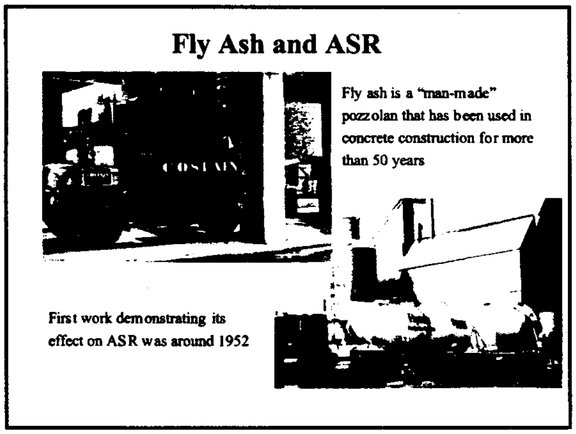
Calculated alkali content from records = 2.4 kg/m^3 Na_2O_e (4 lb/yd^3)

Measured alkali content on core samples = 2.8 kg/m^3 Na_2O_e (4.7 lb/yd^3)

Thomas, 1996



Using SCMs



Fly Ash and ASR

Fly ash is a "man-made" pozzolan that has been used in concrete construction for more than 50 years

First work demonstrating its effect on ASR was around 1952

Fly Ash and ASR

There are hundreds of publications on fly ash and ASR; and these show that the effect of fly ash depends on:

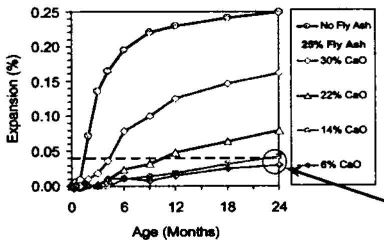
- Amount of fly ash used
- Fly ash composition
- Nature of reactive aggregate
- Amount of alkali present in the concrete (e.g. from cement)

Fly Ash and ASR

ASTM C 618 Classification

Class F	Normally from bituminous and anthracite coal	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$
Class C	Normally from sub-bituminous and lignite coal	$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 50\%$

Fly Ash and ASR



ASTM C 1293

- **Siliceous limestone**
- **1.25% Na_2O_e**
- **38°C and 100% RH**

Expansion limit of 0.04% at 2 years used by a number of agencies

Low calcium fly ash is generally more efficient in controlling expansion than high calcium fly ash

Shehata and Thomas, 2000

Fly Ash and ASR

Typically the amount of fly ash required to control ASR increases as:

- Calcium content of the fly ash increases
- Alkali content of the fly ash increases
- Reactivity of the aggregate increases
- Amount of available alkali in the concrete increases

Slag and ASR

Ground granulated blast-furnace slag (GGBFS) is a by-product of the iron-making industry.

Commonly known as slag or slag cement

Used in concrete for > 100 years

First work demonstrating its effect on ASR was around 1952

Slag and ASR

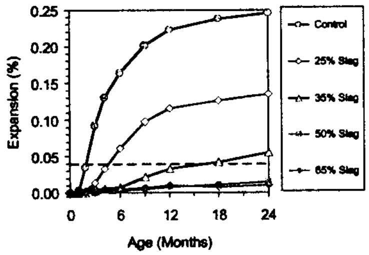
There are hundreds of publications on slag and ASR; and these show that the effect of slag depends on:

- Amount of slag used
- Nature of reactive aggregate
- Amount of alkali present in the concrete (e.g. from cement)

Slag and ASR

ASTM C 1293

- Siliceous limestone
- 1.25% Na_2O_e
- 38°C and 100% RH

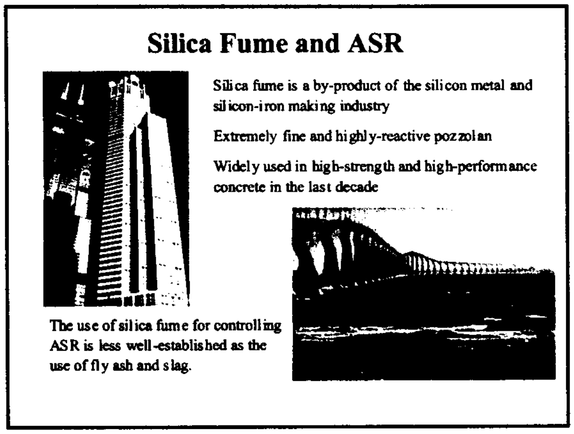


Thomas and Innis, 1998

Slag and ASR

Typically the amount of slag required to control ASR increases as:

- Reactivity of the aggregate increases
- Amount of available alkali in the concrete increases



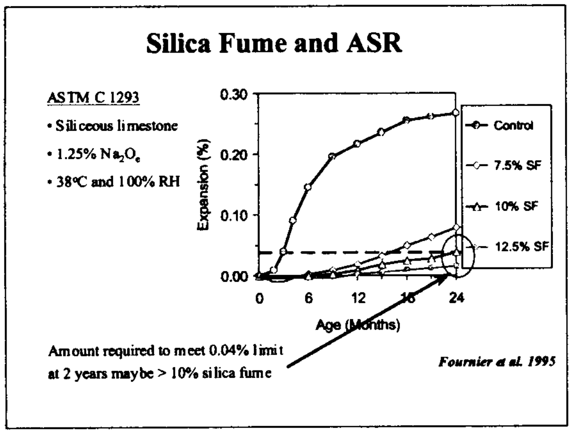
Silica Fume and ASR

Silica fume is a by-product of the silicon metal and silicon-iron making industry

Extremely fine and highly-reactive pozzolan

Widely used in high-strength and high-performance concrete in the last decade

The use of silica fume for controlling ASR is less well-established as the use of fly ash and slag.



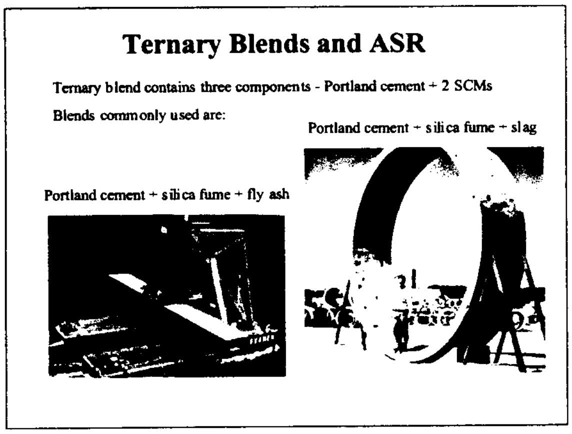
Silica Fume and ASR

ASTM C 1293

- Siliceous limestone
- 1.25% Na_2O_e
- 38°C and 100% RH

Amount required to meet 0.04% limit at 2 years maybe > 10% silica fume

Fournier et al. 1995



Ternary Blends and ASR

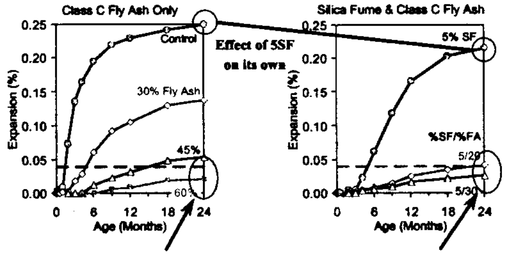
Ternary blend contains three components - Portland cement + 2 SCMs

Blends commonly used are:

Portland cement + silica fume + fly ash

Portland cement + silica fume + slag

Silica Fume and Class C Fly Ash



50% or more Class C fly ash required with highly-reactive aggregate

Practical levels of silica fume and Class C fly ash work together well to control expansion ***Shehata and Thomas, 2002***

Lithium compounds

Lithium compounds can be used to prevent ASR-induced damage in new concrete and to treat existing structures suffering from ASR.

Lithium does not prevent gel from forming, but rather renders gel non-expansive.

Effectiveness depends on materials and aggregate reactivity. Cost may be an issue for new concrete.

Commonly Used ASR Test Methods

- **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)

Aggregate 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 Reactivity of Aggregates (Mortar-Bar Method)

Mortar Tests

Recommended Tests

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

Concrete Test

ASR Specifications

Two main approaches to specifications:

1. ***Prescriptive*** **specifications**
2. ***Performance-based*** **specifications**

Some agencies or organizations use a combination of these two approaches for ASR specifications

Prescriptive Specifications

An Example:

If a reactive aggregate is to be used, one of the following options shall be adopted:

- Limit concrete alkali content ≤ 4 lbs/yd^3 Na_2O_e
- Use a minimum of 50% slag
- Use a minimum of 20% Class F fly ash
- Use a minimum of 10% silica fume
- Use a minimum of 15% metakaolin
- Use a combination of a minimum of 5% silica fume and 30% Class C fly ash
- Use a 30% lithium nitrate solution at a dosage of 4.6 liters of $LiNO_3$ solution per 1 kg or Na_2O_e (based on cement alkalinity)

Performance-based Specifications

An Example:

Use an aggregate that passes either ASTM C 1260 or ASTM C 1293.

If the aggregate to be used does not pass these tests, then it may still be used in combination with fly ash, slag, silica fume, natural pozzolan, or any blend of these SCM's provided that the combination of SCM's and aggregate passes a modified version of either ASTM C 1260 or ASTM C 1293.

Alternatively, the aggregate can be used with lithium nitrate (with or without SCM's), provided the combination of materials passes ASTM C 1293.

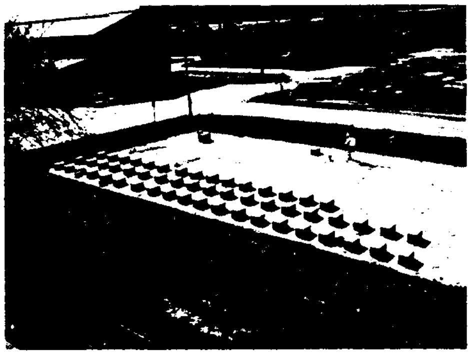
ASR Research at UT

TxDOT Project 0-4085

A Snapshot...

- 4.5-year project (March 2000-August 2004)
- Surveying the state-of-the-art
- Assessing new or modified test methods
- Assessing mitigation options under new specifications
- Assessing relationships between ASR and DEF
- Outdoor exposure site developed to link lab and field
- Mechanistic studies (particular focus on Class C fly ash due to importance in TX)
- "Showcase bridge" for all-in-one ASR shopping

Outdoor Exposure Site at UT



Showcase Bridge Structure

- 12-span bridge near Houston
- "All-in-one-shopping" - all mitigation options on one bridge
- Using highly reactive TX aggregate
- Separate control structure near bridge site
- Long-term monitoring program
- Compare laboratory, exposure site, and bridge performance

Conclusions

- ASR is a reaction between the alkalis from portland cement (and other sources) and certain siliceous minerals in some aggregates.
- Under certain conditions the reaction can result in expansion and cracking of concrete.
- The risk of expansion and damage can be minimized by:
  - ➢ Avoiding reactive aggregates
  - ➢ Controlling the alkali content of the concrete
  - ➢ Appropriate use of SCMs
  - ➢ Use of chemical admixtures (e.g. lithium)

Ø Through appropriate test methods and specifications, ASR can be controlled – STAY TUNED FOR DETAILS…

TxDOT Workshop

Design of Durable Concrete

Session 5: Freezing and Thawing

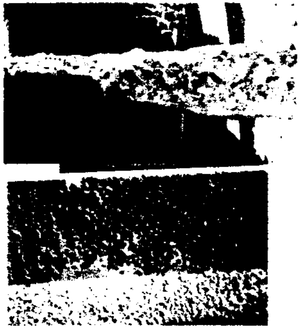
CONCRETE DURABILITY CENTER (CDC)

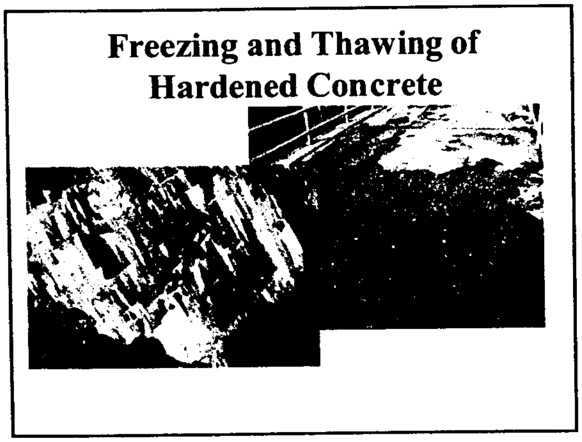
Outline of Presentation

- History and Background
- Freezing and Thawing of Hardened Concrete
- Factors Affecting Frost Resistance of Concrete
- Salt Scaling
- Practical Considerations

Two Common Types of Distress

- Internal Damage - Hydraulic Pressure
- External Damage - Scaling (Hydraulic & Osmotic Pressures)

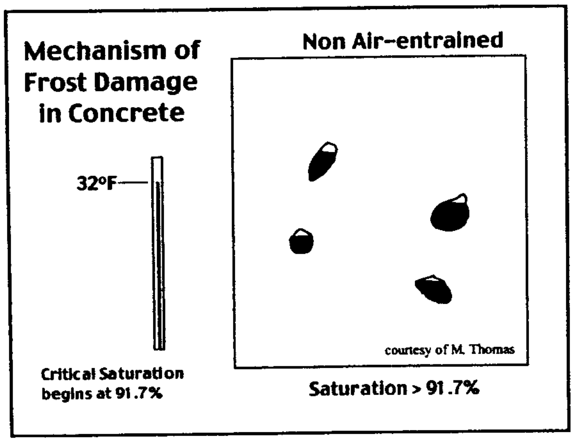




Freezing and Thawing of Hardened Concrete

Mechanisms of Freezing and Thawing Damage

- T.C. Powers and his coworkers first to study freezing-and-thawing problems
- Concept of spacing factor proposed by Powers
- Two mechanisms usually cited:
  - Hydraulic pressure & osmotic pressure
- More complex models available related to ice formation and water migration



Mechanism of Frost Damage in Concrete

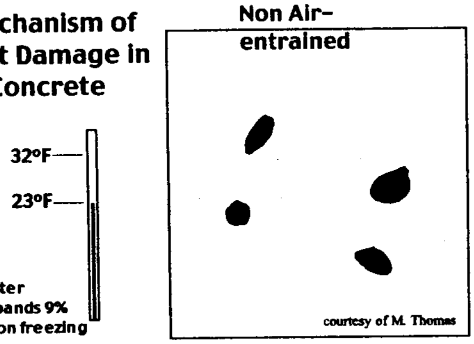
Non Air-entrained

courtesy of M. Thomas

Critical Saturation begins at 91.7%

Saturation > 91.7%

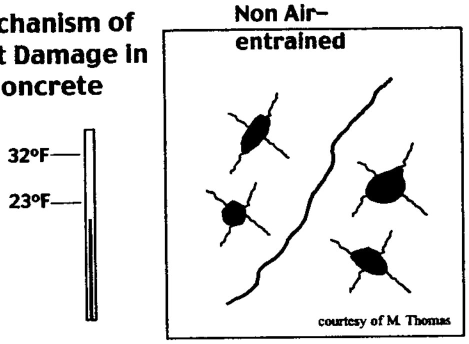
Mechanism of Frost Damage in Concrete



Water Expands 9% Upon freezing

Saturation > 91.7%

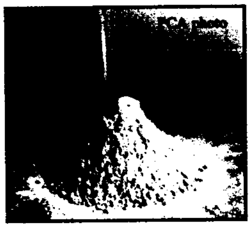
Mechanism of Frost Damage in Concrete

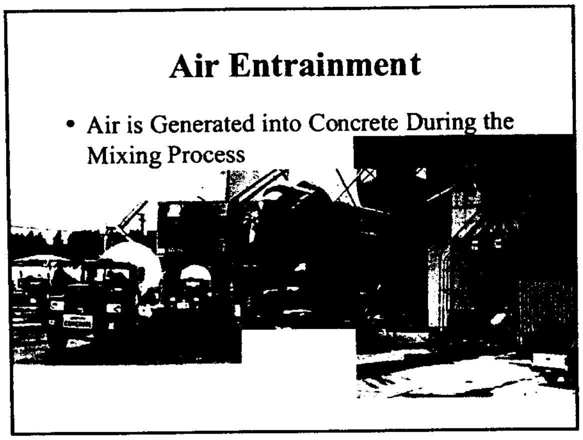


Saturation > 91.7%

History

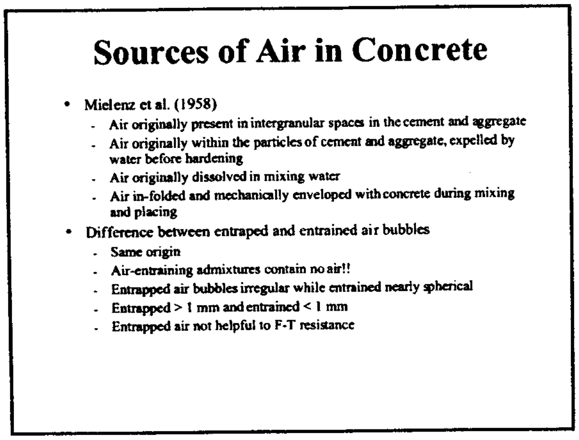
- Freezing-and-Thawing damage unsolved until air-entrainment was discovered accidentally in the 1930's
- Several pavements in New York had survived severe freeze-thaw exposure
- Cement manufactured with grinding aids - beef tallow





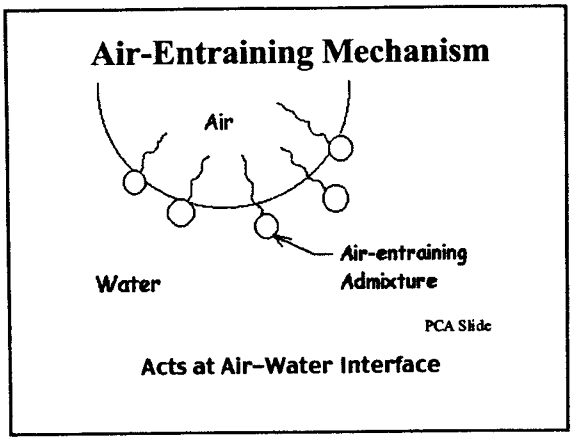
Air Entrainment

- Air is Generated into Concrete During the Mixing Process



Sources of Air in Concrete

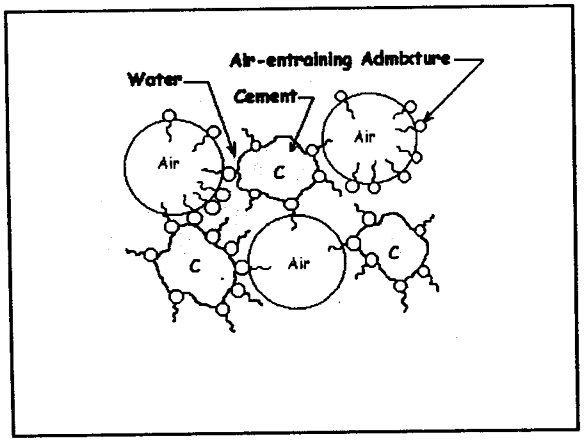
- Mielenz et al. (1958)
  - Air originally present in intergranular spaces in the cement and aggregate
  - Air originally within the particles of cement and aggregate, expelled by water before hardening
  - Air originally dissolved in mixing water
  - Air in-folded and mechanically enveloped with concrete during mixing and placing
- Difference between entraped and entrained air bubbles
  - Same origin
  - Air-entraining admixtures contain no air!!
  - Entrapped air bubbles irregular while entrained nearly spherical
  - Entrapped > 1 mm and entrained < 1 mm
  - Entrapped air not helpful to F-T resistance

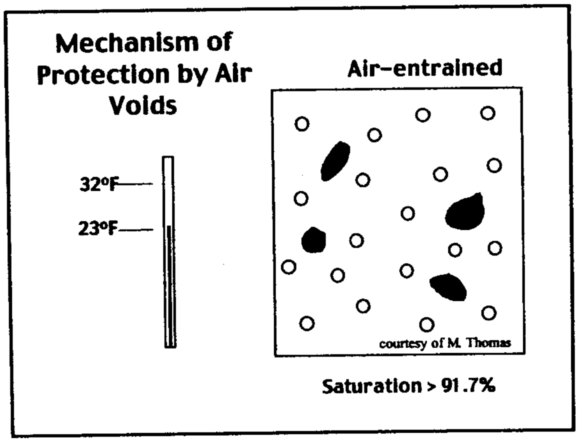


Air-Entraining Mechanism

PCA Slide

Acts at Air-Water Interface



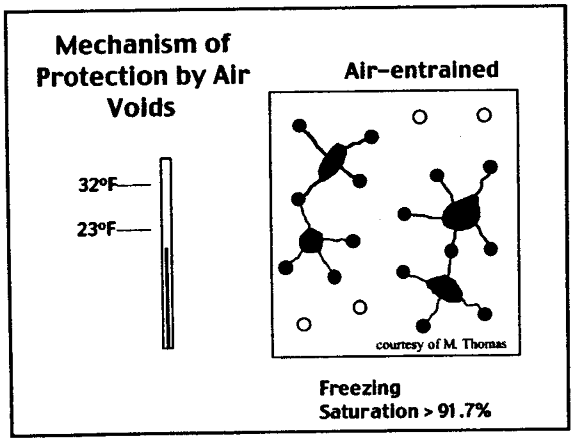


Mechanism of Protection by Air Voids

Air-entrained

courtesy of M. Thomas

Saturation > 91.7%

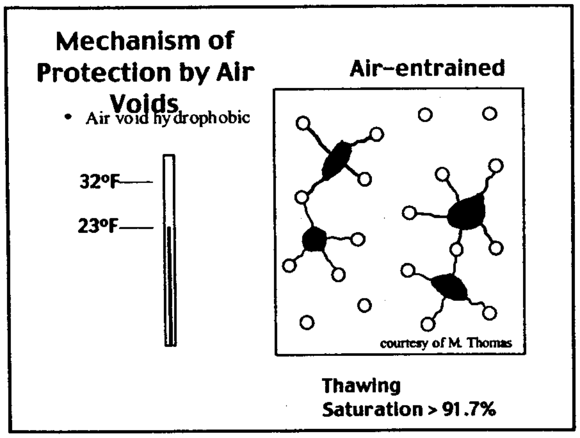


Mechanism of Protection by Air Voids

Air-entrained

courtesy of M. Thomas

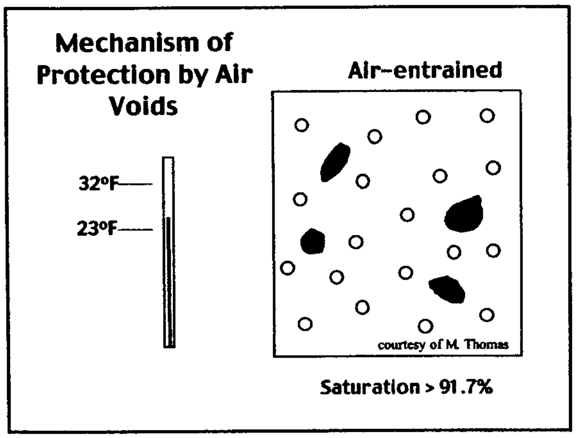
Freezing
Saturation > 91.7%



Mechanism of Protection by Air Voids

- Air void hydrophobic

Thawing
Saturation > 91.7%



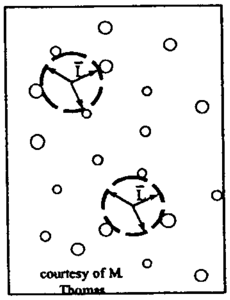
Mechanism of Protection by Air Voids

Saturation > 91.7%

Characteristics of Air System

- Air voids in concrete of various size and most larger than 10 µm
- Size and distribution more important than total volume of entrained air
- Difficult to obtain direct information on air voids system, especially for fresh concrete
- Current techniques on spacing factor and specific surface based on statistics

Air Void Spacing & Volume



courtesy of M. Thomas

- **Spacing factor** ($\bar{L}$): the maximum distance of any point in the the cement paste from the periphery of an air void.
- **Specific surface**: the surface area of a quantity of air voids that have a total volume of 1 in^3 (16 cm^3).

