Supplementary Cementitious Materials (SCMs):
Slag Cement

Understanding ASTM International Test Procedures for Cement and Concrete - Staying Up to Standard

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Outline

- Supplementary Cementitious Materials Overview
  - Slag Cement Comparison
- Manufacturing
- Specification
- Benefits
  - Fresh Properties
  - Hardened Properties
- Case Studies/Applications

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Terminology

- ***Slag Cement***
- Ground Granulated Blast Furnace Slag (GGBFS)
- Granulated blastfurnace slag (GBFS)

What are SCMs?

- Supplementary Cementing Materials (SCMs)
  - A material that, when used in conjunction with portland cement, contributes to the properties of the hardened concrete through hydraulic or pozzolanic activity.

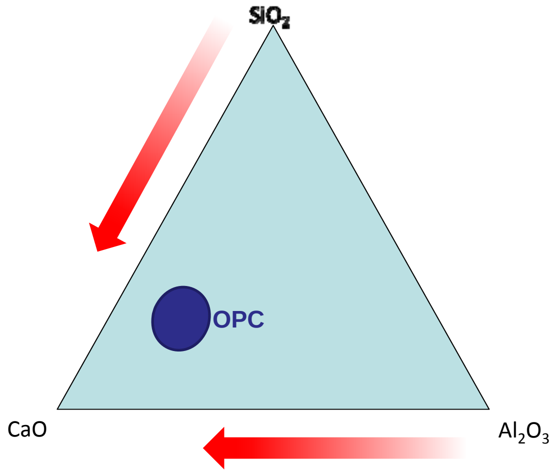
From left to right:

- Fly ash (Class C)
- Metakaolin (calcined clay)
- Silica fume
- Fly ash (Class F)
- Slag
- Calcined shale

Two Categories of SCMs

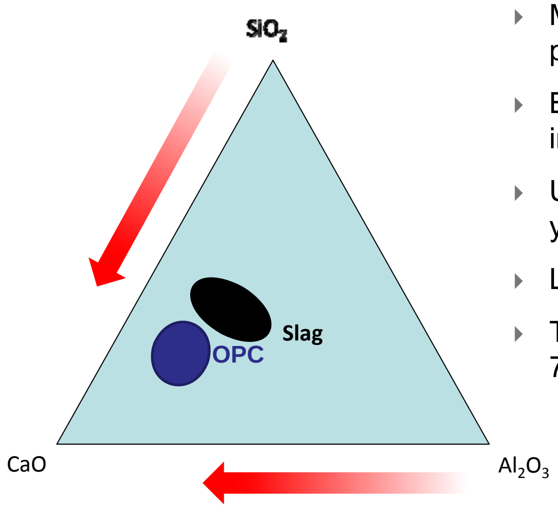
- **<u>Pozzolanic</u>** – a <u>siliceous</u> or <u>alumnino-siliceous</u> material, chemically <u>reacts</u> at ordinary temperatures with <u>calcium hydroxide</u> released by hydration products of portland cement to form cementing properties.
  - Does **<u>NOT</u>** in itself produce hydration products
- **<u>Hydraulic</u>** – a material that <u>reacts</u> chemically with <u>water</u> to form compounds that have <u>cementing</u> properties
  - Forms hydration products in itself e.g. portland cement

Ordinary Portland Cement (OPC)



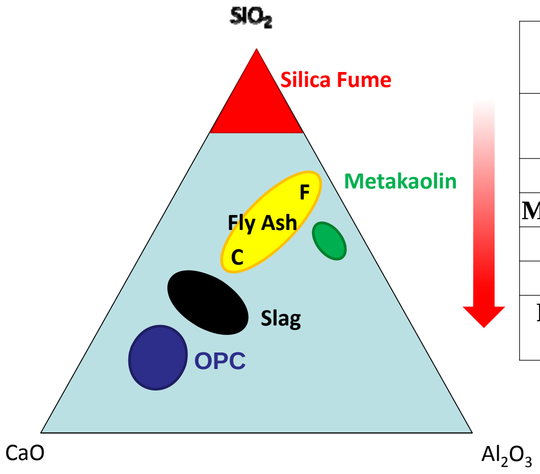
- Composition:
  - 60% CaO
  - 20% SiO_2
  - 5-10% Al_2O_3
- CaO indicator of hydraulic product

Slag Cement



- Most cementitious and least pozzolanic SCM
- Byproduct of the Steel industry
- Used in concrete >100 years
- Latent hydraulic reaction
- Typ. OPC replacement 20-70%

Effect of SCMs on Concrete Durability



SCM	Pozzolanic	Hydraulic
Silica Fume	XXXXX	
F-Ash	XXXX	
Metakaolin	XXXX	
C-Ash	XX	XX
Slag	X	XXXX
Portland Cement		XXXXX

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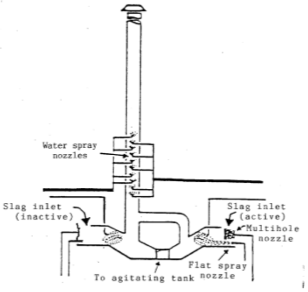
Manufacturing

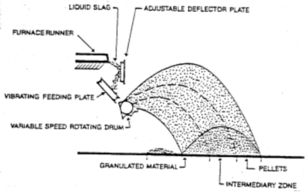
- Byproduct of iron and steel manufacturing process
- Materials fed into furnace:
  - coke, natural gas, oxygen and pulverised coal and also limestone as a fluxing agent
- Two Products:
  - Molten iron metal
  - Molten blast furnace slag

Slag Run-off from an Open Hearth Furnace

Quenching Molten Slag and Grinding

- Two Methods:
  - Water granulator
  - Air granulator
- Dried and Dewatered
- Crushed Using Traditional Ball Mill
  - Usually finer than cement





Specifications and Grade of Ground Granulated Iron Blast-Furnace Slags

ASTM C 989 (AASHTO M 302)

- Grade 80
  - Slags with a low activity index
- Grade 100
  - Slags with a moderate activity index
- Grade 120
  - Slags with a high activity index

Slag Cement

- Glassy granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water
- Non-metallic product, consisting of silicates and aluminosilicates of calcium and other bases

Component	Mass (%)
CaO	30-50
SiO_2	28-38
Al_2O_3	8-24
MgO	1-18

Classification

- Slag is Classified as Grade 80, 100, and 120
- Determined from compressive strength
- ASTM C109 and ASTM C1437
- (2 Mixes)
  - Slag mixture 50/50 slag and reference cement
  - Reference mixture – only reference cement

