Slag Cement Production, Cementitious Properties and Performance

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SCA Slag Cement School, Chicago, IL

4/29 – 4/30/24

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Presentation Overview

- Manufacturing Slag Cement
- Slag Cement Properties, Applications and Benefits
  - Compressive and Flexural Strength
  - Permeability / Durability
  - Alkali Silica Reactivity (ASR)
  - Sulfate Resistance
  - Mass Concrete

What Is Slag Cement?

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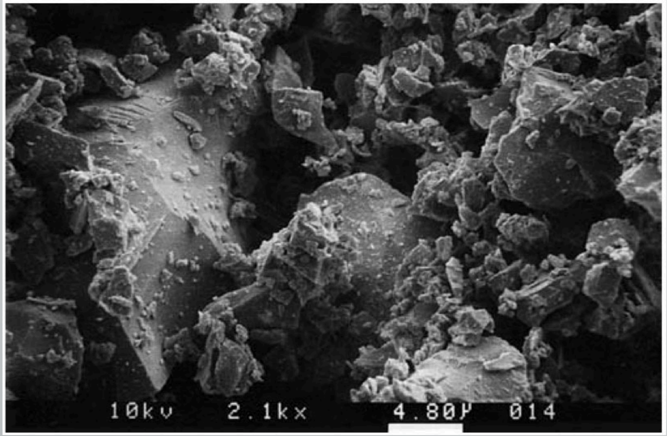
- Non-metallic molten material (slag) is diverted (by product) from the waste stream of iron ore **blast furnace for steel manufacturing**
- A fine white powder that can be used as a SCM to enhance concrete properties
- Is considered a hydraulic cement similar to portland cement
- Used in concrete mixtures to enhance durability and sustainability



Microscopic View
Of Slag Cement

From left to right:
Fly ash (Class C)
Metakaolin (calcined clay)
Silica Fume
Fly ash (Class F)
Slag Cement
Calcined shale