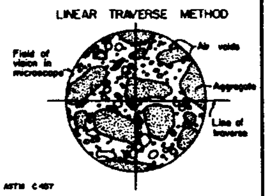
Characteristics of an Adequate Air Void System

ASTM C 457

- Spacing factor $\leq$ 0.008 in (0.203 mm)
- Specific surface $\geq$ 600 in^2/in^3 (24 mm^2/mm^3)
- Voids per linear inch: 1.5 - 2 times the percentage of air

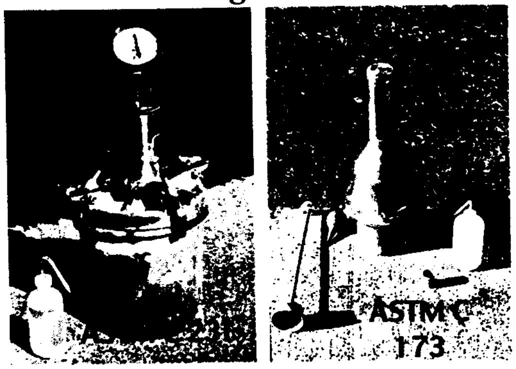
Volume of Air in Concrete

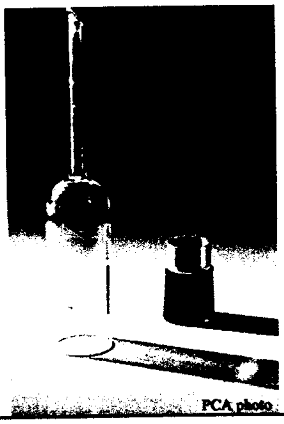
- Only practical to directly measure volume content in fresh concrete
- ASTM C 231 and C 173 for fresh concrete
- Microscope for hardened concrete
- Fresh concrete air void analyzer (?)



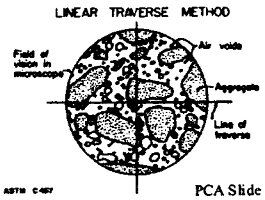
PCA

Measuring Air Content



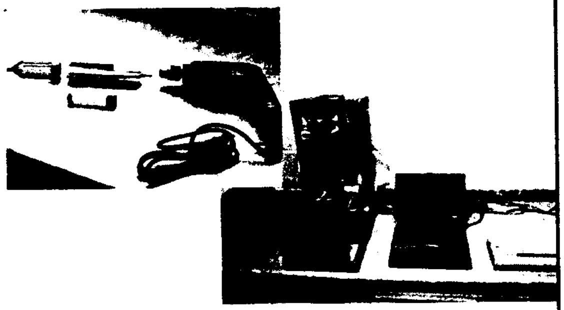


Measuring Air in Hardened Concrete



PCA Slide

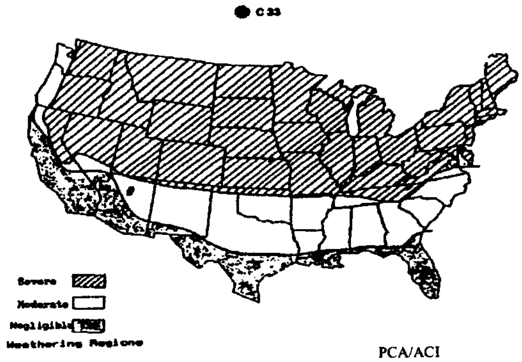
Fresh Concrete Air Void Analyzer



Recommended Air Content

Effective For Durability:

- When volume of air in mortar fraction of concrete is about 9 ± 1% (or about 18% by paste volume).
- Required air increases as coarse aggregate size is reduced (due to greater paste volume)
- Required air increases as exposure conditions become more severe.



PCA/ACI

RECOMMENDED AVERAGE AIR CONTENT PERCENTAGE FOR LEVEL OF EXPOSURE

	Nominal maximum sizes of aggregates					
Exposure	3/8 in. (9.5mm)	1/2 in. (12.5mm)	3/4 in. (19mm)	1 in. (25mm)	1-1/2 in. (37.5mm)	2 in. (50mm)
Mild	4.5	4.0	3.5	3.0	2.5	2.0
Moderate	6.0	5.5	5.0	4.5	4.5	4.0
Severe	7.5	7.0	6.0	6.0	5.5	5.0

Air-Entraining Admixtures

- 4 Categories:
  1. Wood Derived Products: Vinsol® resin, Tall oil, Wood rosin
  2. Synthetic Materials: Alky-aryl sulfonates and sulfates
  3. Vegetable Acids: Coconut fatty acids, Alkanolamine salt
  4. Miscellaneous: Alkali/alkanolamine acid salts, Animal tallows
- Must pass ASTM C 260

Wood Rosin vs. Synthetic

Wood Rosins	Synthetic Materials
• Quick air generation • Minor air gain with initial mixing • Air Loss with prolonged mixing • Mid-sized air bubbles • Compatible with most other admixtures	• Quick air generation • Minor air loss with mixing • Smaller coarser bubbles • May be incompatible with some HRWR.

So All We Need is Air-Entrainment for Frost Resistance..

What Factors Affect Air-Entrainment?

Got an Hour?

Control of Air Content
Materials

- Cement
  - Admixture dosage based on cement content
  - Higher fineness requires higher dosage
  - Alkalies in increase air entrainment
- Supplementary Materials
  - Fly ash, silica fume may increase dosages 2 – 6 times
  - Be careful for unburned carbon in fly ash
- Aggregates
  - Increased sand content helps air entrainment
  - Ultra fines (< #200) harmful
- Admixtures
  - Compatibility should be examined
  - Added separately to mixtures
  - Some supers affect spacing factor

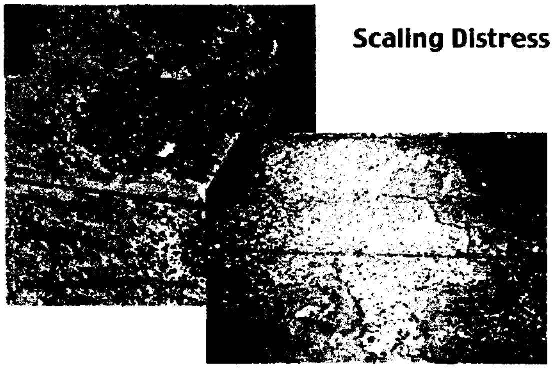
Control of Air Content
Mix Design and Processing

- w/c
- Slump;
  <3-in. (75mm),
  >6-in. (150mm)
- Temperature
- Mixing Speed, Order of Addition, Drum Capacity, etc.

Control of Air Content

Placement

- Transportation
- Placement; Pumping
- Consolidation
- Finishing



Scaling Distress

Mechanism of Salt Scaling Damage

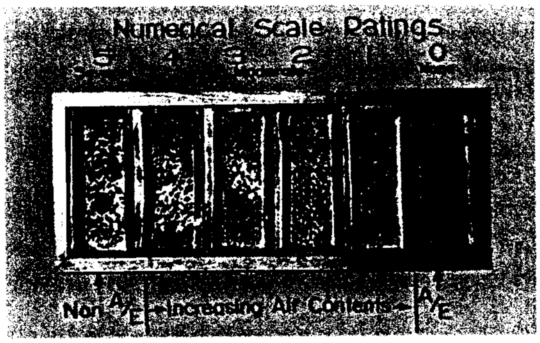
ASTM C 672

- Salt Scaling Test

  4% $CaCl_2$

- 50 Cycles

- **Hydraulic pressures from 9% expansion of water when freezing**
- **Osmotic pressures from differential concentrations of salt (alkali) solutions in paste**
- **Salt lowers freezing point, thereby increasing saturation near surface of concrete**

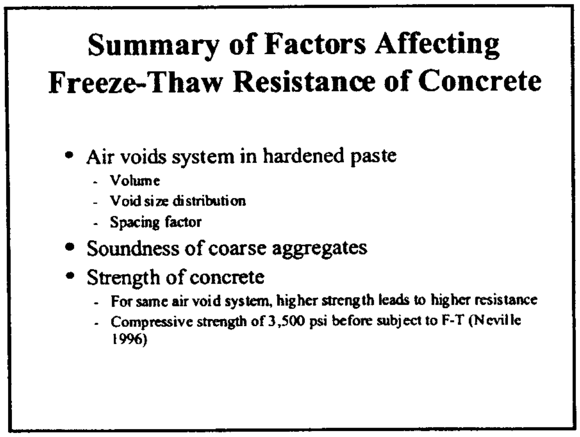


Issues with Salt Scaling

- **ASTM C 672 is very severe and often predicts scaling for mixtures that perform well in the field (especially mixtures with high levels of fly ash and slag)**
- **Some state DOTs limit amount of fly ash or slag to prevent scaling, but is it really a valid concern?**
- **If above is a concern, why would high levels of SCMs adversely affect scaling?**
    - **-Increased level of saturation**
    - **-Increased capillary suction**
    - **-More sensitive to finishing**
- **How do alternative de-icing salts affect scaling?**

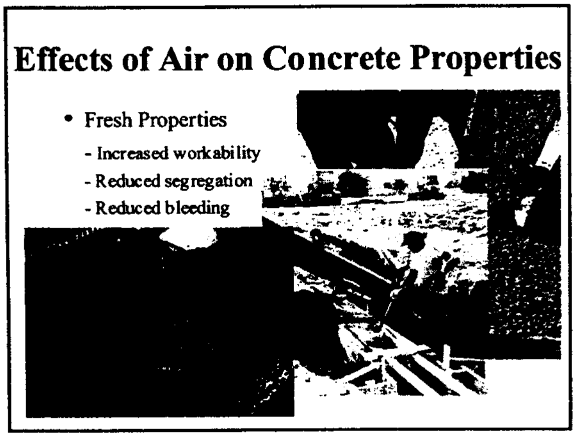
Frost-Susceptible Aggregates

- Unsound Aggregates
    - Porous cherts, shales, some limestones, particularly laminated limestones, and some sandstones
    - High absorption is common characteristic
    - Air entrainment not very effective
- Damage Caused by Unsound Aggregates
    - Critical conditions: water content and lack of drainage (pore system of aggregate)
    - Pores smaller than 4 to 5 μm critical
    - Local scaling (pop-outs) close to surface
    - Extensive scaling
    - D-cracking of free edges of slabs (reduce agg. size)



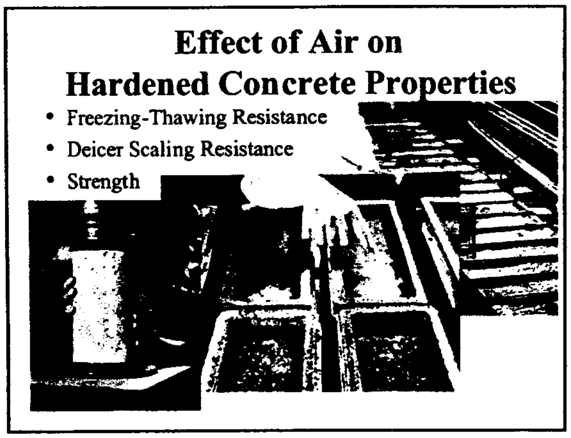
Summary of Factors Affecting Freeze-Thaw Resistance of Concrete

- Air voids system in hardened paste
  - Volume
  - Void size distribution
  - Spacing factor
- Soundness of coarse aggregates
- Strength of concrete
  - For same air void system, higher strength leads to higher resistance
  - Compressive strength of 3,500 psi before subject to F-T (Neville 1996)



Effects of Air on Concrete Properties

- Fresh Properties
  - Increased workability
  - Reduced segregation
  - Reduced bleeding



Effect of Air on Hardened Concrete Properties

- Freezing-Thawing Resistance
- Deicer Scaling Resistance
- Strength

Conclusions

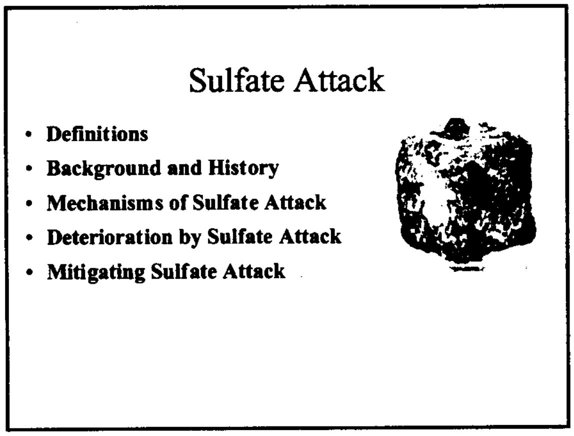
- Freezing and thawing damage can occur both external and internal to concrete
- Air-entrainment is essential to durability
- Aggregates susceptible to D-cracking must be identified and either not used or reduced in size to avoid damage
- Some unanswered questions remain with salt scaling...
- Everything affects air in concrete -- QC/QA is critical

TxDOT Workshop

Design of Durable Concrete

Session 6: Sulfate Attack (including DEF)

CONCRETE DURABILITY CENTER (CDC)



Sulfate Attack

- **Definitions**
- **Background and History**
- **Mechanisms of Sulfate Attack**
- **Deterioration by Sulfate Attack**
- **Mitigating Sulfate Attack**

Sulfate Attack: Definitions and Differentiation

Sulfate attack: Deterioration of concrete through the actions of sulfate salts and/or acids, chemically or physically

- Internal versus External
- Chemical versus Physical

Internal vs External

- Internal Sulfate Attack
  ...source of sulfate is internal to concrete, including excessive cement sulfate and delayed ettingite formation (DEF)
- 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.

Skalny et. al 2002

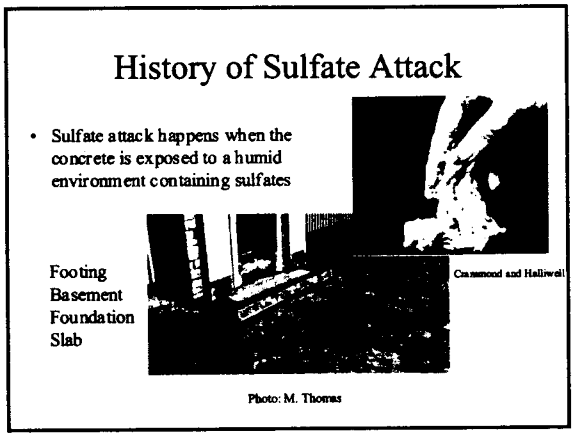
Chemical vs Physical

- Chemical Sulfate Attack
  ...sulfate attack is considered to be the result of chemical reactions involving sulfate anion, SO_4^{2-}, which forms ettringite from monosulfate and gypsum, and/or forms gypsum
- Physical Sulfate Attack
  ...usually refers to (a) formation from the solution of sodium sulfate mirabilite, $Na_2SO_4 \cdot 10H_2$, followed by (b) its repeated recrystallization into thenardite, Na_2SO_4 and vice versa.

Skalny et. al 2002

History of Sulfate Attack

- Sulfate Attack Reported in the Early Years of 19th Century in Europe
- In 1892, Formation of Ettringite identified for Causing Expansion and Cracking
- In 1915, Wig and Williams Published Their Observations on Sulfate Attack in Western U.S. (Mehta 2000)
- Several Multimillion-Dollar Lawsuits Filed Recently on Behalf of Homeowners in California



History of Sulfate Attack

- Sulfate attack happens when the concrete is exposed to a humid environment containing sulfates

Footing
Basement
Foundation
Slab

Cammond and Halliwell

Photo: M. Thomas

Mechanisms of Chemical Type Attack (Classical Form)

- Formation of **Ettringite**

$3(CaSO_4{\cdot}2H_2O)$ + $3CaO{\cdot}Al_2O_3$ + $26H_2O \longrightarrow$
Gypsum Tricalcium aluminate Water
$3CaO{\cdot}Al_2O_3 3CaSO_4.32H_2O$
Ettringite

$3CaO{\cdot}Al_2O_3 CaSO_4{\cdot}12H_2O$ + $2CaSO_4{\cdot}2H_2O$ + $16H_2O \longrightarrow$
Monosulfate Gypsum Water
$3CaO{\cdot}Al_2O_3 3CaSO_4.32H_2O$
Ettringite

Ettringite formation from "classical" sulfate attack

Once ettringite forms, it imbibes water, leading to expansion.

Expansion leads to tensile stresses that can crack concrete.

Note the early formation of ettringite during cement hydration can be accomodated by the fresh concrete, but later formation and expansion will crack concrete

Type K cement takes advantage of above reactions…

Mechanisms of Chemical Type Attack (Classical Form)

- Formation of **<u>Gypsum</u>** and **<u>Brucite</u>**
  - Formation of <u>Gypsum</u>

$$\underset{\text{Portlandite}}{Ca(OH)_2} + \underset{\text{Sulfate}}{SO_4^{2-}} + \underset{\text{Water}}{2H_2O} \longrightarrow \underset{\text{Gypsum}}{CaSO_4} + \underset{\text{Hydroxide}}{2OH^-}$$

* Gypsum formation usually leads to mass loss or "mushy" appearance.