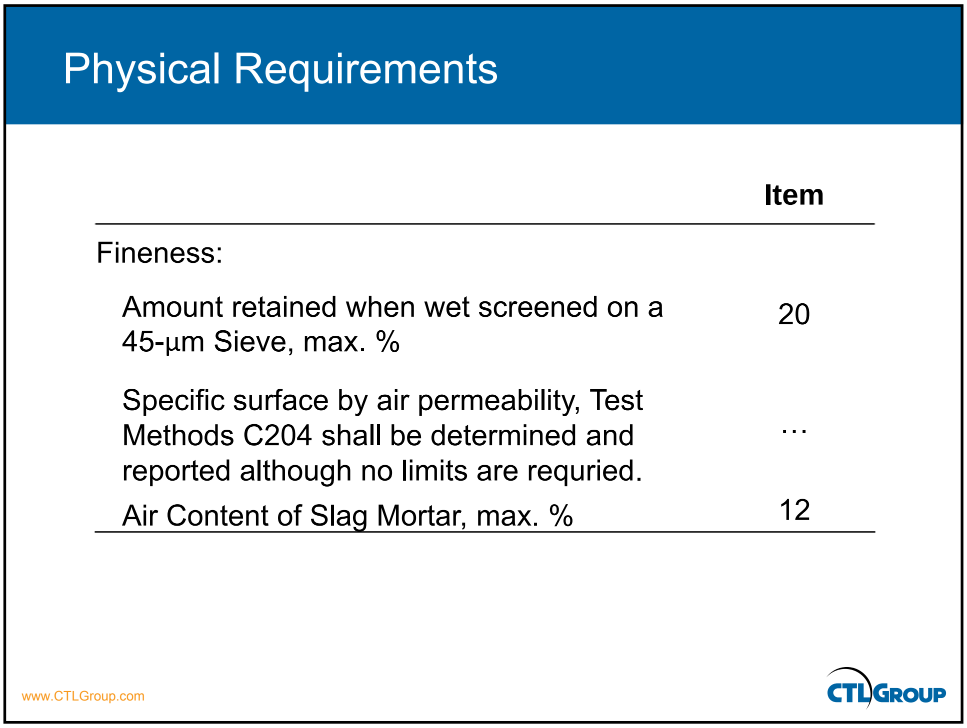
Total Alkalies (Na_2O + 0.658 K_2O)	min %	0.60
	max %	0.90
Compressive Strength, MPa, min, 28 days[A]		35 [5000 psi]

Classification

Slag Activity Index, % = (SP / P) X 100

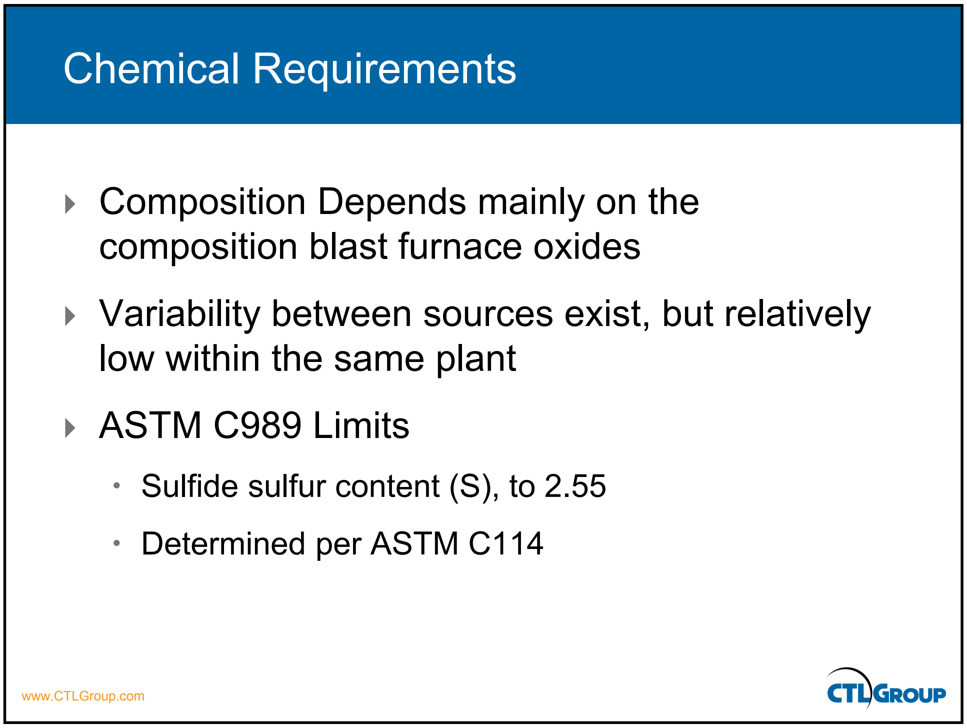
SP = Average compressive strength of slag−cement mortar cubes, MPa
P = Average compressive strength of cement mortar cubes, MPa

	Average of Last Five Consecutive Samples	**Any Individual Sample**
Slag Activity Index		
28-Day Index, min.%		
Grade 80	75	70
Grade 100	95	90
Grade 120	115	120



Physical Requirements

	Item
Fineness:	
Amount retained when wet screened on a 45-µm Sieve, max. %	20
Specific surface by air permeability, Test Methods C204 shall be determined and reported although no limits are requried.	…
Air Content of Slag Mortar, max. %	12



Chemical Requirements

- Composition Depends mainly on the composition blast furnace oxides
- Variability between sources exist, but relatively low within the same plant
- ASTM C989 Limits
  - Sulfide sulfur content (S), to 2.55
  - Determined per ASTM C114

Typical Dosage

Application	Dosage (% by wt.)
Exterior Flatwork	≤ 35%
General Usage	35 to 50%
Mass Concrete	60 to 80%
Sulfate Resistance	
ASTM C150 – Type II Equivalent	≥ 35%
ASTM C150 – Type V Equivalent	≥ 50%
Marine Exposure	> 50% < 80%

Mixture Proportioning

- Typical Dosage – 35-50%
- w/c ratio – w/(cement + slag) ratio
- Water Demand – 1 to 5% lower
- Admixture dosage
  - Similar for air-entraining admixtures
  - Slightly lower for other admixtures
- SG 2.90

Slag Benefits – Water Demand

- Reduces Water Demand
- Improved Pumpability

Slag Benefits – Workability

- Improved Workability Due To:
  - Smooth surface creating slip planes
  - Low absorption of water (unlike OPC)
  - Better particle dispersion
  - Consolidates better under mechanical vibration

Slag Benefits – Finishability and Increase Setting Time

- Improve Finishability
- Extends Setting Time
  - Latent hydraulic material
  - Benefit in weather environments

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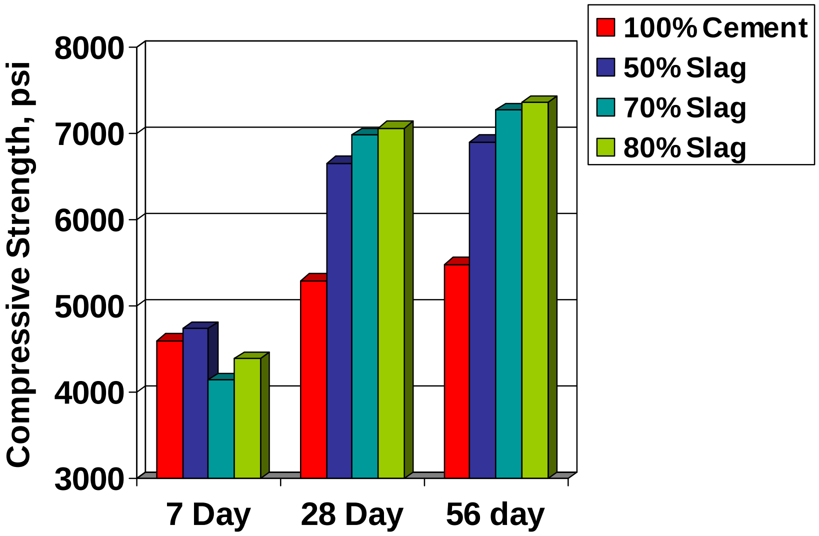
Effects of SCMs on fresh concrete

↓ *Reduced* → *No/Little Effect* ↑ *Increased* ↕ *Varies*	Fly ash	Slag	Silica fume	Nat. Pozzolans
Water Requirements	↓	↓	↑	→
Workability	↑	↑	↓	↑
Bleeding and Segregation	↓	↕	↓	→
Air Content	↓	↕	↓	→
Heat of Hydration	↓	↓	↕	↓
Setting Time	↑	↑	→	→
Finishability	↑	↑	↕	↑
Pumpability	↑	↑	↑	↑
Plastic Shrinkage Cracking	→	→	↑	→

Slag and Higher Strengths

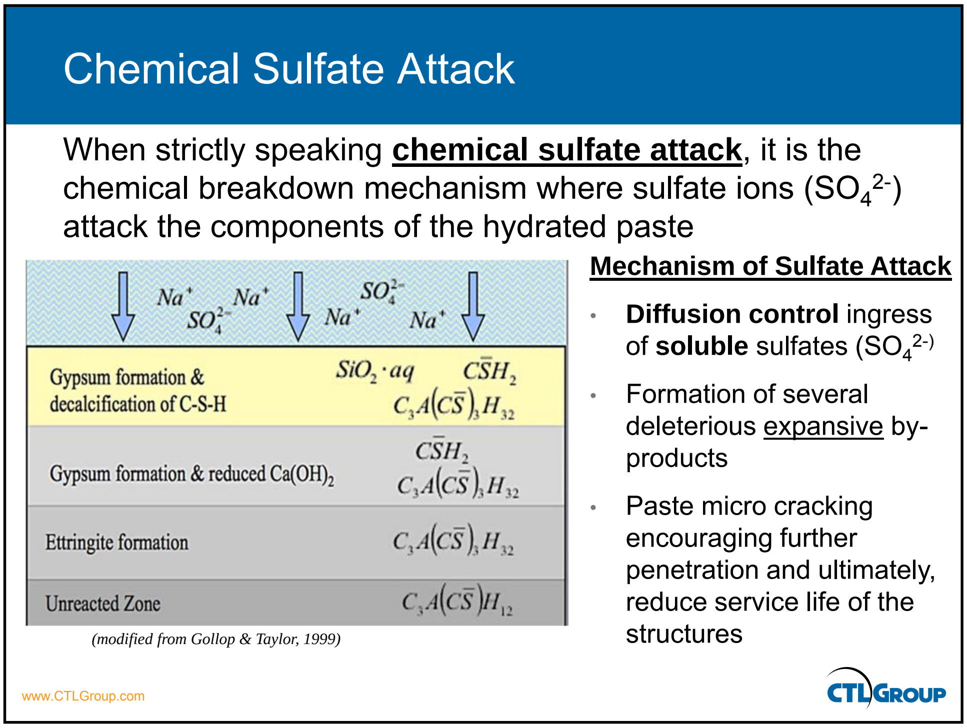


Effect of Slag Cement on Concrete Durability

- Materials Improve Durability due to:
  - Refined Pore Structure
    - Particle Packing
    - Formation of C-S-H
  - Improved Transition Zone Properties
  - Reduction in soluble transition zone hydrates (e.g. CH)

} Decreased Permeability

What are the effects on Sulfate Attack, Alkali-silica Reaction, Chloride Induced Corrosion, and Carbonation Induced Corrosion?



Chemical Sulfate Attack

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

(modified from Gollop & Taylor, 1999)

Mechanism of Sulfate Attack

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

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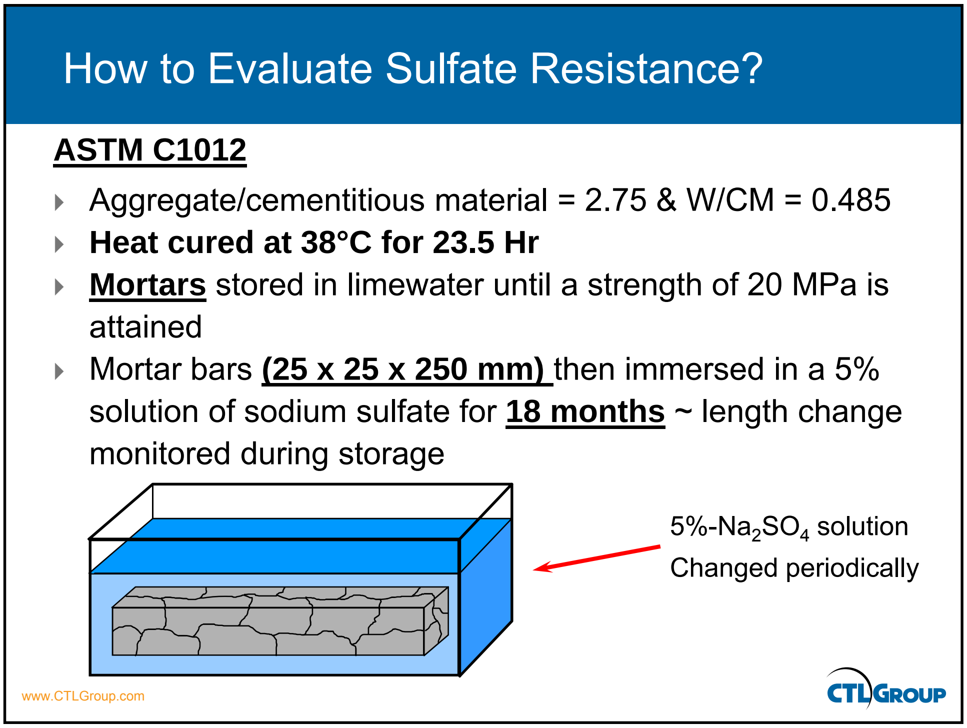

How to Evaluate Sulfate Resistance?