  - Formation of <u>Brucite</u>

$$\underset{\text{Portlandite}}{Ca(OH)2} + MgSO4 + 2H_2O \longrightarrow \underset{\text{Gypsum}}{CaSO_4{\cdot}2H_2O} + \underset{\text{Brucite}}{Mg(OH)2}$$

Deteriorations by Sulfate Attack
<u>Physical Manifestations</u>

- Appearances
  - Map cracking
  - Spalling
  - Efflorescence
  - Turns "mushy"
  - Pop-outs

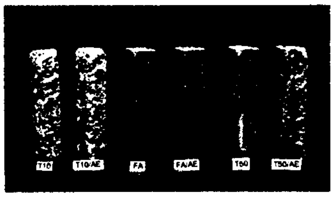
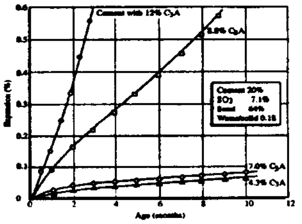


Photo: M. Thomas

Deteriorations by Sulfate Attack
<u>Physical Manifestations</u>

- Expansion



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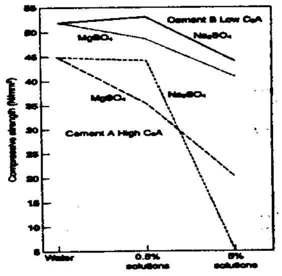
Deteriorations by Sulfate Attack

Physical Manifestations

Compressive Strength*

1 year soaking



Eglinton 1998

Mitigating Sulfate Attack

- Susceptibility of Sulfate Attack
- Mitigation Strategies
  - Use of Sulfate-Resisting Cement
  - Use of SCMs
  - Combination of Sulfate-Resisting Cement and SCMs

Susceptibility of Sulfate Attack

- Standard Tests and Specifications
  - ASTM E 150 – Specification for portland cement
  - ASTM C 452 – Test method for potential expansion of portland cement mortars exposed to sulfate
  - ASTM C 632 – Standard practice for developing accelerated tests to aid prediction of the service life of building components and materials
  - ASTM C 1012 – Test method for length change of hydraulic-cement mortars exposed to a sulfate solution
  - ASTM C 1157M – Performance specification for blended hydraulic cement

ACI 201 Guidelines on Sulfate Attack

(ACI 201-2R)

Severity of potential exposure	Water-Soluble soluble sulfate (SO_4)^{A} in soil, percent by mass	Sulfate (SO_4)^{A} in water, ppm	(w/cm) by mass, max.$^{B, C}$	Cementitious-material requirements
Class 0 exposure	0.00 - 0.10	0 - 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^{C}	C 150 Type II or Equivalent^{D}
Class 2 exposure	0.20 to <2.0	1500 to <10,000	0.45^{C}	C 150 Type V or Equivalent^{D}
Class 3 exposure	2.0 or greater	10,000 or greater or greater	0.40^{C}	C 150 Type V plus pozzolan or slag^{D}
Seawater exposure			See Section 2.4	See Section 2.4

Factors Affecting Classical Sulfate Attack

- Composition of the cement or hardened cement paste (C_3A)
- Form of sulfate participating in the process (anions)
- Sulfate concentration (reaction and diffusion rates)
- Sulfate ion availability to reactants in concrete
- Available of moisture to inside of concrete ("Ions swims, they don't fly!!", P.K. Mehta)

Mitigation Strategies

- Reduce Sulfate Penetration (low permeability is the key!!)
- Modification of Cement Components (e.g., lower C_3A with Type II or Type V cements)
- Incorporation of SCMs
- Good Construction Practice!!

Mitigating Strategies

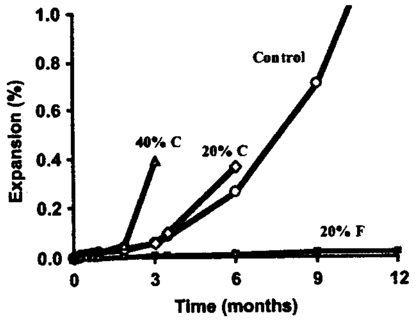
- Modification of Cement Components
  - High C_3A content increases susceptibility of sulfate attack (greatest single factor)
  - Le Chatelier suggested large replacement of C_3A by C_4AF
  - Type II cement, C_3A less than 8%
  - Type V cement, C_3A less than 5% and combination of C_3A and C_4AF less than 25%

Mitigating Strategies

- Incorporation of SCMs
  - Reduce C_3A and CH content
  - Modify microstructure, reduce sulfate ions' penetration, thus smaller reaction rate
  - Consuming $Ca(OH)_2$, which is subject to sulfate (forming gypsum) and magnesium ions (forming brucite)

Effect of Fly Ash on Sulfate Resistance

ASTM C 1012



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Fly Ash Mineralogy

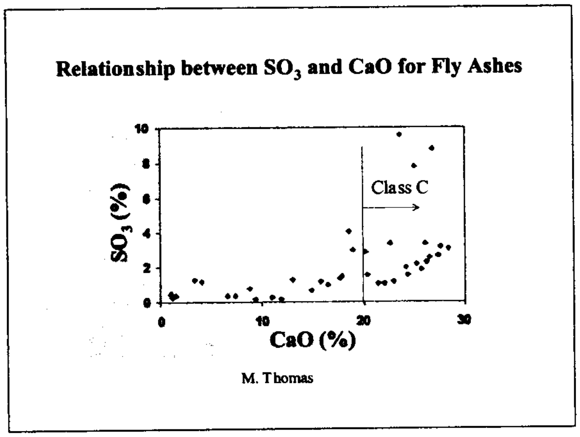
Most fly ashes contain:

Mullite - $Al_6Si_2O_{13}$
Magnetite - Fe_3O_4
Hematite - Fe_2O_3
Quartz - SiO_2
These phases are generally insoluble and do not participate in hydration reactions

Class C Fly Ash

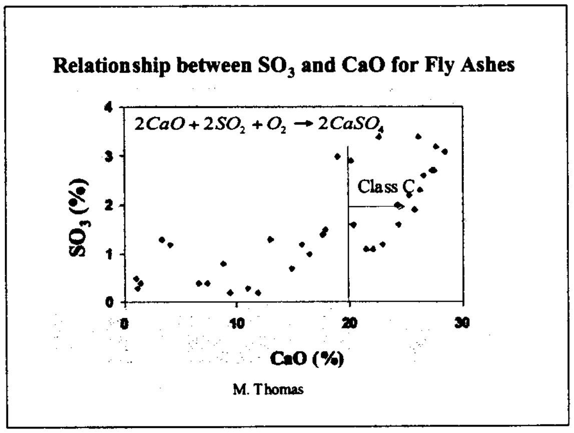
High-CaO ashes may also contain:

C_3A
C_2S
Lime - CaO
Anhydrite - $CaSO_4$
Melilite - $Ca_2(Mg,Al)(Al,Si)_2O_7$
Alkali sulphates - $(Na,K)_2SO_4$
Hematite - Fe_2O_3
Merwinite - $Ca_3Mg(SiO_4)_2$
Ferrite spinel - $(Mg,Fe)(Fe,Al)_2O_4$
Sodalite - $Ca_2(Ca,Na)_6(Al,Si)_{12}O_{24}(SO_4)_{1-2}$



Relationship between SO_3 and CaO for Fly Ashes

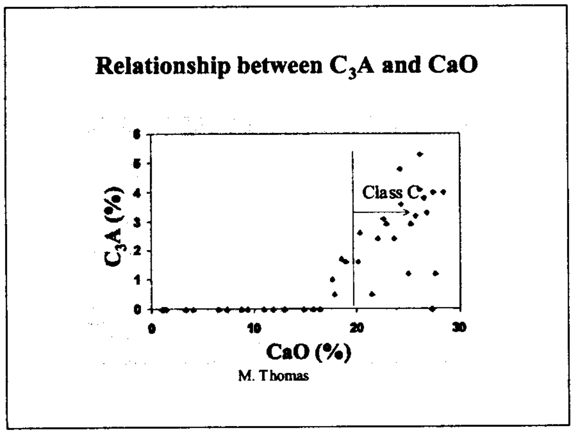
M. Thomas



Relationship between SO_3 and CaO for Fly Ashes

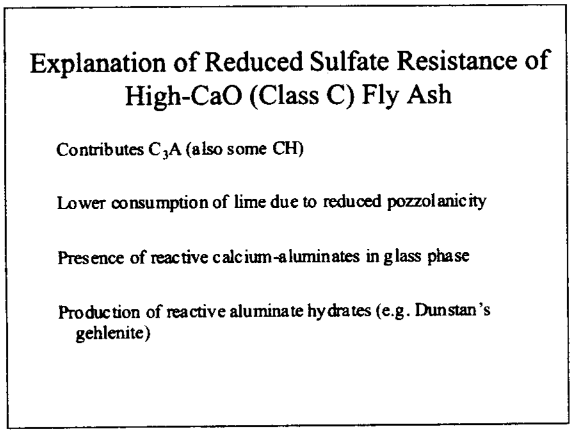
$2CaO + 2SO_2 + O_2 \rightarrow 2CaSO_4$

M. Thomas



Relationship between C_3A and CaO

M. Thomas



Explanation of Reduced Sulfate Resistance of High-CaO (Class C) Fly Ash

Contributes C_3A (also some CH)

Lower consumption of lime due to reduced pozzolanicity

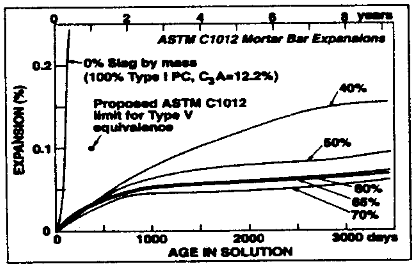
Presence of reactive calcium-aluminates in glass phase

Production of reactive aluminate hydrates (e.g. Dunstan's gehlenite)

Differentiating High- and Low-Calcium Fly Ash

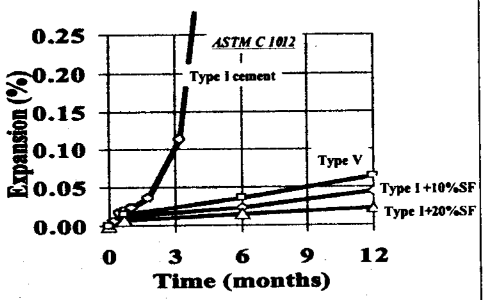
- Low-CaO Fly Ash
  - Reduced available aluminates
  - Reduced available lime
  - Reduced ion penetration (lower permeability)
  - Changed properties of hydrated aluminates (?)
- High-CaO Fly Ash: ??
  - C_3A and CH not significantly reduced
  - Presence of reactive calcium-aluminates in glass phase
  - Production of reactive aluminate hydrates (e.g. gehlenite)

Effects of Replacement by Slag



Hooton, 1993

Using Silica Fume to Combat Sulfate Attack



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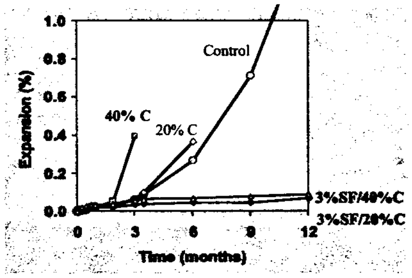
Ternary Blends for Sulfate Resistance

ASTM C 1012



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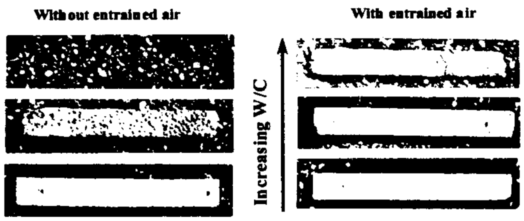
Type V Equivalence*

Generally, equivalent performance to Type V cement can be achieved by blending a Type I cement with:

- 20 to 25% low-CaO fly ash
- 35 to 50% slag
- 5 to 10% silica fume
- 10 to 15% metakaolin

* Striving for Type V equivalence is becoming more common due to scarcity of Type V cement

Air Entrainment



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

- Its usefulness is limited -- it just buys some time...

Other Forms of Chemical Attack

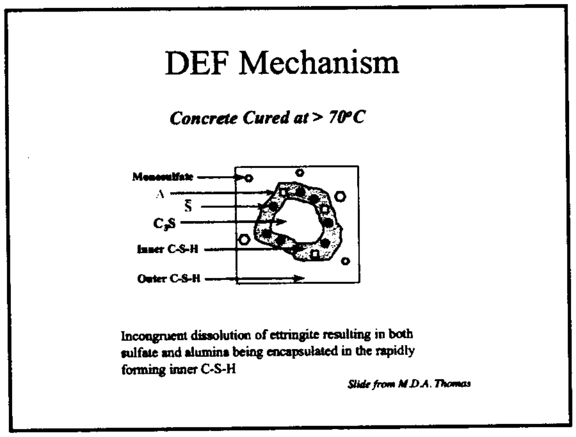
- Formation of Thaumasite
  $[Ca_3Si(OH)_6 \cdot 12H_2O] \cdot (SO_4)(CO_3)$
  - Structurally similar to ettringite
  - Normally lower temperature required (<40 F)
- Delayed Ettringite Formation (DEF)
- Physical Sulfate Attack

Thaumasite Formation - A New Twist on an Old Problem

- Thaumasite can form through a combination of sulfate attack and carbonation
- With limestone fines (providing CO_3^{2-}) and sulfate ions available, the formation of thaumasite is limited only by available CaO and SiO_2
- Low concentration of $MgSO_4$ may help initiate its formation probably by releasing SiO_2 from C-S-H
- Thaumasite formation decomposes C-S-H!!!
- Low temperature (~40 F) normally required
- HOT TOPIC – more so because ASTM is considering allowing the addition of limestone fines to cement…

What is Delayed Ettringite Formation?

- Damage (expansion & cracking) of concrete due to the formation of ettringite after the concrete has hardened.
- The result of excessive temperatures during curing which prevent the normal "early" formation of ettringite.
- The term DEF, as used here, does not include damage resulting from **excessive** amounts of sulfate in the cement (or other components of the concrete) or from external sources of sulfate.

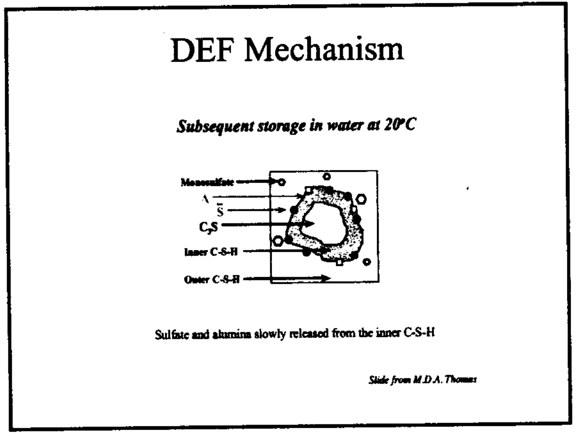


DEF Mechanism

Concrete Cured at > 70°C

Incongruent dissolution of ettringite resulting in both sulfate and alumina being encapsulated in the rapidly forming inner C-S-H

Slide from M.D.A. Thomas

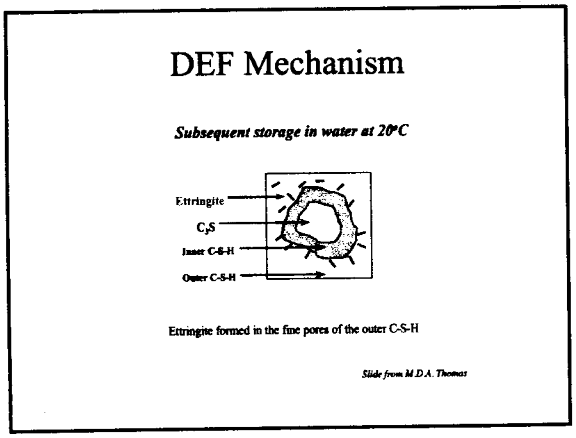


DEF Mechanism

Subsequent storage in water at 20°C

Sulfate and alumina slowly released from the inner C-S-H

Slide from M.D.A. Thomas

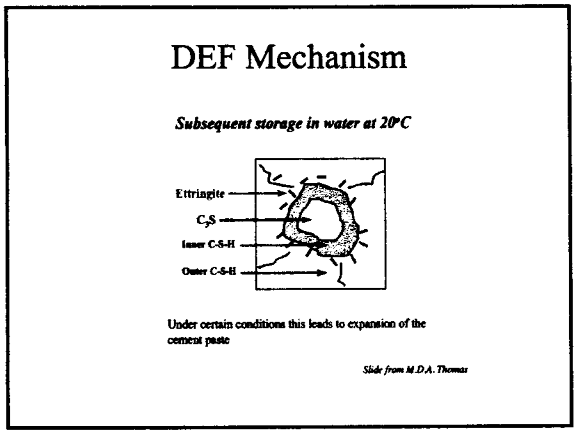


DEF Mechanism

Subsequent storage in water at 20°C

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

Slide from M.D.A. Thomas

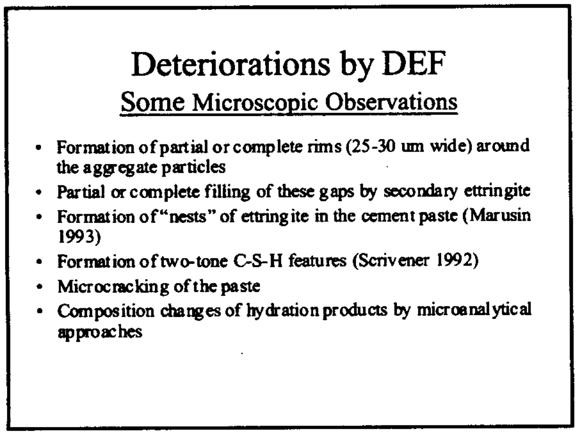


DEF Mechanism

Subsequent storage in water at 20°C

Under certain conditions this leads to expansion of the cement paste

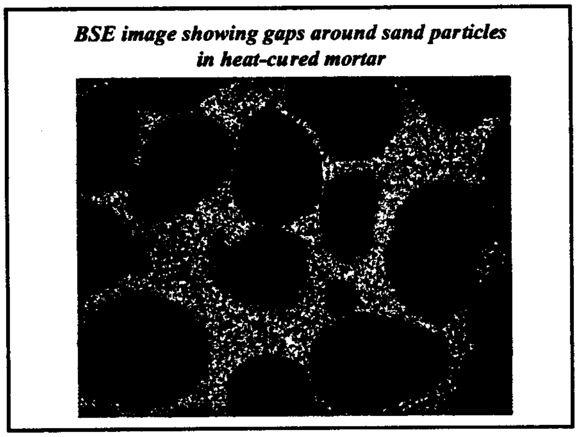
Slide from M.D.A. Thomas



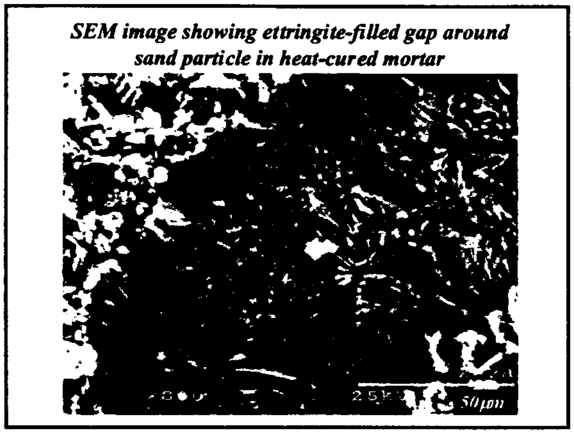
Deteriorations by DEF

Some Microscopic Observations

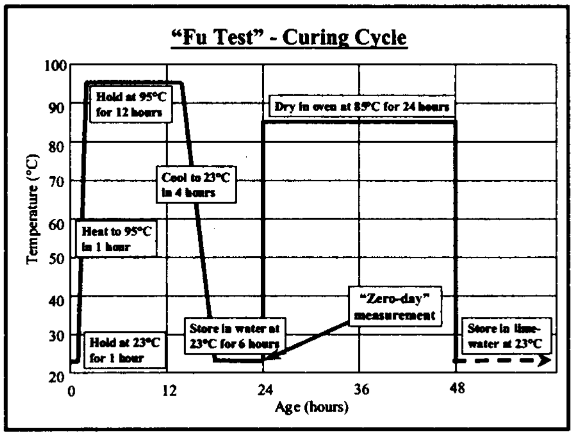
- Formation of partial or complete rims (25-30 um wide) around the aggregate particles
- Partial or complete filling of these gaps by secondary ettringite
- Formation of "nests" of ettringite in the cement paste (Marusin 1993)
- Formation of two-tone C-S-H features (Scrivener 1992)
- Microcracking of the paste
- Composition changes of hydration products by microanalytical approaches



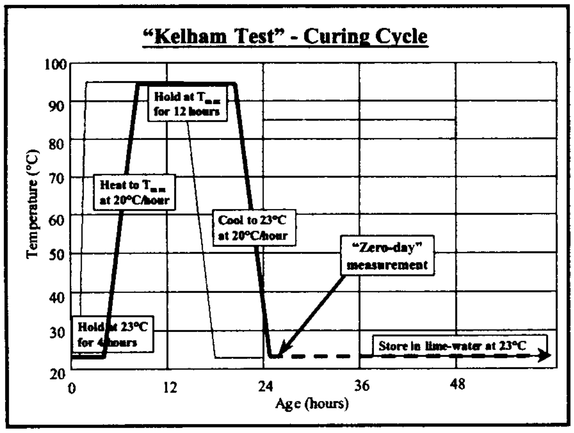
BSE image showing gaps around sand particles in heat-cured mortar



SEM image showing ettringite-filled gap around sand particle in heat-cured mortar

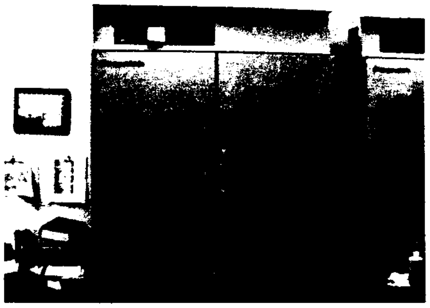


"Fu Test" - Curing Cycle

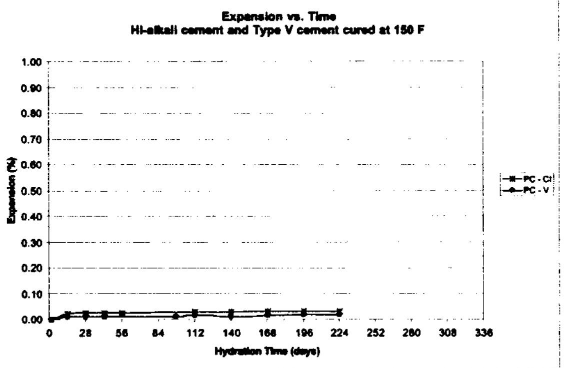


"Kelham Test" - Curing Cycle

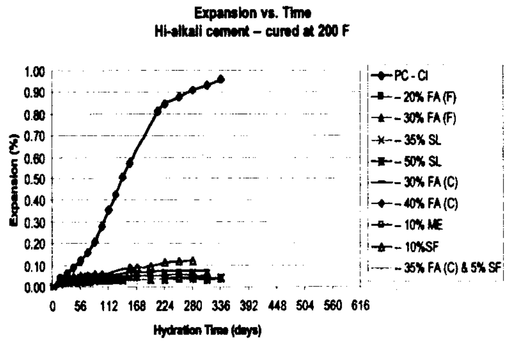
Ovens for ASTM C 1260 and DEF Testing



UT Research -- Effects of Curing Temperature

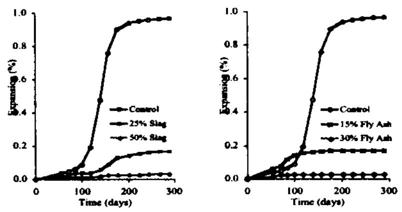


UT Research -- What if we exceed 158 F during curing?*



* Results shown are for 200 F curing -- similar results observed at 176 F

Effects of slag and fly ash on DEF



Effect of Slag on DEF-Expansion (Ghorab et al. 1980)

To control DEF, we can either:
Limit temperature to 158 F during curing
or
Use suitable pozzolan at sufficient dosage*
(>25% Class F ash, >35% slag, etc.)