ASTM C1012

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

5%-Na_2SO_4 solution
Changed periodically

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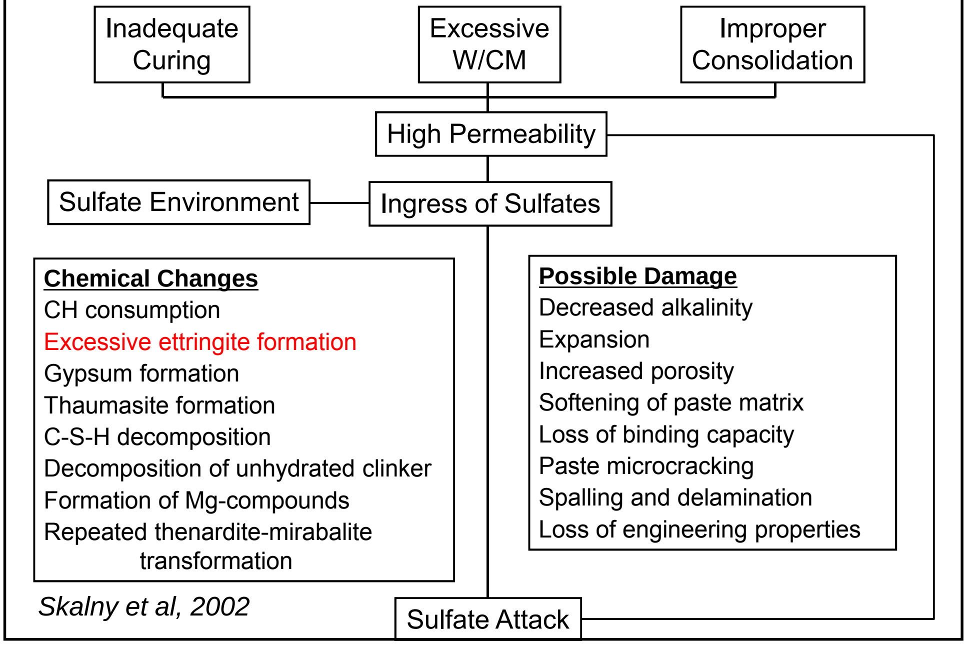
Summary of External Sulfate Attack



Inadequate Curing

Excessive W/CM

Improper Consolidation

High Permeability

Sulfate Environment

Ingress of Sulfates

Chemical Changes
- CH consumption
- Excessive ettringite formation
- Gypsum formation
- Thaumasite formation
- C-S-H decomposition
- Decomposition of unhydrated clinker
- Formation of Mg-compounds
- Repeated thenardite-mirabalite transformation

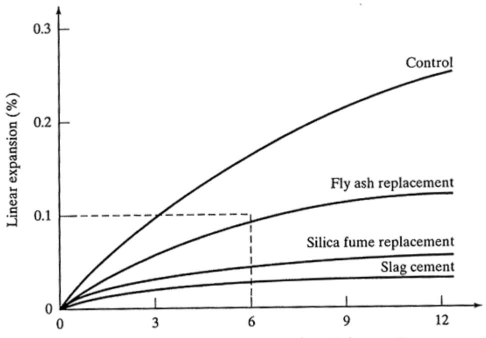
Possible Damage
- Decreased alkalinity
- Expansion
- Increased porosity
- Softening of paste matrix
- Loss of binding capacity
- Paste microcracking
- Spalling and delamination
- Loss of engineering properties

Sulfate Attack

Skalny et al, 2002

Slag Benefits – Sulfate Attack

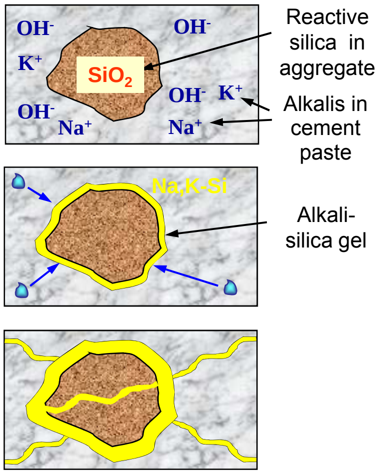
- SCMs generally improve **sulfate resistance**
- **Slag > Class F** fly ash > **Class C**
- Can **equal** or **exceed** performance of **Type V** cement by using SCMs



Why Slag Cement Prevents Sulfate Attack?

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

What is Alkali-silica Reaction (ASR)?



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

The reaction produces an alkali-silica gel

The gel absorbs water from the surrounding paste …

… and expands.

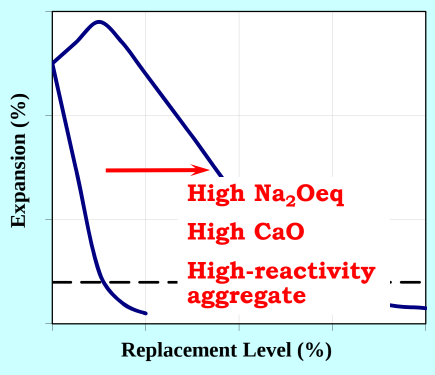
The internal expansion eventually leads to cracking of the surrounding concrete.

Preventing ASR: Using SCMs

Fly Ash
Slag
Silica Fume
Natural Pozzolans

Almost all sources of these materials are effective in controlling ASR

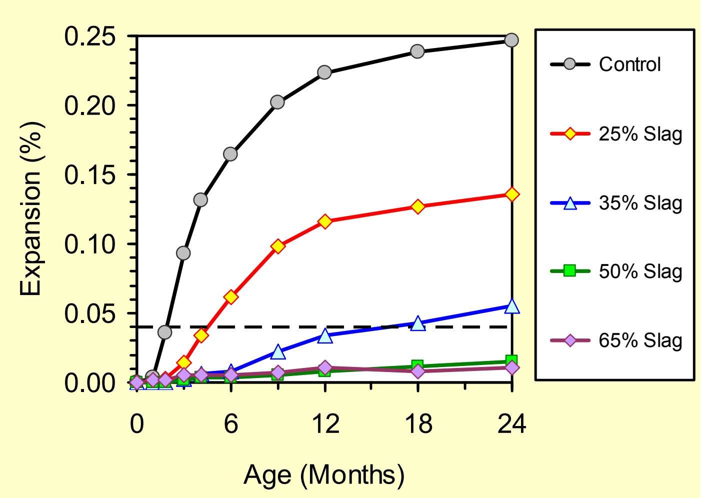
IF used in sufficient quantity



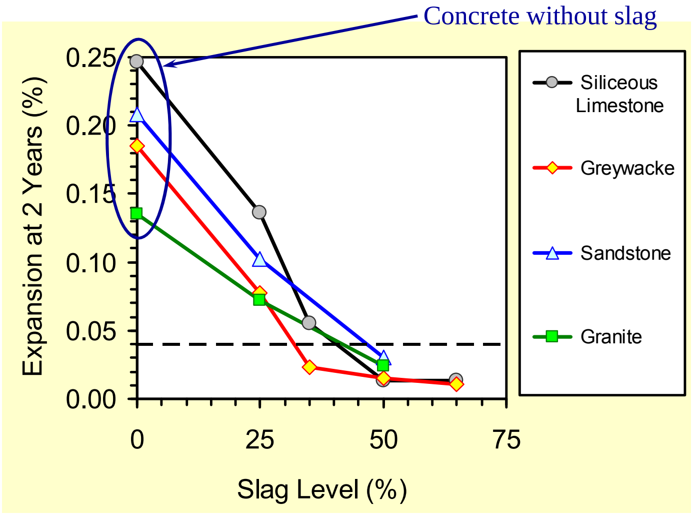
Amount of preventive required depends on:

- Composition of material (esp. Na_2Oeq, SiO_2, CaO)
- Available alkali in the system
- Nature of the reactive aggregate

Preventing ASR: Using Slag Cement



Slag Cement: Requirements by Aggregate Type

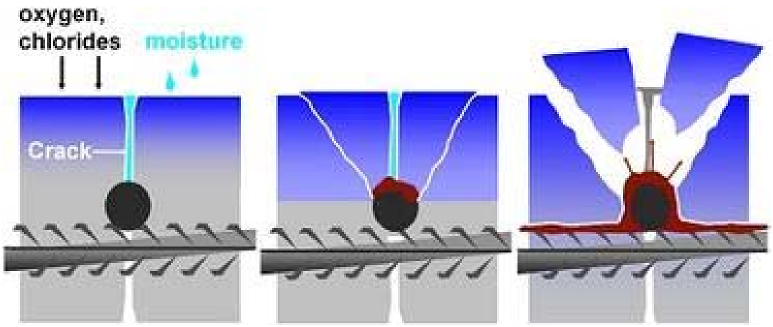


Thomas and Innis, 1998

How Slag Cement Prevents ASR?

- Reduced permeability,
- Change of the alkali-silica ratio,
- dissolution and consumption of the alkali species,
- direct reduction of available alkali in the system, and
- reduction of calcium hydroxide needed to support the reaction.

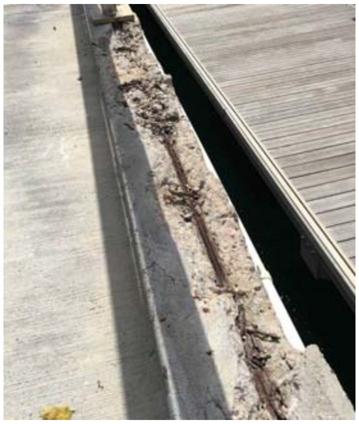
Chloride-Induced Corrosion of Concrete



- Chlorides from deicing salts or seawater penetrate and reach the steel
- Chloride ions lead to corrosion if O_2 and H_2O are present

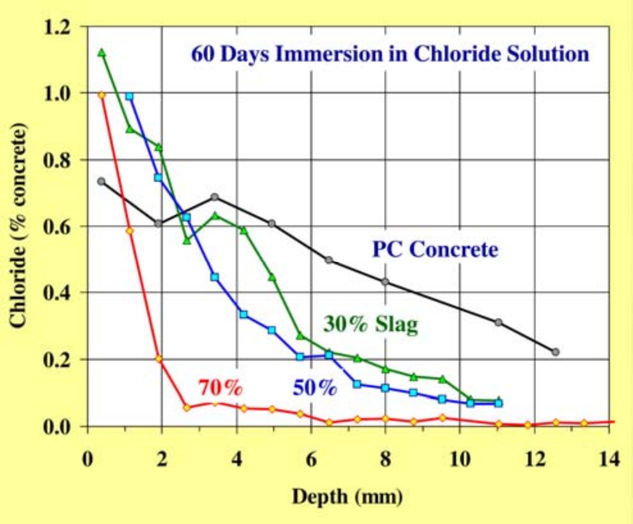
External Sources of Chlorides

- Chloride in seawater
  - Affects marine structures, harbors, oil platforms, coastal bridges, and ships
- Chloride in ground water
  - Affects buried structures, piles, tunnels and foundations
- Chloride from deicing chemicals
  - Affects highway structures, bridges and parking structures.



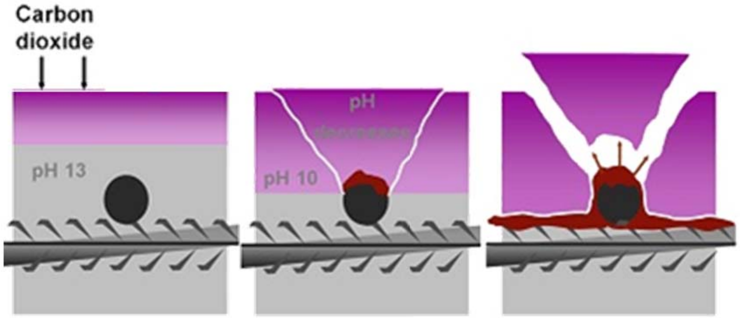
The Challenge Remains: to slow or prevent the ingress of chloride ions through the use of **SCMs**.

Effect of Slag Cement on Chloride Diffusion



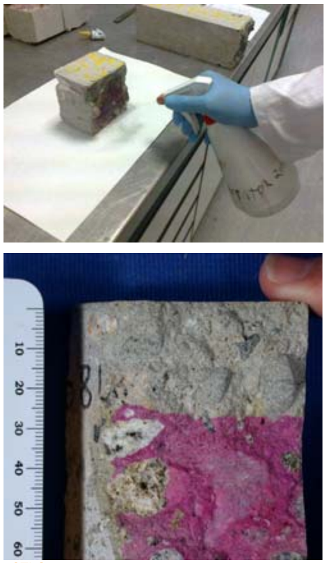
Source: Thomas

Carbonation-Induced Corrosion of Concrete



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

Carbonation Testing



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

🟪 pH > 9 (purple)

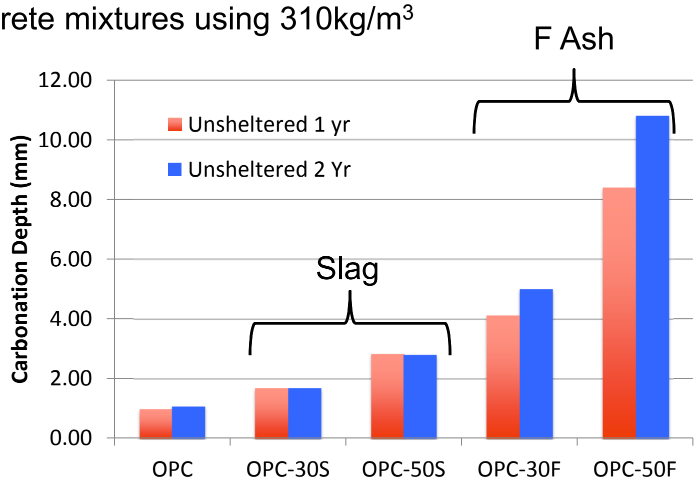
⬜ pH < 9 (colorless)

Preventing Carbonation-Induced Corrosion

- Deterioration generally occurs when there is:
  - Poor quality concrete
  - Inadequate curing
  - Low depths of cover
- When high volumes of SCMs are used
- When high volume SCMs are used extra attention is needed to quality (w/cm), curing, and depth of cover

Depth of Carbonation

Concrete mixtures using 310kg/m^3



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Effects of SCMs on hardened concrete

⬇ *Reduced* ➡ *No/Little Effect* ⬆ *Increased* ⬍ *Varies*	Fly ash	Slag	Silica fume	Nat. Pozzolans
Strength Gain	⬍	⬍	⬆	⬍
Abrasion Resistance	➡	➡	➡	➡
Freeze-Thaw and Deicer-Scaling Resistance	➡	➡	➡	➡
Drying Shrinkage and Creep	➡	➡	➡	➡
Permeability	⬇	⬇	⬇	⬇
Alkali-Silica Reactivity	⬇	⬇	⬇	⬇
Chemical Resistance	⬆	⬆	⬆	⬆
Carbonation	➡	➡	➡	➡
Concrete Color	⬍	⬍	⬍	⬍

Slage Cement – Durability Benefits

- Variety of SCMs available on the market not all are created equal
  - Different replacement levels need for different durability mechanisms
- Slag cement can act like Type V cement to prevent sulfate attack
- ASR can be prevented with Slag Cement
- Chloride-Induced Corrosion of Concrete
  - Use SCMs and ternary blends to lower permeability and slow ingress of Cl ions
- Carbonation-Induced Corrosion of Concrete
  - Slight-to-Significant increase in depth of carbonation with increased SCM content

What is Mass Concrete?