** Must still consider thermal cracking if higher curing temperatures are used (being studied under TxDOT 4563)*

How have others dealt with the problem?

Temperature Control….

Country	Agency/Specificatio	Max. Temperature	Temp. applies to:	Other Comments
Canada	CSA/A23.4-94	158 °F	Concrete	
Denmark	DS482 (draft as of Jan 1999)	158 °F	Concrete	
England	Manual of Contract Documents for Highway Works	158 °F	Concrete	Concrete shall be le for 4 hours without additional heat
Germany	Committee for Reinforced Concrete	140 °F	Concrete	Initial set required before application o heat
South Afric	SABS/0100-2:1992	140 °F	Steam	Ambient temperatur limits also apply
Spain	UNE/83-301-91	158 °F	Not Specified	

Draft Approach to Controlling DEF (as proposed to ACI)

T < 70°C	None
70°C ≤ T < 85°C	Portland cement with strength at 1 day < 20 MPa or, Any Portland cement with the following replacements: ≥ 25% Class F fly ash or, ≥ 35% slag or, ≥ 5% silica fume with at least 25% slag
70°C ≤ T < 85°C	Provided there is data to show that the specific combination of materials can be used at T°C without adverse effect under the intended exposure conditions Suitable sources of data are: Field performance (minimum 10 years) Laboratory testing (e.g. 'Kelham method')

Physical Sulfate Attack

- Physical attack involving phase changes of salt solution as temperature changes
- No chemical attack on cement paste (e.g., no ettringite or gypsum formed)
- Similar in nature to freeze-thaw
- Some have specified Type V cement to control (chemical solutions to physical problems don't work well...)
- Low permeability concrete is the best defense!!! (again)
- Subject of major lawsuit in Southern California

In summary,

Sulfate attack can be chemical or physical...

It can arise from an internal or external source of sulfate...

It's not your father's sulfate attack anymore!!

The answer is…

Sound understanding of the underlying mechanisms, <u>and</u>

Strategies based on controlling the physical aspects of concrete (permeability), the chemical aspects (Type II cement, SCMs, etc.), and/or controlling curing temperatures (for DEF)

Any Questions?

Premature Concrete Deterioration Field Case Studies

Brian Merrill, P.E.
Bridge Section
Construction & Maintenance Division

What is Premature Concrete Deterioration? (PCD)

- Symptoms in Bridge Structures
- Causes

Symptoms

- Longitudinal cracks along prestressed beams
- "Map" cracking in box beams and bent/abutment caps
- Vertical cracking in columns
- "Map" cracking in other concrete members

Causes

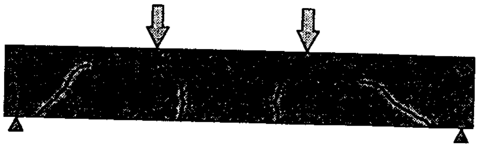
- Material based: ASR or DEF (or both)
- Cracking is not the result of rebar corrosion
- Cracking is not the result of concrete placing operations or fabrication practices
- Cracking is not the result of loading (i.e.: flexural or shear cracking)

Concrete Cracking

- All concrete cracks
- Cracks are perpendicular to tensile stresses
- Two primary causes of cracking
  - * Load induced
  - * Material induced

Load Induced Cracking

- Flexural cracks (bending)
- Shear cracks



Material Induced Cracking

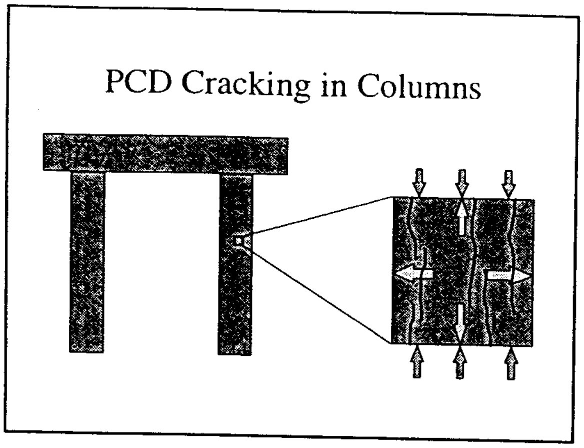
- Shrinkage (drying or plastic)
- Thermal effects (restraint)
- Creep (restraint)
- Corrosion of rebar
- ASR/DEF (internal material expansion)
- Other (sulfates, carbonation,...)

How do we determine the cause of a given crack?

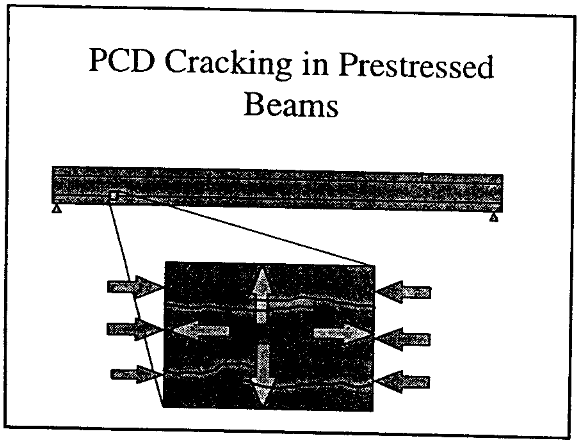
- Familiarity with structural behavior
- Familiarity with typical crack patterns
- Observation of crack orientation
- Sometimes an educated guess

Crack Orientation: Why are PCD cracks oriented this way?

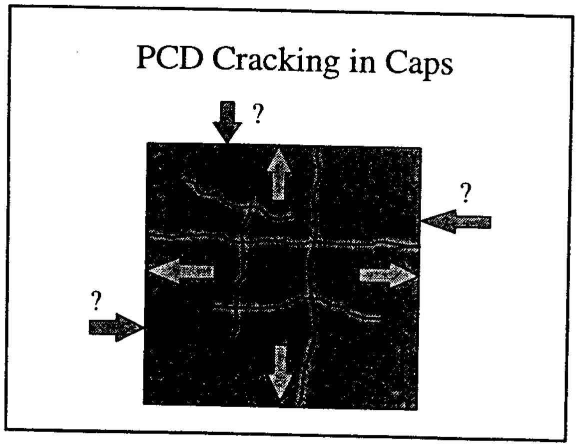
- Cracks form perpendicular to tensile stress
- Tensile stresses are the result of material expansion



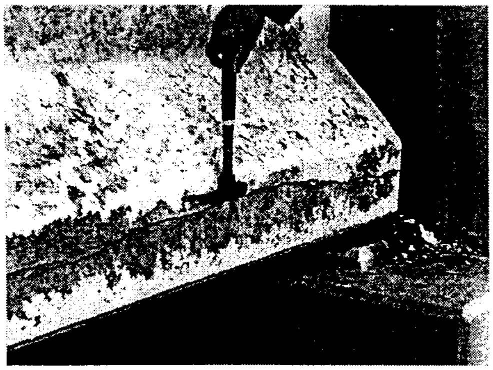
PCD Cracking in Columns

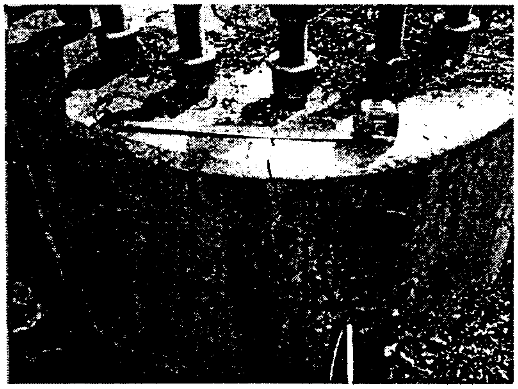


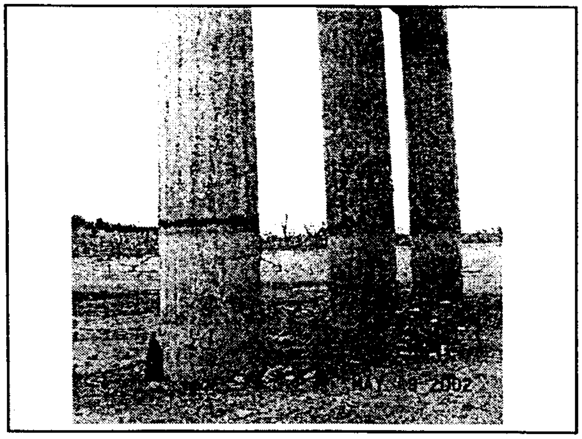
PCD Cracking in Prestressed Beams



PCD Cracking in Caps



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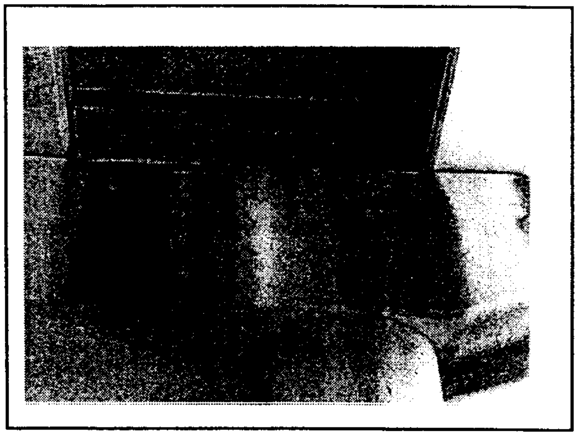
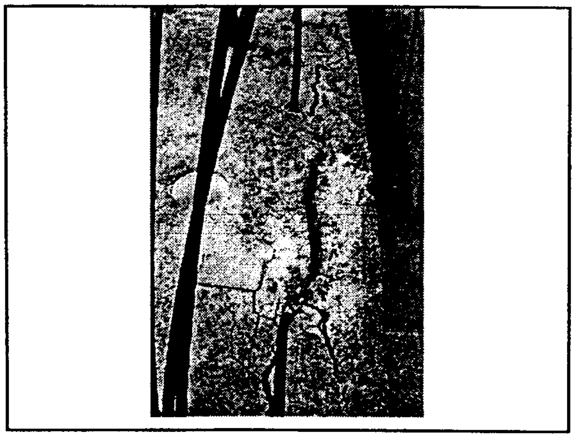




Structural Effects of ASR/DEF

- 10 - 15% Reduction in Compressive Strength
- Up to 50% Reduction in Tensile Strength
- Reduced Bond with Rebar/Prestressing Strands
- Reduced Stiffness - Increased Cracking
- Increased Potential for Damage due to Freeze-Thaw, Corrosion

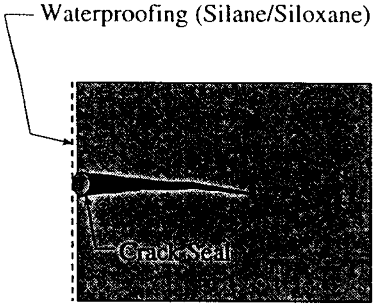
Repair Strategies

- Lithium salt application for ASR (limited effectiveness in retrofit application)
- Waterproof: both ASR and DEF are driven by moisture - keep the water out and they do not occur. The waterproofing should not be a vapor barrier - the concrete needs to "breathe".

Repair/Maintenance Options

- Do Nothing - Monitor
- Seal Cracks and Waterproof
- Retrofit: Additional Capacity or Confinement
- Replace

Seal Cracks & Waterproof



Decision factors

- Element in Question (beam, cap, column,..)
- Severity of Damage
- Potential for Further Damage
- Consequences of "Failure"
- Feasibility of Repairs
- Cost of Repairs

TxDOT Workshop

Design of Durable Concrete

Session 8: Corrosion of Reinforcing Steel

CONCRETE DURABILITY CENTER (CDC)

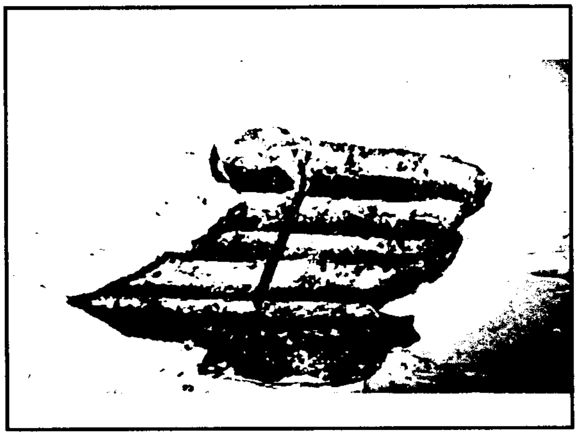
Outline of Presentation

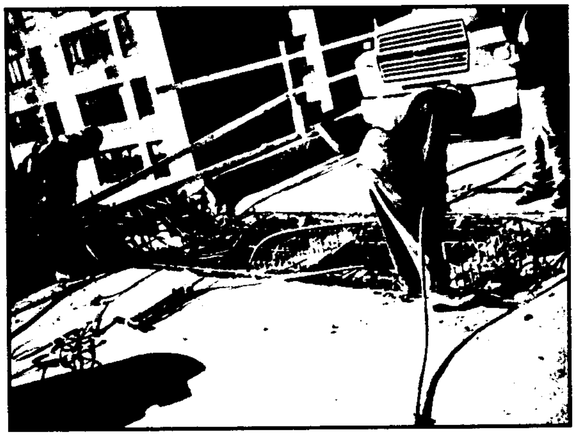
- **Significance**
- **Fundamental Science of Corrosion**
- **Corrosion of Steel in Concrete**
- **Corrosion Damage Evaluation**
- **Mitigation/Prevention Strategies**

Corrosion Is Everywhere

Bent cap in Lubbock…

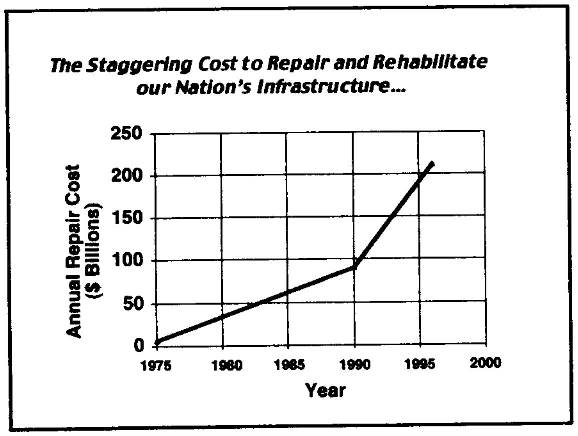
Rust Never Sleeps!!





Don't let corrosion destroy your concrete structure!

Master Builders



The Staggering Cost to Repair and Rehabilitate our Nation's Infrastructure...

Fundamental Science of Corrosion

- Definition

  Corrosion is the destructive result of chemical reaction between a metal or metal alloy and its environment. (Jones 1996)

- A Spontaneous Process

  Corrosion returns the metal to its combined state in chemical compounds that are similar or even identical to the minerals from which the metals were extracted.

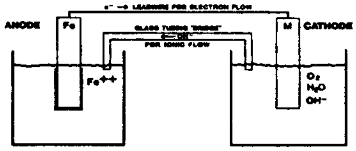
Electrochemical Nature of Aqueous Corrosion

- Electrochemical process (e.g. Galvanic)

  Potential differences between the two half cells

  A chemical process (Fe →Fe^{++})

  Flow of electrical current involved (e^- and OH^-)



Hime and Erlin 1987

Definitions of Terms

- Anodic Reaction (oxidation)

  Reaction involving loss of electron (Fe →Fe^{2+})

  Anode is where the reaction happens (corrosion phenomena)
- Cathodic Reaction (reduction)

  -Reaction involving gain of electron (O_2+H_2O+e → OH^-)

  - Cathode is site where reaction happens
- Half Cell

  Usually a pure metal in a solution of (fixed) concentration

  Two half cells to make an electrochemical cell
- Standard Electromotive Force (emf) Potential

  Half cell potential (referenced by standard hydrogen electrode SHE)

  Reaction written as reduction reactions

emf potentials of Metals

- Au
- Pt
- Ag
- Hg
- Fe^{3+}
- Cu
- Pb
- Ni
- Fe^{2+}
- Cr
- Zn
- Al
- Mg
- Na
- K

More Noble

- Only for standard solutions
- Metal may have different positions depending the valence
- Indicating which one may be corroded (anode) when a cell is formed with two metals

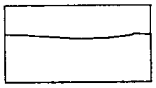
Forms of Corrosion

- Uniform Corrosion

  A uniform, regular remove of metal from the surface

  Preferred form if corrosion is not avoidable

  Characterized by mass loss or corroding depth (MPY: Mils per Year)



Jones 1996

Forms of Corrosion

- Pitting

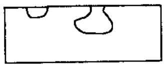
  Localized attack in an otherwise resistant surface

  Pits may be deep, shallow or undercut

  Stainless steel and nickel alloys especially susceptible to pitting by local breakdown of the film at isolated sites

  Worst case for steel corrosion in concrete

  Difficult to detect and to quantify the damage



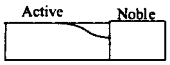
Jones 1996

Forms of Corrosion

- Galvanic

  When two dissimilar alloys are **coupled** in the presence of a corrosive electrolyte, one of them is preferentially corroded while the other is protected from corrosion

  Generally speaking, most of the corrosions are of galvanic type



Jones 1996

Forms of Corrosion

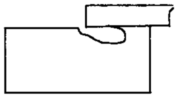
- Crevice

  Corrosion in the small sheltered volume of the crevice

  Corrosion is often greater than unsheltered part

  Localized anode vs large cathode

  Accumulating of electrolytes



Jones 1996

Factors Affecting Corrosion

- Formation of Corrosion Cell

  Coupling of anode and cathode (path for electron)

  Environment containing electrolyte (ions closing the circuit)
- Potential Difference between Anode and Cathode

  Higher difference means higher possibility for corrosion

  Not necessarily proportioned to corrosion rate
- Kinetics

  The slowest process decides the corrosion rate

  Anodic reaction (migration of metallic ions)

  Cathodic reaction (availability of O_2)

  Ionic current flow rate (resistivity of concrete)

  Potential difference

Corrosion of Steel in Concrete

- Marine exposure or application of de-icing salts most common culprits
- 44% of more than 500,000 bridges ranked as structurally deficient (1993)
- $50 to 200 million for bridge deck repair
- Repair is necessary but nonproductive use of DOT resources
- Caused by corrosion of steel in concrete!!