What is Mass Concrete?

Mass Concrete

From ACI 207, Mass Concrete is:

> *"any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change, to minimize cracking"*

Thick: Dams, mat foundations, bridge substructure, radiation shielding, etc.

Thinner: High performance concrete (HPC), self-consolidating concrete (SCC), grout, patching material, etc.

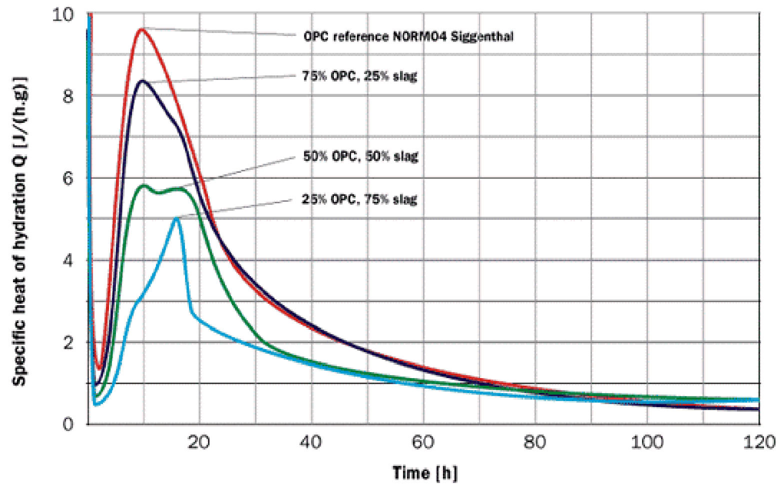
Mass Concrete – Main Considerations

- Minimum Dimension
- Maximum Temperature
  - Cement Type and Quantity
  - Pozzolans
  - Size
- Temperature Difference *(Not Discussed)*

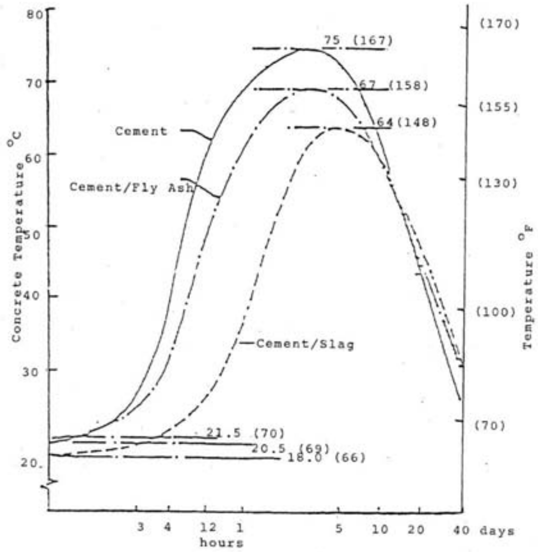
Slag in Mass Concrete

- Discussed in:
  - ACI 207.1R-95, "Mass Concrete"
  - ACI 233R-95, "Ground Granulated Blast Furnace Slag as a Cementitious Constituent in Concrete"
- Documented Use from 1950's
- Reduces Early Heat
- Higher Compressive Strengths
- Improved Physical Properties

Slag Reduces Heat Generation



Slag Reduces Temperatures



- 100% Cement
- 70/30 Blend of Cement and Fly Ash
- 25/75 Blend of Cement and Slag

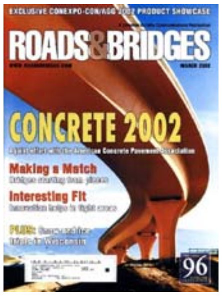
Equivalent cement content

- 1 kg/m^3 of cement = 1 kg/m^3 equiv. cement
- 1 kg/m^3 of class F ash = 0.5 kg/m^3 equiv. cement
- 1 kg/m^3 of class C ash = 0.8 kg/m^3 equiv. cement
- 1 kg/m^3 of Slag (50%) = 0.9 kg/m^3 equiv. cement
- 1 kg/m^3 of Slag (75%) = 0.8 kg/m^3 equiv. cement

- Temperature rise in concrete
  - 0.15°C per 1 kg/m^3 equiv. cement
  - 0.16°F per 1 lb/yd^3 equiv. cement

Slag Increases Maximum Concrete Temperature Limits

- Reduces or Eliminates DEF Concerns



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Reducing DEF expansion

Construction Technology Lab study reveals role of ground granulated blast furnace slag

The exact mechanism of DEF is still not entirely understood. It is believed that most of the sulfate and virtually all the alumina from the ettringite decomposition are absorbed in the calcium silicate hydrate.

Cement and slag chemical analysis

Slag results

Kenco Corporation

Delayed Ettringite Formation (DEF)

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

Types of Structures

- Mass concrete
  - Bridge columns, foundations, etc.
- Precast Concrete
  - Columns, beams, etc.

What is needed for DEF?

- Cementitious chemistry
  - SO_3, C_3A, $Na_2O_{eq.}$, fineness, etc.
- High internal temperatures (greater than 158°F)
- Moisture

The Challenge:
Moderate one of the three requirements to prevent DEF

Source: Folliard, K.

Maximum Temperature Limit

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

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

Mass Concrete Projects with High Slag Contents

- Pocahontas Parkway
- Woodrow Wilson Bridge
- Boston “Big Dig”
- Fitchburg Cable Stay Bridge
- Others

Pocahontas Parkway Bridge

- I-895 in Virginia
- 672 ft Clear Span
- 145 ft High
- 90,000 cu yd
- 75% Slag
- Massive Pours up to 16 ft thick

- Extensive CTL Involvement

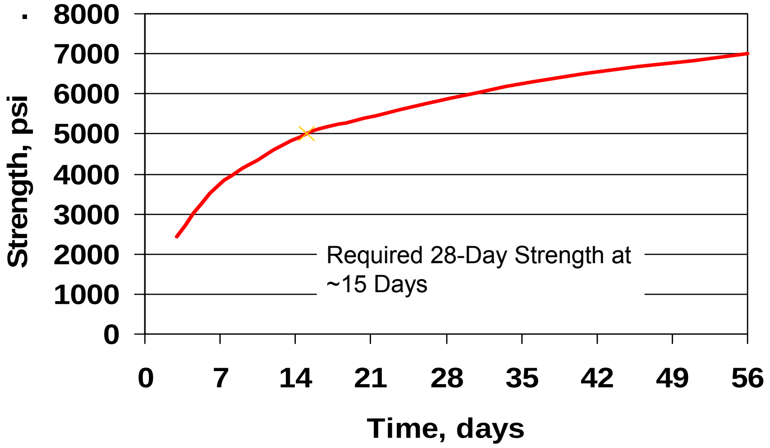
Pocahontas: Overview and Scope

- Design-Build Project
- CTL Helped Speed Construction and Decrease Cost of Mass Concrete
  - Specifications
  - Thermal Modeling
  - Temperature Monitoring
  - Maturity