Broomfield 1997

Corrosion of Reinforcing Steel

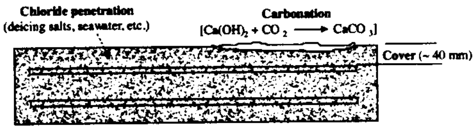
The basics:

- Reinforcing steel is placed in concrete to handle tensile loads.
- **"High-quality" concrete protects steel from corrosion** due to its high alkalinity (pH>13.5). An oxide film forms on the steel surface and this "passive layer" prevents corrosion.
- **Unfortunately, all concrete is not "high-quality," either initially or eventually...**

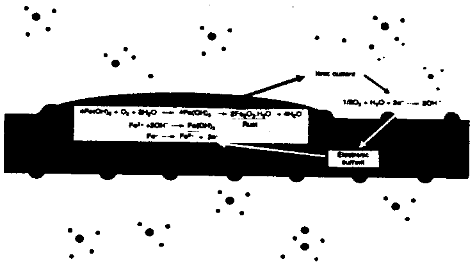
Corrosion of Reinforcing Steel

The first step - breakdown of the passive layer by:

- Chemical, physical or mechanical degradation of concrete cover
- Chloride penetration to the reinforcement ⇒ Chloride-induced corrosion (0.6-0.9 kg of Cl^- per cubic meter of concrete is "threshold value")
- Carbonation of the concrete to reinforcement depth (pH↓)



A Typical Model



Broomfield 1997

Chemical Reactions

- Anodic Reaction (loss of electron)
  $Fe \longrightarrow Fe^{2+} + 2e^-$
- Cathodic Reaction
  $2e^- + H_2O + {}_1{}_/{}_2O_2 \longrightarrow 2OH^-$
- Rust (cause of cracking and spalling)
  $Fe^{2+} + 2OH^- \longrightarrow 4Fe(OH)_3$ (Ferrous hydroxide)
  $4Fe(OH)_2 + O_2 + 2H_2O \longrightarrow 4Fe(OH)_3$ (Ferric hydroxide)
  $2Fe(OH)_3 \longrightarrow Fe_2O3{\cdot}H_2O + 2H_2O$ (Rust)
- Volume Change due to Corrosion
  Volume increase at the steel-concrete interface is two to ten times depends on the degree of hydration of Fe_2O_3

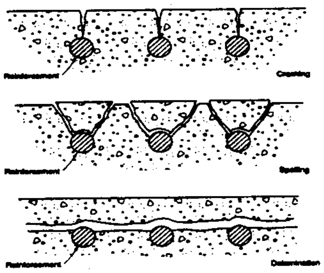
Important Observations

- Corrosion of steel is the oxidation of Fe, i.e. steel is the anode (cathode does not corrode)
- Oxygen and water are necessary for the process of corrosion
- When rust forms, expansion occurs, often followed by cracking and spalling
- The mobility of Fe^{2+} and OH^- are important and are controlled by concrete permeability

The Stages of Corrosion

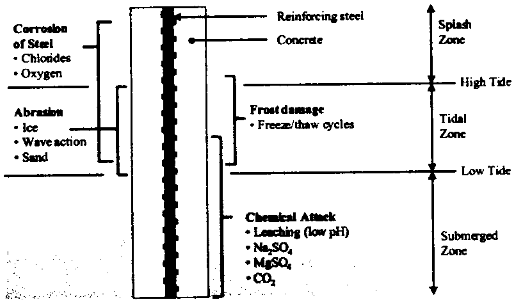
1. **Corrosion Initiation**
2. **Corrosion products become visible**
3. **Cracking, spalling, or both**
4. **Structure loses load-carrying capacity**

Damages Induced by Corrosion

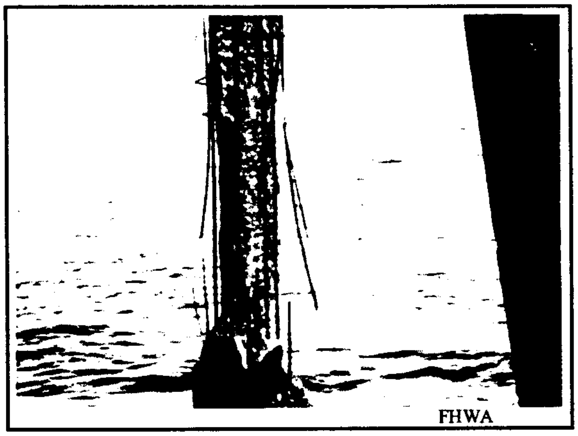


Neville 1996

Physical & Chemical Attack on Marine Concrete



(after Mehta, 1980)



FHWA

Corrosion Forms of Steel in Concrete

- Microcells
  - Anodic and cathodic reactions are immediately adjacent
  - Uniform iron dissolution over the whole surface
  - Carbonation or very high chloride content at the rebars
- Macrocells
  - A net distinction between corroding areas of the rebar (anode) and non-corroding surfaces (cathode)
  - Chloride induced corrosion (pitting)
  - Generally small anode vs large cathode

Carbonation-induced corrosion

- Not very common in most areas:
  - Chemical reactions
    - $CO_2 + H_2O \longrightarrow H_2CO_3$
    - $H_2CO_3 + Ca(OH)_2 \longrightarrow CaCO_3 + 2H_2O$
  - Decreases pH of pore solution
  - Destablizes passive layer of steel
  - Carbonation rate determined by the quality of concrete: permeability and cement content
  - Cover thickness important
  - Environment: Temperature, wet-dry cycles, relative humidity (middle values worst)
  - Microcell corrosion, cracking along rebars

Chloride-induced corrosion

- By far, the most common type of corrosion:
  - Sources of chlorides
    - De-icing salts
    - Accelerating admixture $CaCl_2$ (popular until mid-1970s)
    - Seawater (contained in mixtures or contacting)
    - Brackish ground water
    - Aggregate (contaminated)
  - Ingress of chlorides
    - Transported with water
    - Diffusion of ions in water
    - Absorption
    - Released from bonded state (aggregate or hydration product)

Chloride-induced corrosion (cont'd)

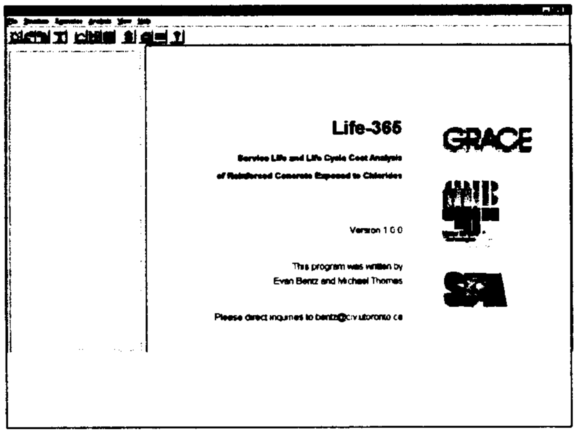
- Attack mechanism
  - Mechanism of Cl^- breaking down passive layer not clear
  - Causes pitting
- Macrocell formation
  - Very prone in chloride-induced corrosion
  - Chlorides in concrete is hygroscopic (absorb and retain moisture)
  - Higher conductivity makes separation of anode and cathode possible

Understanding Corrosion of Steel in Concrete

- Corrosion may be modeled as three stages
  - **Initiation Stage**
    - Diffusion of CO_2
    - Ingress of chlorides
    - Cracks
  - **Activation Stage**
    - Less clear cut phenomenon
    - Rebar network starts to corrode
    - Rust product formed
  - **Deterioration**
    - Cracking
    - Spalling

Service Life Prediction (Corrosion)

- Several service life models available for corrosion of reinforcing steel
- Life-365 has become the most popular model
  - A consensus-based tool that enables designers, owners, governmental agencies, etc. to model alternate corrosion protection design criteria on the basis of performance over a specified time-frame
  - Focuses mainly on initiation phase, makes some assumptions on subsequent processes
  - Developed by M. Thomas and E. Bentz, with input and funding from ACI, FHWA, NIST, PCA, and others
  - Used at UT for graduate level course to design Galveston Causeway for corrosion protection



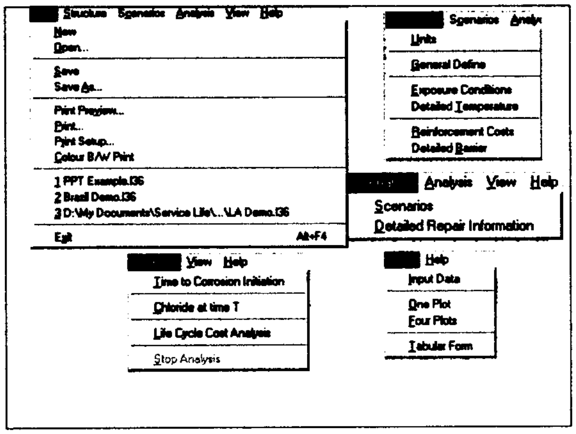
Life-365

Service Life and Life Cycle Cost Analysis of Reinforced Concrete Exposed to Chlorides

Version 1.0.0

This program was written by Evan Bentz and Michael Thomas

Please direct inquiries to bentz@civ.utoronto.ca



Because corrosion is so prevalent, let's look at methods of evaluating, inspecting, and repairing reinforced concrete structures.

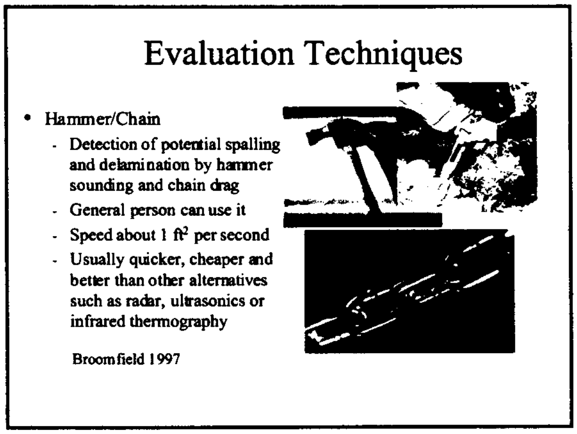
Corrosion Damage Evaluation

- Preliminary Survey
  - Inspection of damage
  - Assessment of structural integrity
  - Cracks, spalls, half-cell measurement, carbonation
- Detailed Survey
  - Accurate survey of extent and severity of deterioration
  - Full survey of repairs

Evaluation Techniques

- Visual Inspection
  - General use for surface defects (cracks and spalls)
  - Approximate speed about 11 ft^2 per second
  - Use of eye and brain, notebook, laptop, camera, card for crack width
  - SHRP expert system HWYCON (1994)

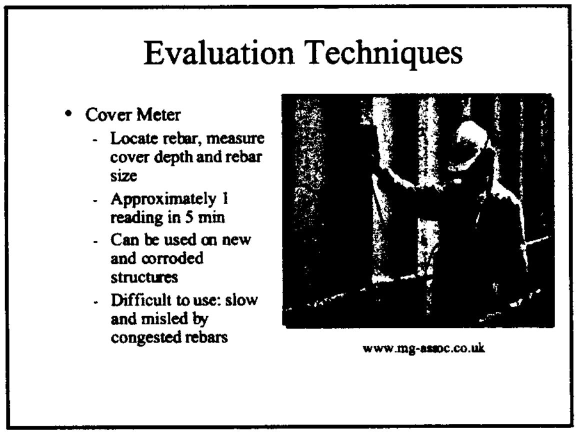
Broomfield 1997



Evaluation Techniques

- Hammer/Chain
  - Detection of potential spalling and delamination by hammer sounding and chain drag
  - General person can use it
  - Speed about 1 ft^2 per second
  - Usually quicker, cheaper and better than other alternatives such as radar, ultrasonics or infrared thermography

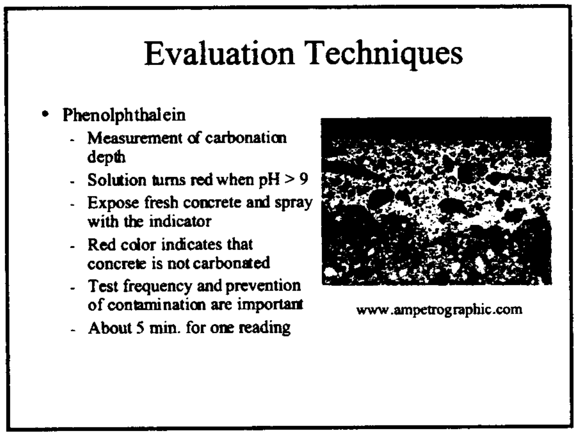
Broomfield 1997



Evaluation Techniques

- Cover Meter
  - Locate rebar, measure cover depth and rebar size
  - Approximately 1 reading in 5 min
  - Can be used on new and corroded structures
  - Difficult to use: slow and misled by congested rebars

www.mg-assoc.co.uk



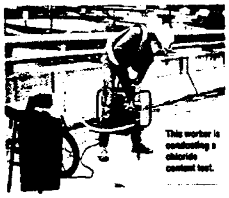
Evaluation Techniques

- Phenolphthalein
  - Measurement of carbonation depth
  - Solution turns red when pH > 9
  - Expose fresh concrete and spray with the indicator
  - Red color indicates that concrete is not carbonated
  - Test frequency and prevention of contamination are important
  - About 5 min. for one reading

www.ampetrographic.com

Evaluation Techniques

- Chloride Content
  - Measure chloride ion content
  - Coring/drilling to obtain samples at different depths
  - Powdered samples dissolved in acid for analysis
  - Determine chloride profile to estimate the ingress rate
  - Can be performed in the lab or in the field (Quantab strips and specific ion electrodes)
  - Field equipments expensive
  - Total chloride (acid soluble) or free chloride content?

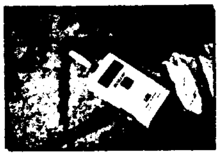


This worker is conducting a chloride content test.

www.tfhrc.gov

Evaluation Techniques

- Half-Cell Potential
  - Simple device
  - Potential of the half cell: Fe in Fe^{2+} solution
  - It is a relative value (referenced to copper/copper sulfate, silver/silver chloride, Calomel, and Standard hydrogen electrode)
  - ASTM C 867 criteria for corrosion of steel in concrete
  - 350 mV to copper/copper sulfate is often quoted as indicating steel is usually corroding actively
  - The fixed -350 mV value is questioned (Elsener 2002) because cover depth and concrete conductivity affecting the readings



Evaluation Techniques

- Half-Cell Potential Mapping
  - Potential map for fuller understanding of corrosion condition
  - Potential "contour lines" showing areas with high and low corrosion risks
  - Steep gradient indicating greater risk of corrosion
  - Note sign of the potential values

www.monosys.net

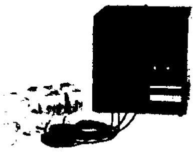
Evaluation Techniques

- Linear Polarization
  - Measures the corrosion rate (how much steel is turning into rust and how much metal is being lost at given moment)
  - Measures electric current generated by anodic reaction and can calculate mass loss using Faraday's law
  - Polarization resistance R_p is obtained and used to rate the corrosion condition
  - A slow process, requires 5-30 min depending on equipment

www.leadstate.tamu.edu

Evaluation Techniques

- Permeability and Absorption Tests
  - Ease of ingress of chlorides, oxygen, water, and CO_2
  - Accurate values obtained under laboratory-controlled conditions
  - Field measurement rates the permeability (using vacuum devices and water absorption kits)
  - Rapid chloride permeability used in lab for lab-prepared or field samples



Other Evaluation Techniques

- Impact/Ultrasonics
  - Using wave propagation to locate cracks and estimate concrete quality
- Petrography
  - Determine w-c ratio, ASR potential and other problems
- Radar/Radiography
  - Non-destructive examination
  - Expensive equipment
- Electrochemcial Impedance Spectroscopy (EIS)
  - Complex
  - Laboratory studies

Mitigation/Prevention Strategies

- Corrosion is common in concrete structures
- Cannot completely stop the corrosion of steel in concrete, but we can slow it down substantially
- Can attack problem through selection of concrete materials, reinforcing steel, or active control sytems (e.g., cathodic protection)

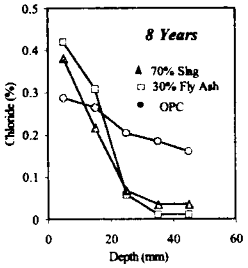
Let's look at some available options...

High-Quality Concrete

- Cl^-, O_2 and CO_2 must reach the reinforcing steel to initiate corrosion
- Salts ingress through alternating wetting and drying
- Lower water-cement ratio and the use of SCMs decrease ingress of harmful entitities and reduce ionic mobility inside concrete
- Concrete must be well-constructed and cured and be resistant to cracks (minimize crack widths as per ACI)
- Adequate cover thickness (not too much for a bridge deck or thermal and shrinkage protection from top mat will decrease)
- C_3A helps to bind Cl^- by forming Friedel's salt - be careful when selecting cement!!

Use of SCMs to Control Corrosion

- Permeability of concrete (diffusion of Cl^- ions) significantly decreased
- 9 % silica fume replacement reduced Cl- diffusivity by a factor about 5 (Gjørv et al. 1994)



M. Thomas

Corrosion Inhibitor

- Definition
  - An admixture that will significantly delay the onset and/or rate of corrosion and, thus, extend the useful service life of reinforced and prestressed concrete structures
- Before mid-1970s, not used in large scale in concrete (Berke 1991)
- Mechanism
  - Most common form (calcium nitrite) works by increasing chloride threshold value
  - Forms a protective coating or competes with Cl^- ions by reaction of the solution with the corroding surface
  - A minimum concentration of the inhibitor to maintain the inhibiting surface film

Commercial Available Inhibitors

- Inorganic
  - Calcium nitrite - most common
  - Sodium nitrite
  - Alkaline Earth Silicate Co-Polymer
- Organic
  - Amines & Fatty Acid Esters
  - Amines & Proprietary Alkanolamines

Calcium Nitrite Inhibitor

- **30% calcium nitrite solution**
- **Anodic corrosion inhibitor - can increase chloride threshold value up to 15 pcy.**
- **Meets ASTM C494 Type C admixture requirements**
- **Recommended dosage of 1.0 to 6.0 gal/yd^3 (5 -30 L/m^3)**

Advantages and Disadvantages of Calcium Nitrite

- **Advantages**
  - Historical data
  - Effect with admixed chlorides
  - Can double as an accelerator in cold weather applications
  - Early concrete strengths are equal or better than reference mixes
  - Best if used in conjunction with SCMs
- **Disadvantages**
  - Accelerating effect (neutral set version also available)
  - Effectiveness in cracked concrete?

Amine / Ester Inhibitor

- **Advantages**
  - Film-forming and permeability reducing mechanism
  - Mixed inhibitor (anodic / cathodic)
  - Single dosage of 1.0 gal/yd^3 (5 L/m^3)
  - Normal set product
  - Better corrosion inhibition in cracked concrete?
  - Sulfate resistance
- **Disadvantages**
  - May require increased dosage of air-entraining admixture
  - May experience some compressive strength loss (typically, 5-10%)
  - Cannot be used with admixed chlorides

FHWA

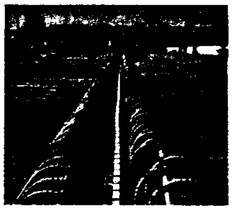
Corrosion-Resistant Alloys

- Austenitic Stainless Steel
  - Type 304 and 316
  - Nitronic 50
- Duplex Stainless Steel
  - Alloy 2205
  - Newer composite steels (MMFX, etc.)?
- Oregon DOT specs calls for use of stainless steel bar in corrosion critical areas
- Cost can be very high.
- Stainless-steel cladding becoming an option

Cramer et al. 2002

Epoxy-Coated Rebars

- First used in a four-lane bridge in America in 1973 as full scale application
- Incorporated into 100,000 structures in North America
- Over two million tons of epoxy-coated rebars
- Contradicting conclusions
  - Prolonged service lives
  - Bridges in Florida Keys constructed in the late 1970s deteriorated in 10 years
  - **Holidays** (holes in coating) may bring about corrosion



PennDOT I-95 Revive Project
Nov. 2002 (Holidays?)