Pocahontas:
Concrete Mix Designs

- Needed High Strength and Low Heat
- Fly Ash Mixes Considered but Dismissed
- 75% Slag – 25% Type II
- Typically 564 pcy
- 5000 psi at 28 days

Pocahontas:
Compressive Strength

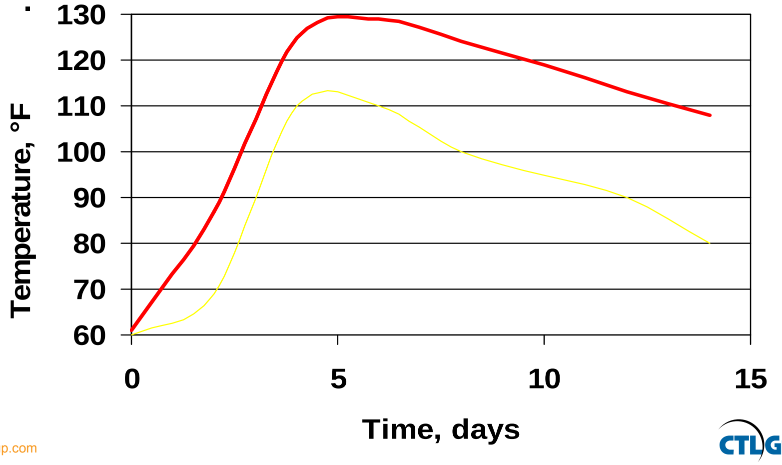


Pocahontas:
Mass Concrete Dimensions

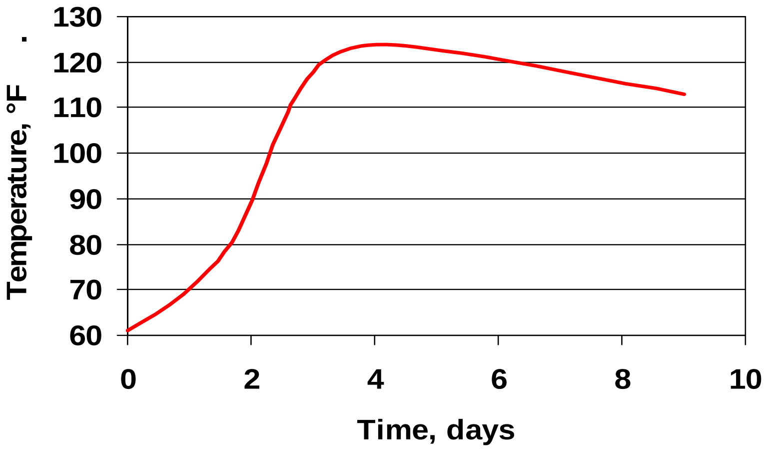
Footings-
  9 to 16 ft thick

Columns-
  7 to 12 ft diameter
  (typical)

Pocahontas:
Temperatures in 10 ft Footing



Pocahontas:
Temperatures in 12 ft Column



Woodrow Wilson Bridge

- I-95/495 Washington DC
- 55,000 cu yd of Foundation Work
- 75% Slag – 25% Type II
- Massive Pours from 9 to 16 ft thick

- Extensive CTL Involvement

Wilson Bridge: Project Scale

- 1.5 Miles
- 12 Traffic Lanes

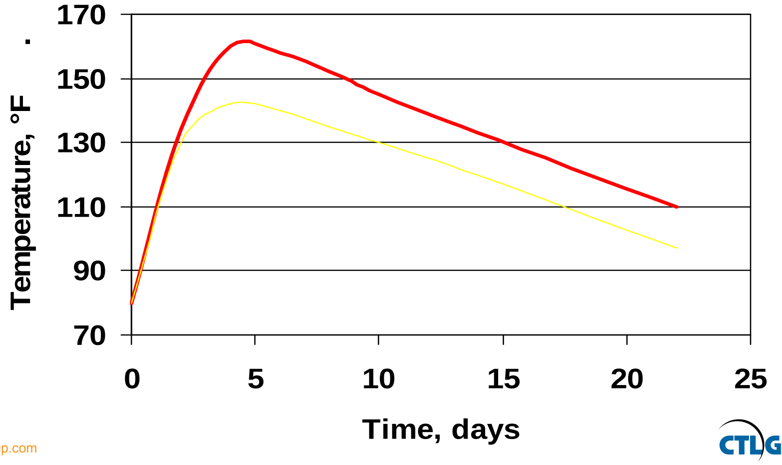
Wilson Bridge: CTL Involvement

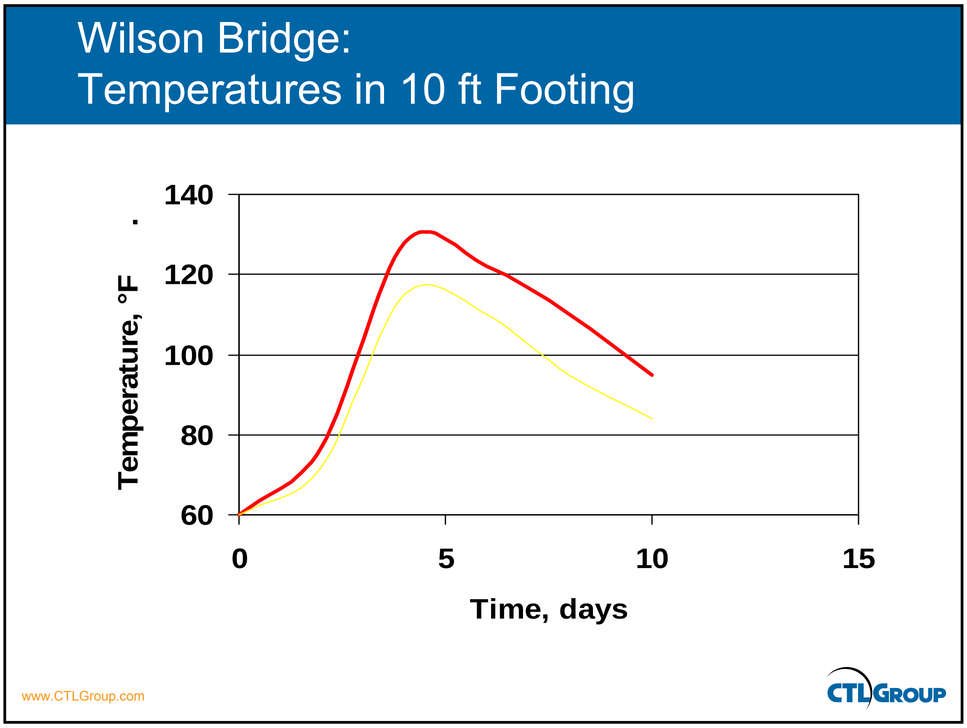
- Help Contractor with Bid
- Planned on Using 25% Class F Fly Ash
- Switched to 75% Slag for Reduced Heat (prior to Construction)
- Thermal Modeling
- Temperature Monitoring

Wilson Bridge: Concrete

- 56-day Design Strength of 4000 and 6500 psi
- 165 pcy of Cement and 494 pcy of Slag
- 5100 psi at 7 days
  7900 psi at 28 days
  8400 psi at 56 days
- Low Permeability (<800 Coulombs)

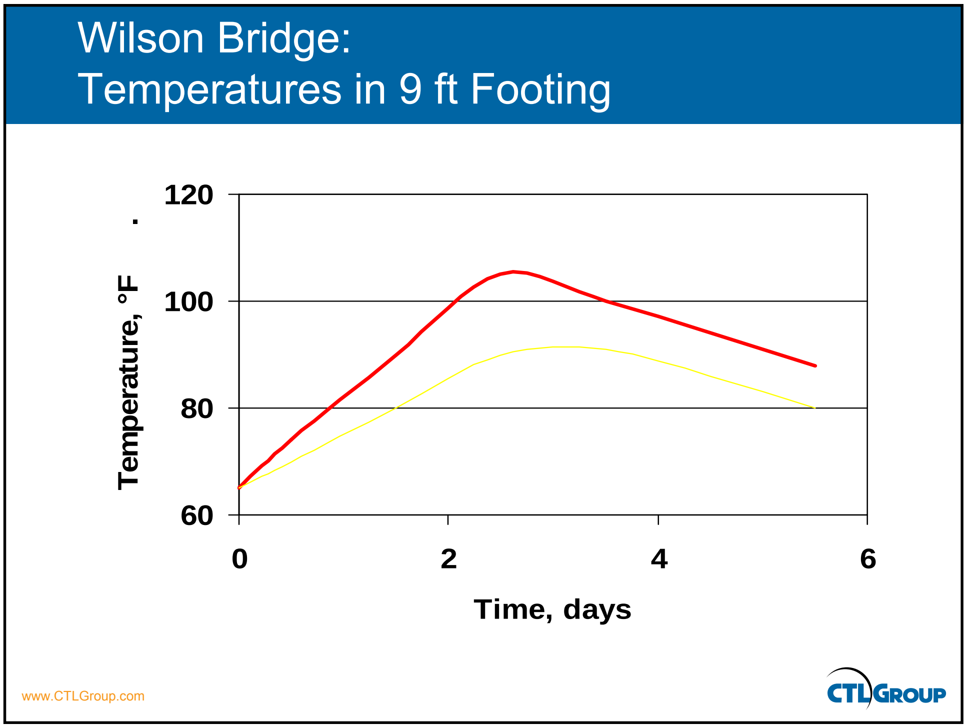
Wilson Bridge: Temperatures in 11 ft Footing





Wilson Bridge:
Temperatures in 10 ft Footing

www.CTLGroup.com



Wilson Bridge:
Temperatures in 9 ft Footing

www.CTLGroup.com

Wilson Bridge: Photos

www.CTLGroup.com

Wilson Bridge: Photos

www.CTLGroup.com

Wilson Bridge: Photos

Week of
October 22, 2001

Wilson Bridge: Photos

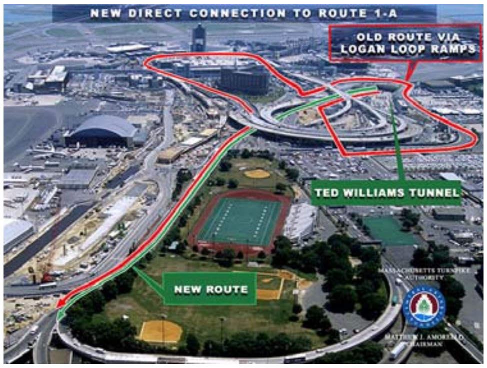
Wilson Bridge: Photos

Boston “Big Dig”

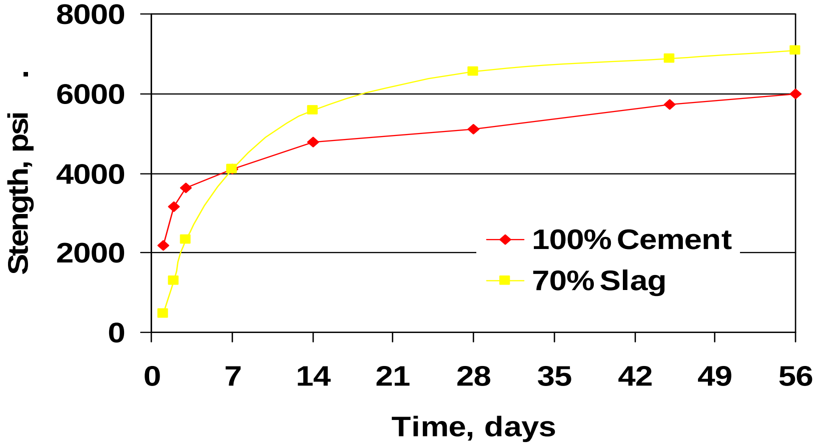
- Mass Concrete Tunnels
- Switched from 15-30% Fly Ash to 75% Slag
- Pours up to 16 ft thick

Boston “Big Dig”: CTL Involvement

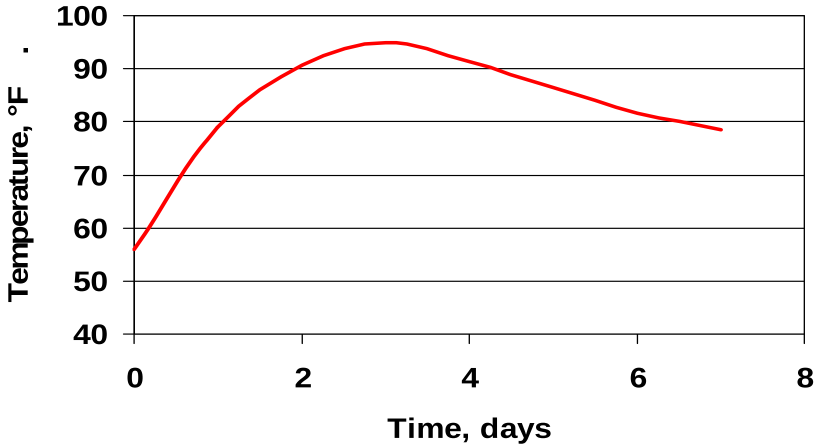
- Thermal Modeling to Identify Initial Temperatures to meet Specs.
- No Involvement after Switch to Slag



Boston “Big Dig”: Compressive Strength



Boston “Big Dig”: Temperatures in 5 ft Roof Slab



Boston “Big Dig”: Photos

Fitchburg Cable Stay Bridge

- Smaller Bridge in Fitchburg, MA
- 4,000 cu yd with 75% Slag
- Pours up to 15 ft diameter

- CTL Assistance to Owner

Fitchburg: Photos

Summary

- Benefits of Slag Cement
  - Heat of Hydration
  - Concrete Fresh Properties
  - Durability
    - Chloride Induced Corrosion
    - Alkali-silica Reaction (ASR)
    - Sulfate Attack
    - Delayed Ettringite Formation (DEF)
- Mass Concrete
  - Case Studies

Questions & Answers