Epoxy-Coated Rebar

The Big Debate

Mixed Lab Results...... Mixed Field Results

Potential Issues

- Nicks, scratches in coatings lead to accelerated corrosion (small anode + large cathode ⇒ Pitting corrosion)
- Not possible to monitor corrosion in the field (no electrical connectivity of rebar)
- Does epoxy soften and de-bond from steel?
- Some states have stopped using ECR (e.g., Virginia)
- Is epoxy coating thermodynamically unstable in concrete? (reported in recent studies)

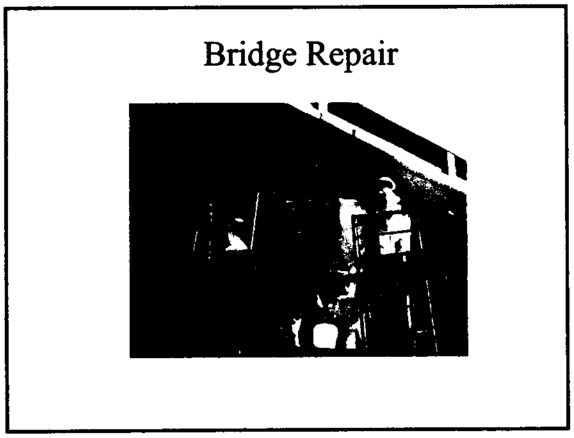
Cathodic Protection

- Based on the fact -- cathodes does not corrode
  - Galvanized rebars
    - Zinc is the anode
    - No protection remains when zinc consumed
    - Not enough for long serve life requirement
  - Use of sacrificial anode system
    - Practical when included in construction
    - Expensive for repair and rehabilitation
  - Use of impressed current system
    - Expensive and extremely complex
    - Stray current may cause more corrosion and trigger ASR

Repair of Corroded Structures

- Condition Evaluation (discussed above)
- Corrosion Severity and Main Causes
- Repair and Rehabilitation
  - Remove concrete and prepare surfaces
    - Pneumatic machines
    - Hydrojetting
    - Milling machines
  - Repair materials
    - Material compatibility (incipient anodes
    - Load transfer and structural safety
  - Additional measures
    - Coatings, sealers, membranes, and barriers
    - Encasement and overlay
    - Realkalization and desalination (extraction of chlorides)

Bridge Repair



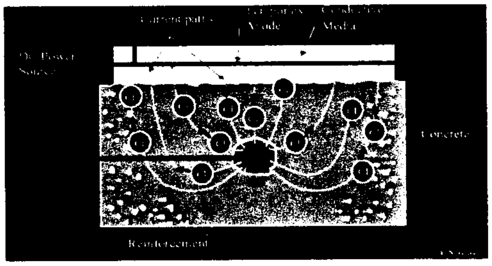
Treatment of Carbonation

- Patch Repair
  - with an anti-carbonaation coating afterwards
- Realkalization
  - Very little in US (Broomfield 1997)
  - Cheap and all surfaces treated
  - Using potential to drive hydroxide into concrete
  - Make sure no risk of ASR and hydrogen embrittlement to prestressing wires
- Corrosion Inhibitors
  - Penetration rate ?
  - Still experimental

Treatment of Chlorides

- Patch repair and coating
  - Effective in patched area, may cause "ring" effect
- Patch repair and overlay/encase
  - Depends on chloride levels and concrete removed
- Cathodic protection
  - Effective if carefully design and monitored
  - Can aggravate ASR and embrittle tendons
- Chloride removal
  - Effective at treated area
  - Lifetime unknown
  - Can aggravate ASR and embrittle tendons
- Inhibitors
  - Effective across treated area
  - Low dosing could cause pitting

Chloride Extraction



http://www.norcure.com/

**Can also be used in conjunction with lithium for ASR control*

Summary

- Corrosion of reinforcing steel is the most common durability problem in the world.
- There are various strategies for preventing damage up front -- it's better to do it right in the first place then to have to pay for repairs...
- Understanding the mechanisms of corrosion help in selecting prevention/mitigation options

Durable/High-Performance Concrete Structures Specifications

Kevin Pruski, P.E.
Bridge Division

Anatomy of HPC Bridge Project

- *Plans*
- *Awarding Contract*
- *Constructing Bridge*
- *Time*

Plans

- *Quantities*
- *Specifications*
- *Contract Drawings*

Quantities

- *Non-Specific HPC Concrete Items*
- *Specific HPC Concrete Items*

Specifications

- *Standard Specifications*
  - *Used for all Contracts*
  - *Contractors know well*
- *Special HPC Specifications*
  - *Used to address specific needs*
  - *Contractors don't always read*

Special Specifications

- *Performance Based Specifications*
  - ***End result parameters for Contractor to achieve***
- *Prescriptive Based Specifications*
  - ***Specific requirements for Contractor to follow***

HPC Performance Specification

- *Concrete Shall Meet the Following:*
  - *Minimum of 4,000 psi at 28 days*
  - *Maximum of 2,000 coulombs at 56 days*

HPC Prescriptive Specification

- *Concrete Shall Contain the Following:*
  - *Maximum w/c ratio of 0.45*
  - *Minimum of 30% Class F fly ash*
  - *5% to 8% Entrained Air*

Contract Drawings

- *Contractors become accustomed to the way thing are commonly done*
- *Contractors prefer to bid and build what is shown on the plans*
- *Change from the norm should be clearly and consistently communicated in the contract*

Awarding Contract

- ***Work is awarded based on low bid***
- ***Low bid contractor may not be the best qualified***

Constructing Bridge

- ***Contractor is responsible to do the work outlined in the plans in accordance with the specifications***
- ***Owner is responsible to ensure that the work is performed in accordance with the plans and specifications***

Time

- ***Contractor wants to finish the work with the least amount of his time expended***
- ***Owner wants the work finished in a timely matter but most importantly wants the structure to last***

History of Durable/HPC

Durable Concrete Progression

- *Concrete of Old*
  - *Well graded aggregates*
  - *Coarser Grind Cement (well graded)*
  - *Lower volume of paste*
  - *Construction time slower*
  - *Not always perfect*
  - *Mix Design 1-2-3*

Durable Concrete Progression (cont)

- *Concrete of Late*
  - *Gap graded aggregates*
  - *Finer Grind Cement (faster setting)*
  - *Higher volume of paste*
  - *Construction time faster*
  - *Mix Designed to Meet Strength at Certain Time*

Texas CIP Slab Specifications

Year	Concrete Class	f 'c (psi)	Cement (Sk / CY)	Water (Gal / Sk)	W / C Ratio
2003	S	4000	no min	no max	0.45
1993	S	4000	6.5	5.0	0.44
1982	S	3600	6.0	5.0	0.44
1972	C	3600	6.0	6.0	0.53
1962	A	3000	5.0	6.5	0.58
1951	A	3000	5.0	7.0	0.62

Texas CIP Substructure Specifications

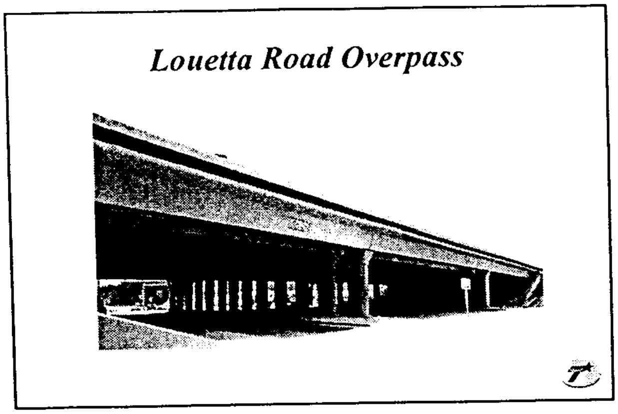
Year	Concrete Class	f 'c (psi)	Cement (Sk / CY)	Water (Gal / Sk)	W / C Ratio
2003	C	3600	no min	no max	0.45
1993	C	3600	6.5	6.0	0.53
1982	C	3600	6.0	6.0	0.53
1972	C	3600	6.0	6.0	0.53
1962	A	3000	5.0	6.5	0.58
1951	A	3000	5.0	7.0	0.62

Initial Texas HPC Projects

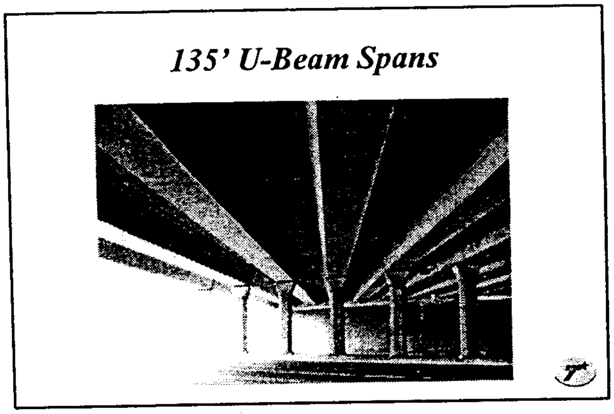
- ***Louetta Road Overpass in Houston***
- ***North Concho River, US 87 & South Orient Railroad Overpass in San Angelo***

SPONSORS

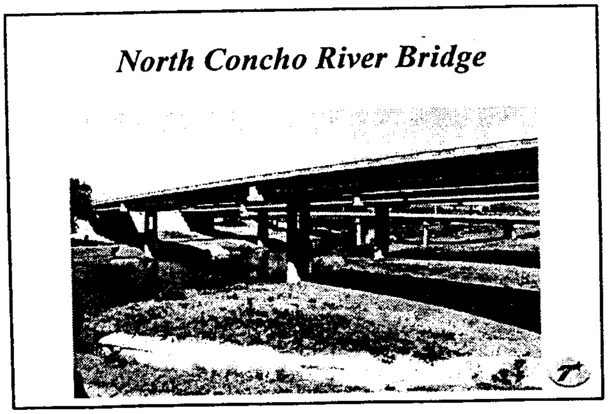
- ***Federal Highway Administration***
- ***Texas Department of Transportation in cooperation with***
- ***The University of Texas at Austin***



Louetta Road Overpass

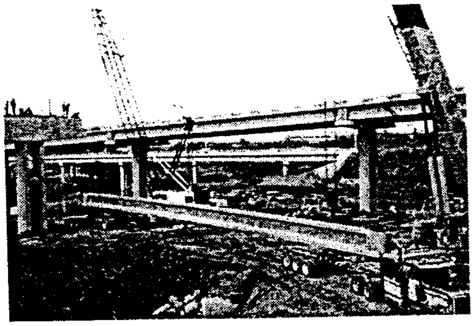


135' U-Beam Spans



North Concho River Bridge

157' Type IV Beam



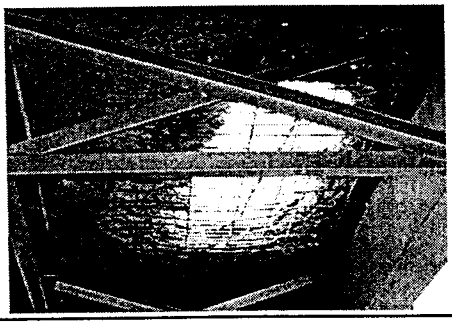
Summary of Projects

What was Learned

- *High strengths are attainable with local materials*
- *Longer spans are attainable but with increased complexity*
- *Wider beam spacings are a direct benefit to higher strength concrete*
- *Higher strengths do not necessary mean increased durability*

Current Use of HPC

Bridge Deck Failure



Substructure Deterioration

Solution: Use High Performance Concrete

How to Obtain HPC

- Specify It
  - End Result Performance Specifications
  - Knowledge Based Prescriptive Specifications

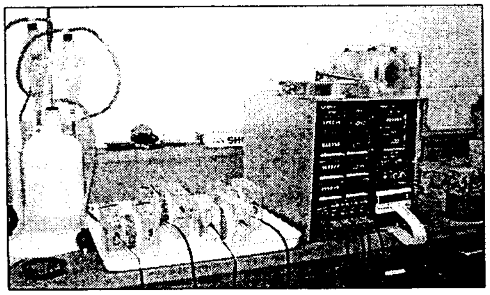
Performance Specification

- Place Responsibility on the Contractor
  - Set Criteria that must be met
  - Have action plan if criteria is not met

Acceptance Criteria

- AASHTO T277, Rapid Chloride Permeability Test
  - Relatively new to Bridge Contractors
  - Perceived variability makes enforcement difficult
  - Uncertainty inflates bid prices

Rapid Chloride Permeability Test



Prescriptive Specification

- Place Responsibility on the Owner
  - Use knowledge that is available to achieve durable concrete
  - Contractor knows exactly what is expected

What Knowledge?

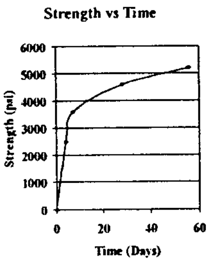
- *The use of Supplementary Cementitious Materials (SCM) can Produce More Durable Concrete*
  - *Fly Ash*
  - *Ground Granulated Blast Furnace Slag*
  - *Silica Fume*
- *Concrete Containing SCM*
  - *Less chloride intrusion (rebar corrosion)*
  - *Mitigates alkali-silica aggregate reactivity*
  - *Resistant to sulfate attack*

Contractor Friendly

- ***Contractor knows in advance what the concrete will cost***
- ***Remove acceptance criteria that is unfamiliar to them***
- ***Require Contractor to be familiar with concrete before construction begins***

Contractor Education

- ***Plot strength versus time curve of concrete at 4, 7, 28, and 56 days***
- ***Shows contractor that the use of SCM can alter the early concrete strengths***



Field Examples

- *Lubbock*
  - *HPC Special Provision to 421*
  - *Substructure - 30% Class F FA, 5% Silica Fume*
  - *Deck - 35% Class F Fly Ash*
  - *Strengths: no problem*
  - *Permeability results:*
    - *Previous with no fly ash - > 4,000 coulombs*
    - *Current with pozzolans < 2,000 coulombs*

Field Examples (cont.)

- *Corpus Christi - PR 22*
  - *HPC Special Provision to 421*
  - *Prestressed Concrete Piling - 25% Class F FA, 8% Silica Fume*
  - *Deck - 35% Class F Fly Ash*
  - *Strengths were slow for prestress release*
    - *Took 3 Mix Designs*
  - *Permeability results:*
    - *Piling Concrete < 350 coulombs*

Change in Philosophy for HPC in Precast/Prestressed Concrete

- *Use Performance Based Criteria*
  - *Allows fabricator to design mix that will optimize casting operation*
  - *Fabricators have more knowledge in concrete production*

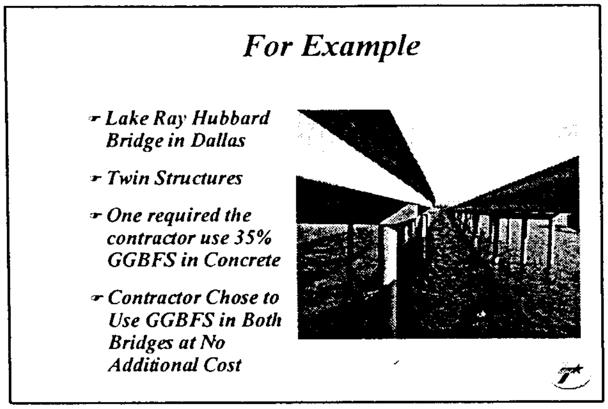
Future Use of HPC

Knowledge Base Grows

- *Test prescribed mix designs*
- *Monitor performance of HPC*
- *Concrete suppliers develop HPC mix designs for future use*
- *Contractors become familiar with HPC*

Options Increase

- *Specifications will have more options*
- *Specifications will allow Contractor freedom to develop own mix designs and we verify*
- *HPC becomes the Standard in Texas*



For Example

- *Lake Ray Hubbard Bridge in Dallas*
- *Twin Structures*
- *One required the contractor use 35% GGBFS in Concrete*
- *Contractor Chose to Use GGBFS in Both Bridges at No Additional Cost*

Current Version of HPC Special Provision to 421

Special Provision to 421

- *High Performance Concrete*
  - *Include air*
  - *Include all ASR mitigation options*
  - *Include Type II Cement for sulfate resistance or allow options*
  - *Require the use of SCM*
  - *Give option to meet performance requirements*
  - *Precast concrete to meet performance requirments*
  - *Reduce w/c ratio*

TxDOT Workshop

Design of Durable Concrete

Session 10: Cracking and Effects on Concrete Durability

CONCRETE DURABILITY CENTER (CDC)

Outline of Presentation

- Significance
- Types of Cracking
- Causes and Preventive Measures

Everything we've discussed the past two days is useless if we can't control cracking...

We must understand why concrete cracks and implement it both technically and practically.

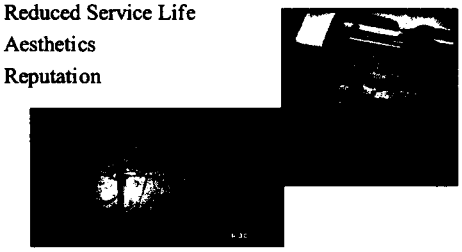
Primary Types of Cracking

- Plastic Shrinkage, Plastic Settlement
- Drying Shrinkage (including autogenous shrinkage)
- Thermal (from initial heat of hydration, ambient fluctuations thereafter)
- Structural (design loads, reflective, creep)
- Chemical (corrosion, ASR, sulfate attack, carbonation)

The focus of this session will be on shrinkage cracking (plastic, autogenous, drying, thermal, etc.)

Negative Effects of Cracking

- Cost to Control, Repair, and Maintain
- Impact on Load Carrying Capacity
- Reduced Service Life
- Aesthetics
- Reputation



Causes and Preventive Measures for Cracks

"Find the cause, and the remedy will suggest itself !"

- Joe W. Kelly, 1963

Why Concrete Cracks ?

- Maximum Stress Rule
  - Stresses induced by physical/chemical factors (internal and external) exceed the strength of concrete at a certain **age**
- Maximum Strain Rule
  - Strains from volume change exceed the deformation capacity of concrete at a certain **age**
- More Complicated Fracture Mechanics Models
  - Not covered here

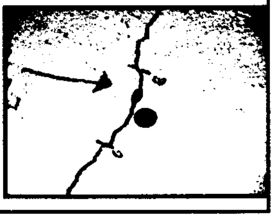
Types of Cracks

- Map Cracks (Pattern Cracks)
  - Restraint of surface layer by inner concreter or backing

Photo: M. Thomas

Single Continuous Cracks

- external restraints or rebars



Volume Change of Paste and Concrete

- Cement Paste
  - Shrinkage or swelling only restrained by crystalline hydration products
  - Shrinkage several times as much as concrete
- Concrete
  - Restrained internally by aggregates and rebar
    - Smaller shrinkage or swelling values
  - Restrained externally
    - Adjacent structures, foundation ...
    - May result in cracking

Plastic Shrinkage Cracking

- Plastic Shrinkage
  - Shrinkage of concrete due to the loss of water when cement paste is plastic
  - Occurs after cumulative evaporation exceeds cumulative bleeding and concrete goes into tension
- Plastic Shrinkage Cracking
  - Surface cracking due to plastic shrinkage
  - Three-dimensional
  - Usually expressed as linear strain
  - Cracks 1 to 3 ft apart and 1 to 2 inches deep

www.beaverconcrete.com

Influencing Factors

- Plastic Shrinkage
  - Higher cement content, higher plastic shrinkage
  - Lower water-cement ratio, higher plastic shrinkage
  - Relation with bleeding not straightforward
    - Retardation causes more bleeding and increased shrinkage
    - Greater bleeding capacity, less plastic shrinkage cracking

When Does Plastic Shrinkage Cracking Occur?

- Before the setting of cement paste (no deformation resistance)
- Exposed concrete surface drying out (capillary pressure increases)
- The contraction of paste restrained by aggregate or subgrade
- Paste can not accommodate the contraction and cracking happens

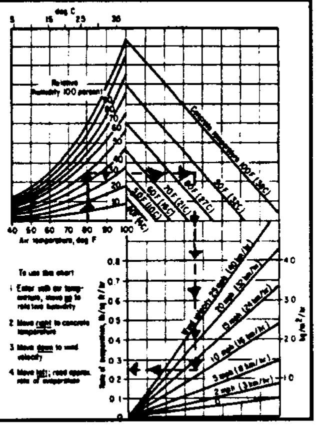
ACI Approach

> "Plastic shrinkage cracking is frequently associated with hot weather concreting in arid climates. It occurs in exposed concrete, primarily in flatwork, but also in beams and footings and may develop in other climates whenever the evaporation rate is greater than the rate at which water rises to the surface to recently placed concrete by bleeding."
>
> – ACI 305R-91

Factors Affecting Evaporation Rate

- Driving Forces
  - Solar radiation
  - Vapor pressure difference
- Wind
  - Many approaches to determine wind speed
  - Even observations about nearby object
- Air Temperature
  - Avoid direct rays of sun during measurement
- Relative Humidity
- Concrete (Water) Temperature

- ACI nomograph for estimating rate of evaporation of surface moisture from concrete
- 0.2 lb/ft^2/hr is the usually assumed to be threshold value



Bleeding Rate and Capacity

- Bleeding due to settlement of aggregate and cement particles
- Bleeding (of free water) may last 15 to 30 minutes at most and thereafter the rate diminishes (Powers 1968)
- Pore structure affects transport of water to surface
- Cement content, mineral admixtures affect available free water for bleeding
- No bleeding for concrete containing silica fume!

What Can We do?

DO NOT WAIT UNTIL CONCRETE DRIES!

Reducing Evaporation Rate

- Erect windbreaks to slow down wind
- Shade surface of concrete from rays of sun
- Cool concrete in hot weather and avoid overheating in cold weather
- Reduce time between placing and start of curing
- Apply protective coverings
  - Sand, wet burlap, paper, or membrane curing compound
- Fog spray immediately after finishing
- Use of retarding admixtures be cautioned

Increasing Bleeding Rate

- Avoid excessive high cement content
- Avoid large amounts of fine aggregate (less absorptive surface areas)
- Water content as high as possible with good design practice
- Dampen dry and absorptive aggregates
- Moisten subgrades and forms before pouring
- OBVIOUSLY – WE DON'T WANT TOO MUCH BLEEDING, JUST ENOUGH TO KEEP PROTECTIVE LAYER ON TOP...

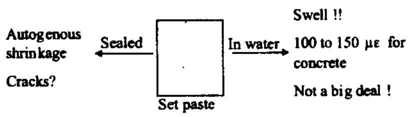
Increase Tensile Strength

- Optimize materials and mixture proportions to win "early strength race"
- Use synthetic fibers (polypropylene, nylon, etc.) to increase early tensile strength and strain capacity. Typical dose is 0.5 to. 1.5 pcy.

Plastic Settlement Cracking

- Caused by differential settlement of fresh concrete
  - Over large aggregate particles or rebar
  - Subsidence of subgrade
  - Movement of formwork
- Proper compaction of subgrade
- Avoid excessive slump or mixtures prone to segregation
- Avoid excessive vibration of formwork or structure
- Can re-vibrate and heal many settlement cracks

Autogenous shrinkage


Autogenous shrinkage

Cracks?

Sealed

Set paste

In water

Swell !!

100 to 150 $\mu\varepsilon$ for concrete

Not a big deal !

- Autogenous shrinkage (self-desiccation, chemical shrinkage): no loss of water
- Happens in the interior of a concrete mass
- Considered alongside drying shrinkage
- Can add to tensile stresses from thermal contraction and drying shrinkage

Autogenous Shrinkage: A Problem?

- Considered to be small in the past
  - In the order of 50 millionths
  - As part of drying shrinkage
- Not negligible now
  - Become significant with use of low w-c ratios, high-range water reducers, and silica fume
  - Increase with higher temp., higher cement content, higher fineness, and higher C_3A and C_4AF contents
  - A value of 700 millionths reported for concrete with a w-c ratio of 0.17

Drying Shrinkage

Bryant Mather - Highway Research Board Committee, 1963

"The reduction in concrete volume resulting from a loss of water from the concrete after hardening"

Magnitude and Timing of Drying Shrinkage

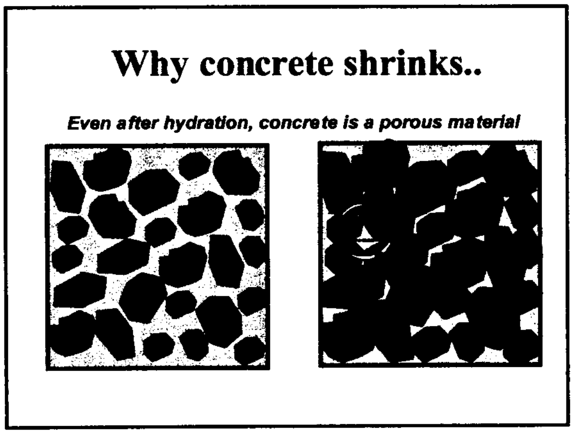
- Drying Shrinkage Magnitude:
  - Typical strains range from 400 to 800 millionths

- Drying Shrinkage Timing
  - *4-34% of ultimate --- 14 days*
  - *40-80% of ultimate --- 90 days*
  - *66 to 85% of ultimate --- 365 days*

What Causes Drying Shrinkage?

- Drying Shrinkage is a complex phenomena involving several different mechanisms .
- Capillary action and surface tension of water are primary causes of shrinkage for internal humidities ranging from 40 to 100%.

  (which covers virtually all field concrete)

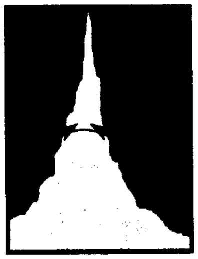


Why concrete shrinks..

Even after hydration, concrete is a porous material

In detail..

- Pores lose water due to cement hydration and evaporation.
- As pores become less than fully saturated, meniscus forms at the air-water interface due to surface tension.
- The surface tension of pore solution which forms meniscus also exerts inward pulling force on the side walls of the pore.
- These forces in all pores in range of 2.5 to 50 nm is primary cause of shrinkage.



Drying Shrinkage

- Factors affecting shrinkage
  (In order of importance - approximately)
  - Aggregate to paste ratio
  - Stiffness of aggregate
  - Water content

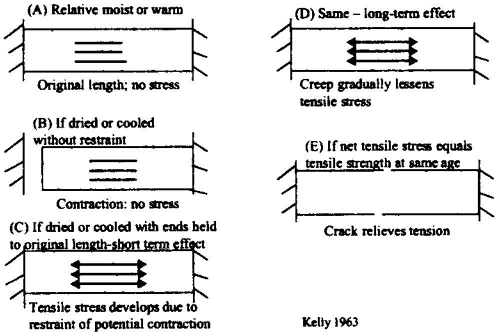
Drying Shrinkage

- Factors affecting shrinkage
  (In order of importance - approximately)
  - Pore size distribution f(w/c, fineness, pozzolans, admixtures)
  - Aggregate absorption and shrinkage
  - Aggregate cleanliness
  - Cement chemistry and fineness
    - Type II < Type I < Type III

Drying Shrinkage

- Other factors affecting shrinkage
  - Placing temperature (mainly due to impact on water demand)
  - Curing temperature (high-temperature curing reduce drying shrinkage significantly)
  - Member volume to surface area ratio (more massive members shrink slower)
  - Maximum aggregate size
  - Environmental conditions
  - Air entraining may increase 5-10 %

Drying Shrinkage Cracking



(A) Relative moist or warm

Original length; no stress

(B) If dried or cooled without restraint

Contraction: no stress

(C) If dried or cooled with ends held to original length-short term effect

Tensile stress develops due to restraint of potential contraction

(D) Same – long-term effect

Creep gradually lessens tensile stress

(E) If net tensile stress equals tensile strength at same age

Crack relieves tension

Kelly 1963

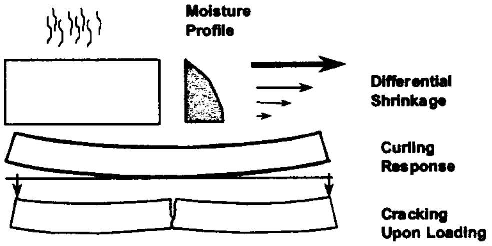
Curling

"Curling is caused by drying shrinkage and by negative moisture or temperature gradients across the thickness of the slab"

R. Yetterberg
Concrete International

Curling Impact on Cracking

- Concrete slabs curl primarily due to differential moisture through the thickness, and the differing shrinkage response.



Curling

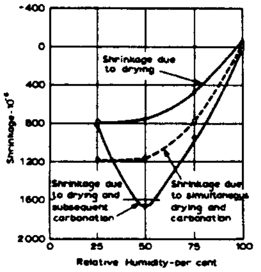
- In slabs on grade, curling is a major contributor to cracking - in many cases it is the predominant factor
- Stiffer subgrades will result in higher tendency to crack for a given amount of curling

Carbonation Shrinkage

- Shrinkage caused by carbonation reaction $Ca(OH)_2 + CO_2 \Longrightarrow CaCO_3$
- Affected by drying and carbonation sequence
- Carbonation is accompanied by drop in pH, as previously discussed.

Drying and Carbonation Shrinkage

- The effect of carbonation shrinkage can not be ignored
- Carbonation most significant at medium relative humidity



Verbeck, 1958

Let's consider a couple other ways to combat shrinkage cracking…

Shrinkage-Compensating Cement

- Early development was in Russia and France
- Formation of expansive ettringite at early age
- ASTM C 845 recognized three types
  - Type K $C_4A_3\overline{S} + C$ (only one available in US)
  - Type M $CA + C_{12}A_7$
  - Type S Excess C_3A
- **Restraint** required during the expansion
- Shrinkage-compensating cement shrinks like normal cement thereafter.

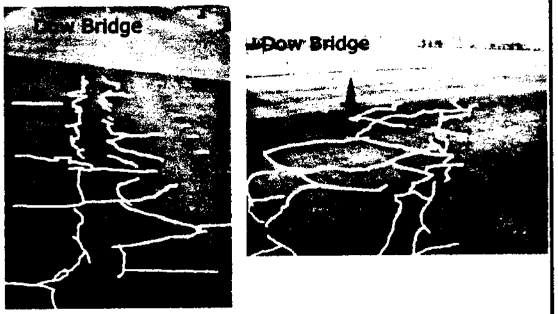
Shrinkage Reducing Admixture

- The inclusion of SRA into the mix design significantly reduces the surface tension of the pore water solution, leading to lower tensile force in pores, and less shrinkage.,,,

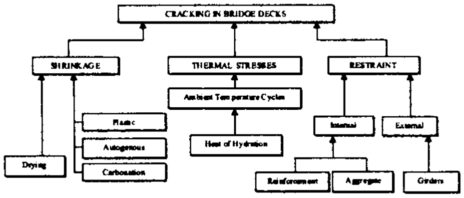
  - Thereby, reducing shrinkage by as much as 80% at 28 days.
  - And, reducing ultimate shrinkage on the order of 35% to 50%.

Research at UT on Shrinkage Cracking

Bridge Deck Cracking in TX



Shrinkage Cracking - TxDOT Projects 4098 and 4563


CRACKING IN BRIDGE DECKS

SHRINKAGE

THERMAL STRESSES

RESTRAINT

Ambient Temperature Cycles

Plastic

Autogenous

Carbonation

Drying

Heat of Hydration

Internal

External

Reinforcement

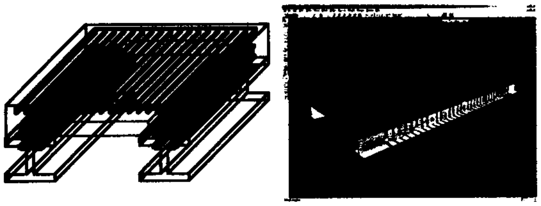
Aggregate

Girders

Flowchart by Mike Brown and Greg Sellers

Shrinkage Cracking - TxDOT Project 4098

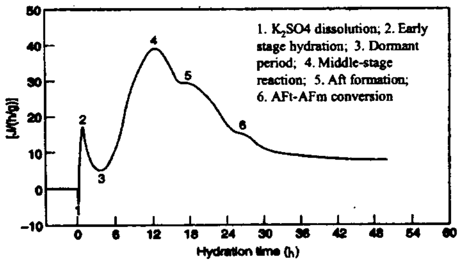
Linking the Lab to the Field



Thermal Shrinkage

- Most solids expand on heating and contract on cooling (including concrete)
- Hydration of concrete is a heat-generating process
- Hydration kinetics of cement changes with cement composition and environment
- Shrinkage (contraction) matters because of the weak tensile strength of concrete
- Mass concrete
  - Massive dimensions (in the paste)
  - Any concrete member where thermal behavior may lead to cracking unless measures taken

Hydration heat evolution of Portland Cement



1. K_2SO4 dissolution; 2. Early stage hydration; 3. Dormant period; 4. Middle-stage reaction; 5. Aft formation; 6. AFt-AFm conversion

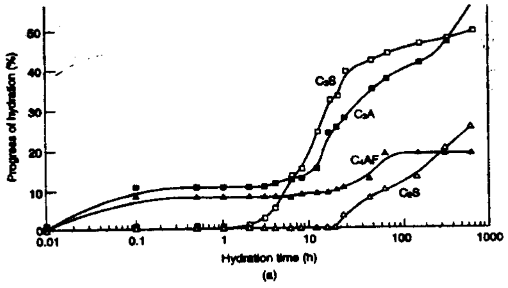
Odler, 1998

Heats of Hydration of Portland Cement compounds

Unit: Cal/g

Compound	3 days	90 days	13 years
C_3S	58	104	122
C_2S	12	42	59
C_3A	212	311	324
C_4AF	69	98	102

Consumption of Clinker Phases



Odler, 1998

Thermal Properties of Concrete

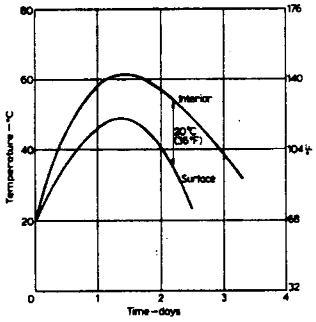
- Thermal Conductivity (K)
  - Ability to conduct heat as ratio of flux of heat to temperature gradient (1.4 to 3.6 J/m^{2}sC/m)
  - Crystallinity of rock increases conductivity (quartz > dolomite > limestone > granite > basalt)
- Specific Heat (C)
  - Ability to resist temperature change (840 to 1170 J/kg per C)
  - Increases with moisture content of concrete
- Thermal Diffusivity
  - Rate at which temperature changes within a mass (0.002 to 0.006 m^2/h)
  - Defined as $\delta = \frac{K}{c\rho}$ _ is density of concrete

Coefficient of Thermal Expansion

- Depends on mixture proportions and materials (especially aggregate type)
- Neat cement paste may have a value of 19 x 10^{-6} per C at the age of 2 years
- Aggregates have much smaller coefficients than that of cement paste
- Typical values of concrete with different aggregates: (x 10^{-6} per C)
  - Gravel: 13.1
  - Granite: 9.5
  - Sandstone: 11.7
  - Limestone: 7.4

Temperature Profile in Concrete

- Hydration generates heat in concrete
- Temperature differences inside concrete may become excessive, especially for mass concrete (particularly after form removal)
- Temperature differences exceeding 35 F cause concern for cracking (topic of TxDOT 4563(



Thermal Cracking Mechanism

- Similar to drying shrinkage
- Complex phenomenon because creep of young concrete is very high
- Restraint includes:
  - Internal: portions of concrete that expand or contract less always restrain other concrete portions to expand or contract more
  - External
    - Concrete not standing alone (existing other structural elements)
    - Difficult to determine the degree of restraint

Thermal Shrinkage at Early Age

- Heat evolution and temperature rise are complex
- Higher temperature accelerates hydration and heat evolution
- Interior concrete has higher temperature than surface concrete
- Temperature-rising stage (surface in tension)
- Cooling stage (interior in tension)

What Can We Do?

Reduce total heat and evolution rate

- Use less cement content (larger aggregate volume)
- Use of fly ash and slag
- Control of concrete temperature before placing (construction time)
- Avoid cement with high specific surface

Understand thermal behavior of concrete

- Appropriate structural detailing of reinforcement
- Measures to cool interior concrete
- Keep temperature differences in concrete within 10 C (18 F) Neville, 1996

Thermal Stress in Hardened Concrete

- Temperature gradient easily formed in concrete structures
- Curling or warping could be formed in concrete pavement (different loading conditions other than considered in design)
- Temperature stress in concrete structure could be highly non-linear along the depth
- Combined with stress due to load, crack may happen
- Temperature shock (27 F) caused contraction were found to cause crack in concrete pavement in Germany
  - Cement with high alkalis
  - Cement with high specific surface area

Springenschmid et al. 1994

What If Concrete Cracks?

- More than 30 variables may be involved
- Durability of concrete jeopardized
  - Water penetrates more easily
    - Accelerates ASR, DEF, etc.
    - Facilitates corrosion
  - CO_2 and Cl^- move in faster
    - Carbonation
    - Triggers corrosion
- Aesthetics -- public concern
- Repair costly

Minimizing Concrete Cracking

"In one respect, concrete is like a pet dog – it will take a lot of abuse and still serve faithfully. If concrete would fail whenever neglected or abused, we would certainly treat it with more respect and care."

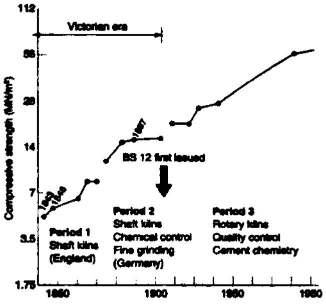
- Kelly, 1963

Nowadays, animal rights are protected!!

Our pet concrete needs more care, especially because it is more fragile with modern cements.

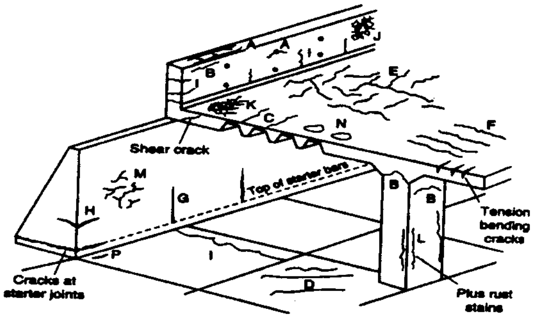
Evolution of Portland Cement

- Increased fineness
- Composition change (higher C_3S)
- Emission of particle matters more strict (more alkali sulfate in cement)
- Modern cement more prone to cracking



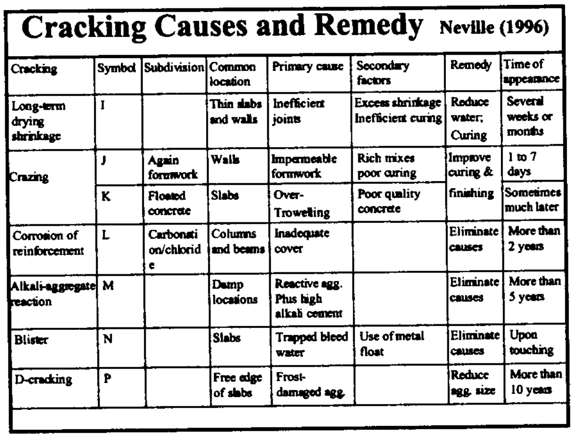
Cracking Diagnosis

- A TOUGH JOB!!



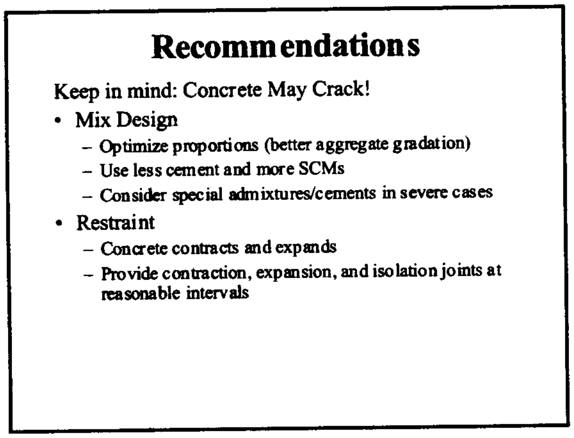
Cracking Causes and Remedy Neville (1996)

Cracking	Symbol	Subdivision	Common location	Primary cause	Secondary factors	Remedy	Time of appearanc
Plastic settlement	A	Over reinforcement	Deep sections	Excess bleeding	Rapid early Drying conditions	Reduce bleeding Or revibrate	10 min to 3 hour
	B	Arching	Top of columns				
	C	Change of depth	Trough and waffle slabs				
Plastic shrinkage	D	Diagonal	Pavement and slabs	Rapid early drying	Low rate of bleeding	Improve early curing	30 min To 6 hour
	E	Random	Reinforced concrete slabs				
	F	Over reinforcement	Reinforced concrete slabs	Rapid early drying or steel near surface			
Early thermal contraction	G	External restraint	Thick walls	Excess heat generation	Rapid cooling	Reduce Heat and/or insulate	1 day To 2 or 3 weeks
	H	Internal restraint	Thick slabs	Excess temperature gradients			



Cracking Causes and Remedy Neville (1996)

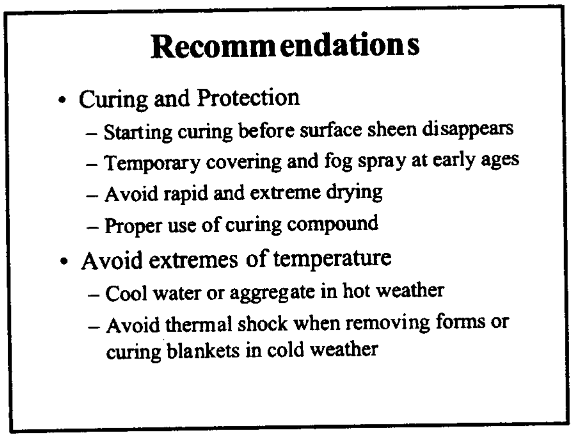
Cracking	Symbol	Subdivision	Common location	Primary cause	Secondary factors	Remedy	Time of appearance
Long-term drying shrinkage	I		Thin slabs and walls	Inefficient joints	Excess shrinkage Inefficient curing	Reduce water; Curing	Several weeks or months
Crazing	J	Again formwork	Walls	Impermeable formwork	Rich mixes poor curing	Improve curing & finishing	1 to 7 days
	K	Floated concrete	Slabs	Over-Troweling	Poor quality concrete		Sometimes much later
Corrosion of reinforcement	L	Carbonation/chloride	Columns and beams	Inadequate cover		Eliminate causes	More than 2 years
Alkali-aggregate reaction	M		Damp locations	Reactive agg. Plus high alkali cement		Eliminate causes	More than 5 years
Blister	N		Slabs	Trapped bleed water	Use of metal float	Eliminate causes	Upon touching
D-cracking	P		Free edge of slabs	Frost-damaged agg.		Reduce agg. size	More than 10 years



Recommendations

Keep in mind: Concrete May Crack!

- Mix Design
  - Optimize proportions (better aggregate gradation)
  - Use less cement and more SCMs
  - Consider special admixtures/cements in severe cases
- Restraint
  - Concrete contracts and expands
  - Provide contraction, expansion, and isolation joints at reasonable intervals



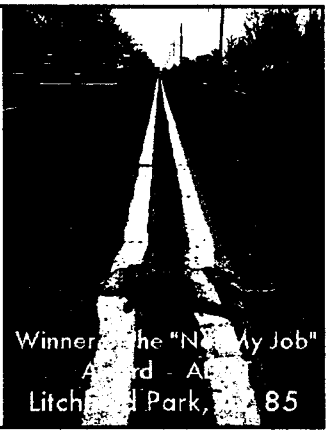
Recommendations

- Curing and Protection
  - Starting curing before surface sheen disappears
  - Temporary covering and fog spray at early ages
  - Avoid rapid and extreme drying
  - Proper use of curing compound
- Avoid extremes of temperature
  - Cool water or aggregate in hot weather
  - Avoid thermal shock when removing forms or curing blankets in cold weather

So Remember…

Design for Durability

But Don’t Forget About Cracking



So You Spec'd HPC

Now what?

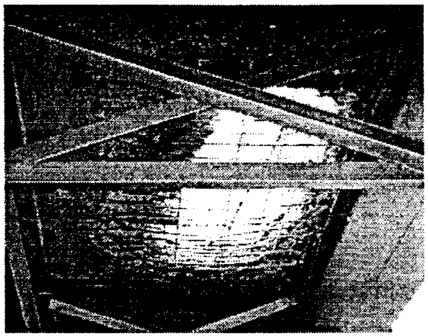
What is HPC for TxDOT?

Concrete that is designed for special requirements

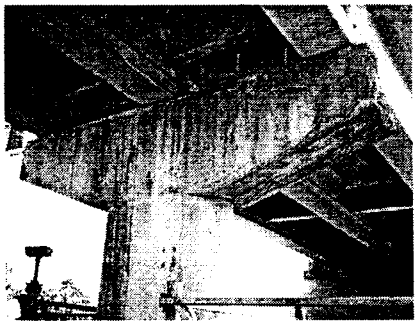
Specialized Concrete

- Durability
- High Strength
- High Early Strength
- Self Consolidating
- Underwater Placements

"LPC"



"LPC"



Constructability Outline

- General Placement Issues
- Supplementary Cementitious Materials (SCM's) - effect on construction
- Plastic Shrinkage Cracking/Water Demand
- Curing
- Form removal

Effect of SCM's on Construction

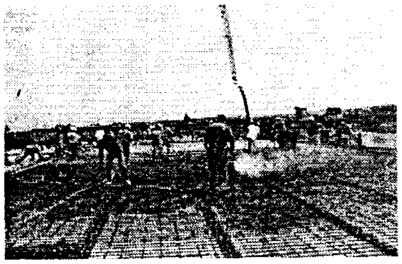
- General Placement Issues

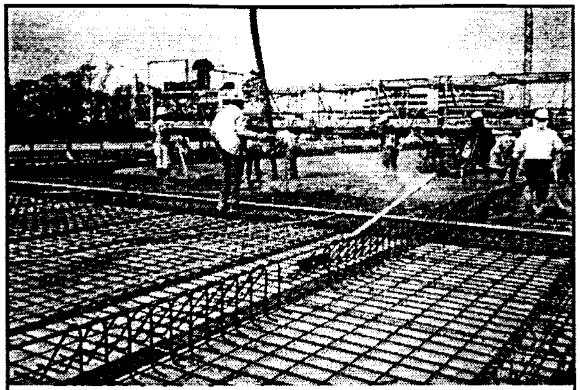
- Fly Ash
- Silica Fume
- GGBF Slag

HPC Placement Issues

"Good Concrete Practice"

Pre-wetting Forms





Too much water?

Effect of SCM's on Construction

- General Placement Issues

- Fly Ash
- Silica Fume
- GGBF Slag

Types of Fly Ash

- Class C - Self-cementing properties
  - produced from burning sub-bituminous coals (lignite)
- Class F - No self-cementing properties
  - produced from burning bituminous coals (anthracite)

Type C flyash

- Delays set but does not affect initial strength gain
- Strength and self cementing properties are gained via CaO.
  - CaO adds heat, but typically not as much as TY I/II cement.
  - Contains small amounts of C_3A that is not reported

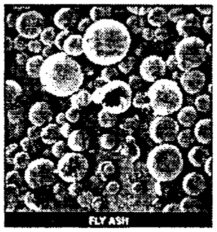
Not good for sulfate resistance

Type F Flyash

- Delays initial strength gain, does not interfere with set.
- Cold weather adds additional strength delay
- Does not add heat to concrete
- Strength is created via chemical reaction with by product of hydration CaOH. Does not possess self cementing properties.

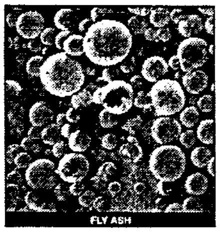
Improved Workability and Finishability

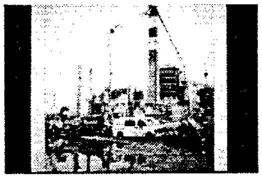
- Ball bearing effect
- Fineness



Improves Pumping

- Particle size and shape





Fly Ash Cautions

- Slower strength gain/delayed form removal
  - Temperature affects this significantly
- Carbon/Air Entraining interaction

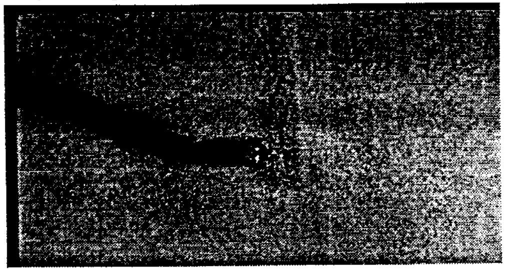
Effect of SCM's on Construction

- General Placement Issues

- Fly Ash
- Silica Fume
- GGBF Slag

Silica Fume

Dry, Compacted



Silica Fume Facts

- A By-Product From The Production Of Silicon Metal Or Ferrosilicon Alloys.
- Consists Primarily of Silicon Dioxide (SiO_2). Which consumes CaOH to form C-S-H.
- 100 Times Smaller Than Cement (0.1um).
  - "Micro-filler"
- Builds high strength, early strength

Silica Fume Facts

- Silica Fume Has More Surface Area Than Cement.
  - ✓ Greater Water Demand
  - ✓ More Cohesive
  - ✓ Less Prone To Segregation
- Slump 1" to 2" Higher Than Normal - may need to use Low/Mid range WR

Silica Fume Cautions

- More difficult to handle, "sticky" to finish
- More expensive than fly ash or GGBFS
- Mix well to avoid "balling"
- Little or no bleed water
- High Plastic Shrinkage Cracking Potential

Finishing Practices

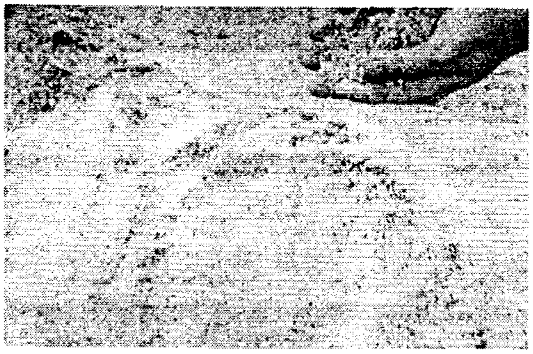
- Conduct A Trial Placement.
- Use Of Vibratory Screed vs drum-type
- Silica Fume Concrete May Be Sticky.
- Fog, Fog, Fog, Fog, Fog, Surface a lot.
- Watch Evaporation Rates
- Golden Rule : Under Finish!

Effect of SCM's on Construction

- General Placement Issues

- Fly Ash
- Silica Fume
- GGBF Slag

GGBFS



GGBFS Facts

- Formed when molten blast furnace slag is rapidly chilled
- Grades 80, 100, 120
- Has significant self-cementing properties => Can be used at higher replacement levels
- Lowers heat of hydration
- May look "stained" initially but whitens upon oxidizing

Ground Granulated Blast Furnace Slag or GGBFS

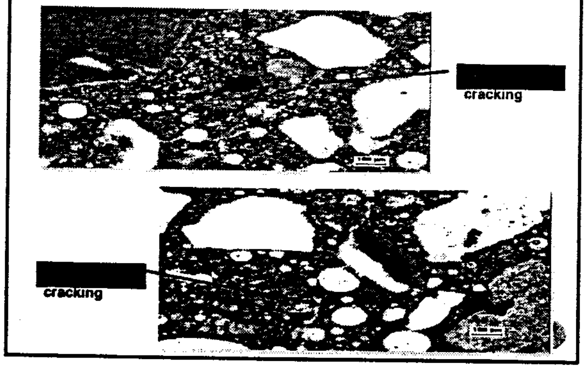
- Delays initial strength gain
- Cold weather adds additional strength gain delay
- GGBFS cement replacement rates over 40% show an increased tendency to dry shrink crack.

GGBFS Cautions

- Increases initial set time
- Lower early strength
- Replacement rates over 40% can Dry Shrink Crack

- May be prone to scaling at higher dosages

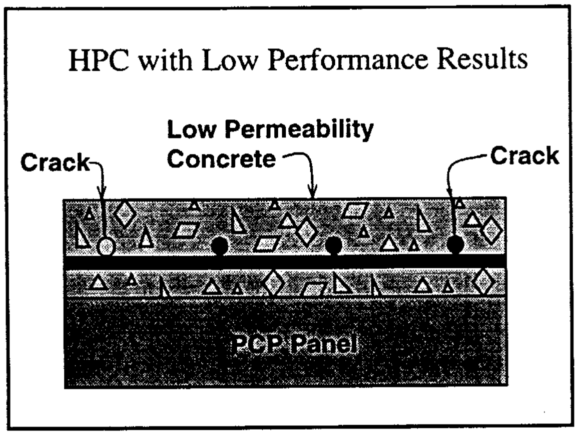
Micro-cracking - Concrete (50% Slag)



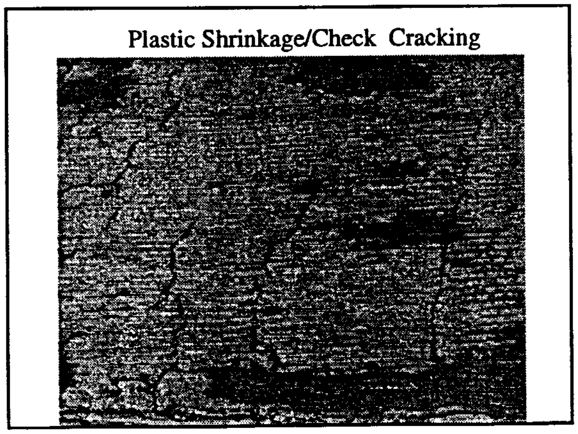
SCM Summary

- Each material contributes pozzolanically - more glue
- Differences in time of set and strength gain
- Each has different side effects/benefits

Plastic Shrinkage & Water Demand



HPC with Low Performance Results



Plastic Shrinkage/Check Cracking

Plastic Shrinkage Cracking

PSC Control

- Erect Wind Breaks?
- Light Fog Spray.
- Evaporation Retardant.
- Cure Immediately After Finishing.

Cracking may begin at rates above 0.10#/sf/hr and will begin at rates above 0.25 #/sf/hr.

From ACI & C-1 Manuals

at 0.1, cracking may occur

at 0.25, cracking will occur

This chart is for "normal" concrete mixes with cement only

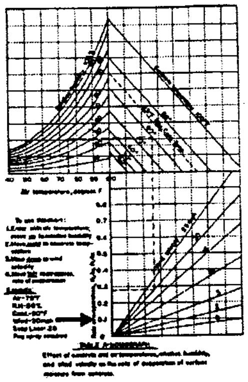
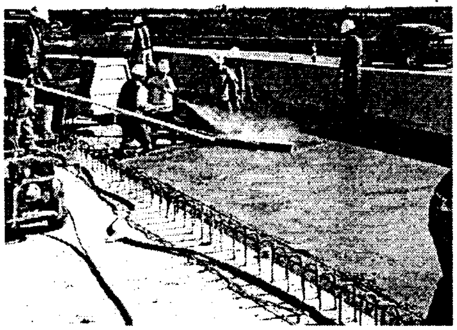


Fig 4-10

Fogging: Yes

Fogging: No



Evaporation Retarder

- CONFILM by MasterBuilders
- EUCOBAR by Euclid
- SIKAFILM by Sika

- Allowed for Concrete Pavement in Special Provision 360-029

Use of Evaporation Retarder

- Use after screeding (but before water sheen disappears)
- Is NOT a curing agent - must still cure properly
- No need to add “finishing water”
- Apply using hand-held sprayer

Curing requirements

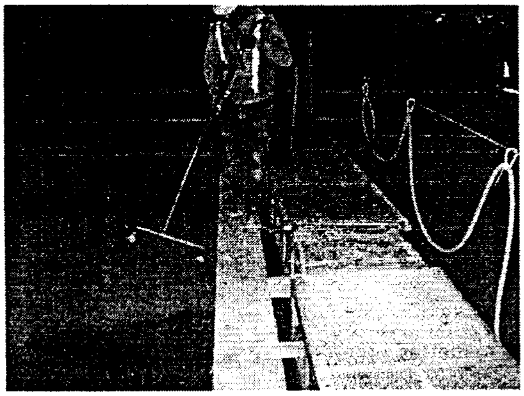
- Bridge Decks with Type I cement require 8 days of wet curing, Decks with Type I/II or II cement, fly ash, or GGBFS require 10 days of wet curing.
- Once design strength is achieved the contractor can use deck but curing must be maintained for required period.

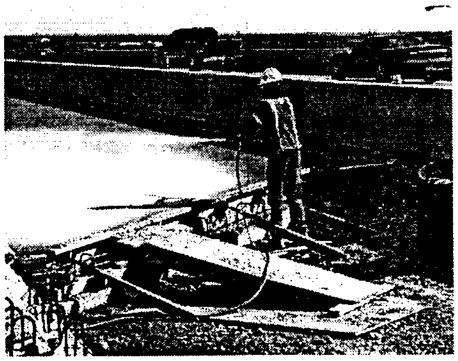
Objectives of Curing

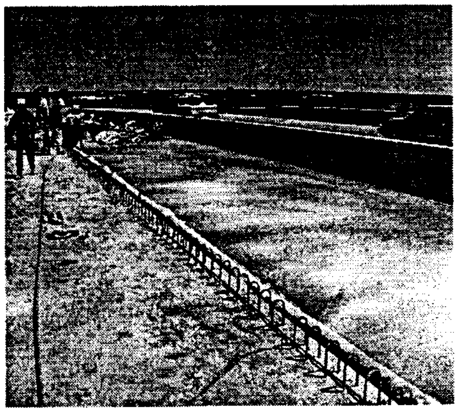
- Stop the loss of water so hydration continues - does not add water
- Maintain favorable temperatures
- Why cure?
  - Stronger Concrete
  - Lower Permeability - Increase Durability

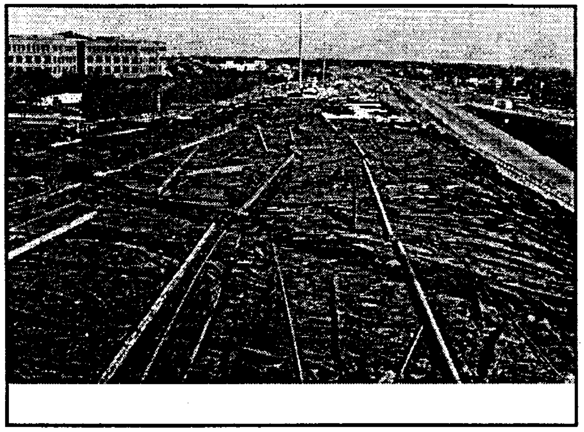
Curing Steps

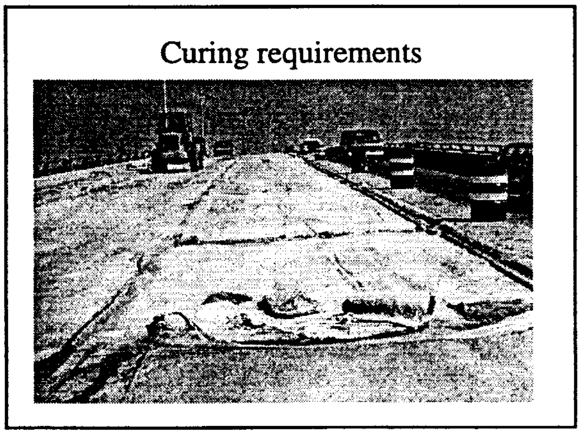
1) Evaporation Retarder (if needed, not req'd in specs)
2) Interim Cure with Curing Compound
   180 sf/gal - apply after water sheen is gone
3) Final Water Cure - usually wet mats - apply as soon as you can walk on it.





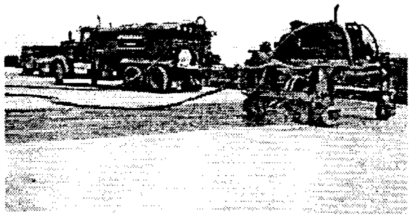






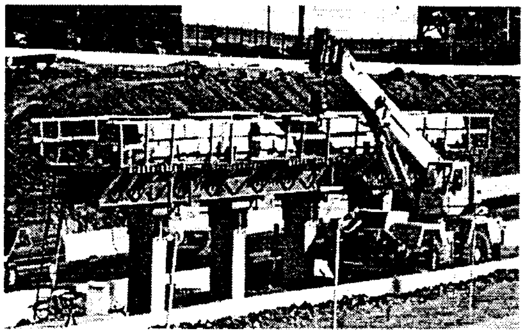
Curing requirements

The future for deck finishing



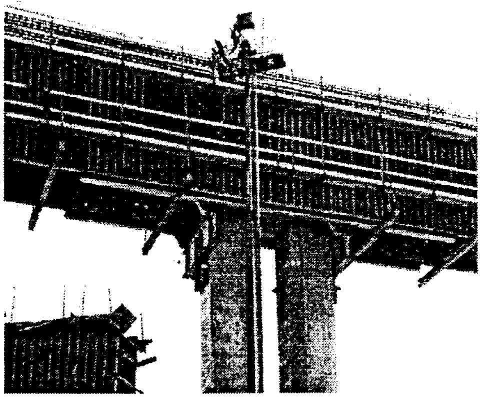
Form removal

- New spec will reduce the strength requirement for weight supporting form removal.
  - But not loading.
  - Loading must be performed at design strength.
- So, forms will be able to be removed sooner but beam placement will not be allowed until design strength is achieved.



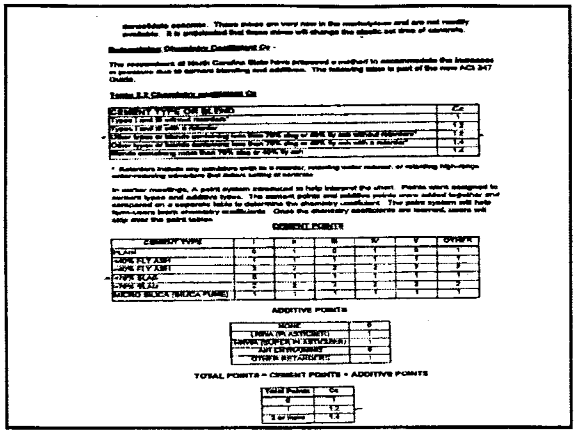
All SCM's affect rate of placement . NCState developed formulas to help model lateral concrete pressure.

- Formula for Columns is as follows:
- $R_{Columns} = T\{ (P/C_w C_c - 150) /9000\}$
  - R = Rate of Placement
  - T = Temperature in °F
  - P = Maximum lateral concrete pressure
  - C_c = Chemistry coefficient
  - C_w = use 1.0 as indicated on the chart



If all variables remain constant except the chemical coefficient (C_C) then rate of placement changes are as follows:

- $P=1{,}400$; $T=80°F$; $C_w=1.0$; C_c= as defined
- When $C_c = 1.0$; $R_{columns}$= 11 ft/Hr
- When $C_c = 1.2$; $R_{columns}$= 9 ft/Hr
- When $C_c = 1.4$; $R_{columns}$= 7.5 ft/Hr



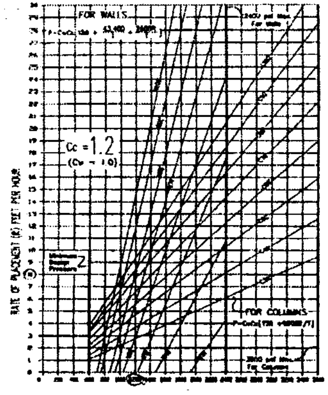
CEMENT POINTS

ADDITIVE POINTS

NONE	0
LRWRA (PLASTICIZER)	1
HRWRA (SUPERPLASTICIZER)	1
AIR ENTRAINING	0
OTHER RETARDERS	1

TOTAL POINTS = CEMENT POINTS + ADDITIVE POINTS

Total Points	Cc
0	1
1	1.2
2 or more	1.4



MAXIMUM LATERAL CONCRETE PRESSURE (P) lbs./sq. ft.

LATERAL CONCRETE PRESSURE vs RATE OF PLACEMENT FOR VARIOUS TEMPERATURES (° F)