Cementitious Materials Comparison

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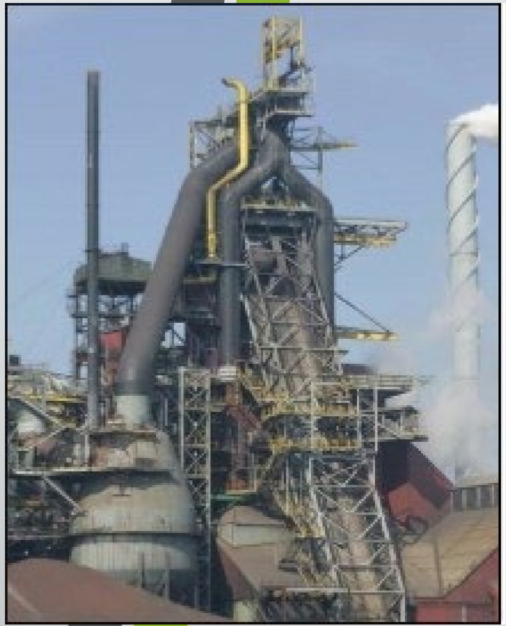
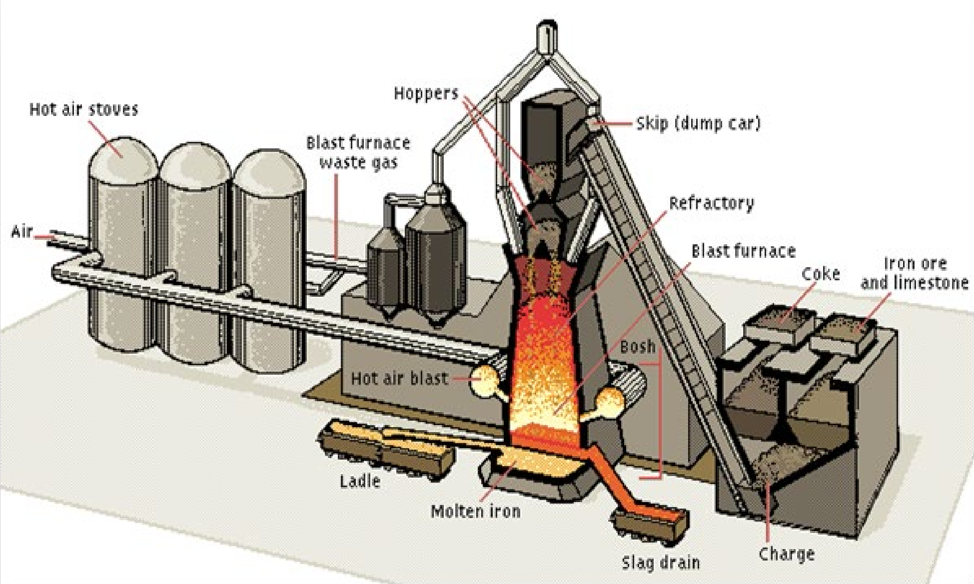
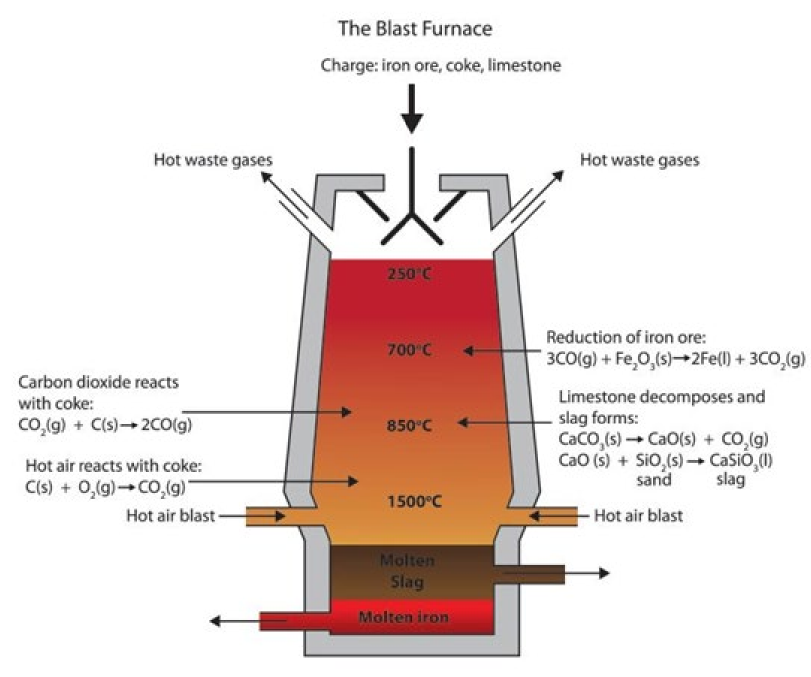
Attribute	Portland Cement	Slag Cement	Fly Ash
Origin	Limestone, Clay, etc.	Iron blast-furnace slag granules	Coal-fired electric power plant byproduct
Production	Manufactured product	Manufactured product	Byproduct
Classification	Hydraulic cement	Hydraulic cement	Pozzolan
Typical Replacement Rates	--	25-50% (60 - 80% in mass conc.)	15-30% (30 - 50% in mass conc.)

How Slag Cement is Made?

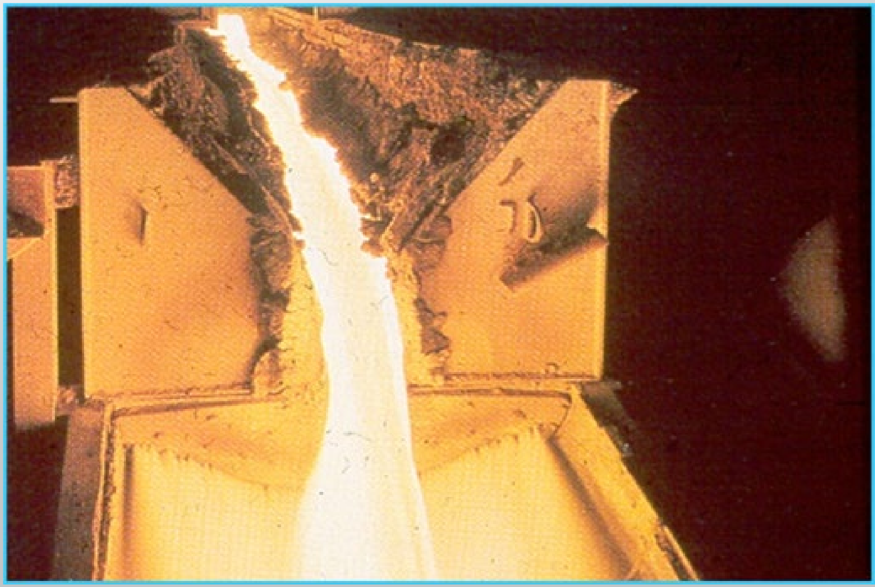






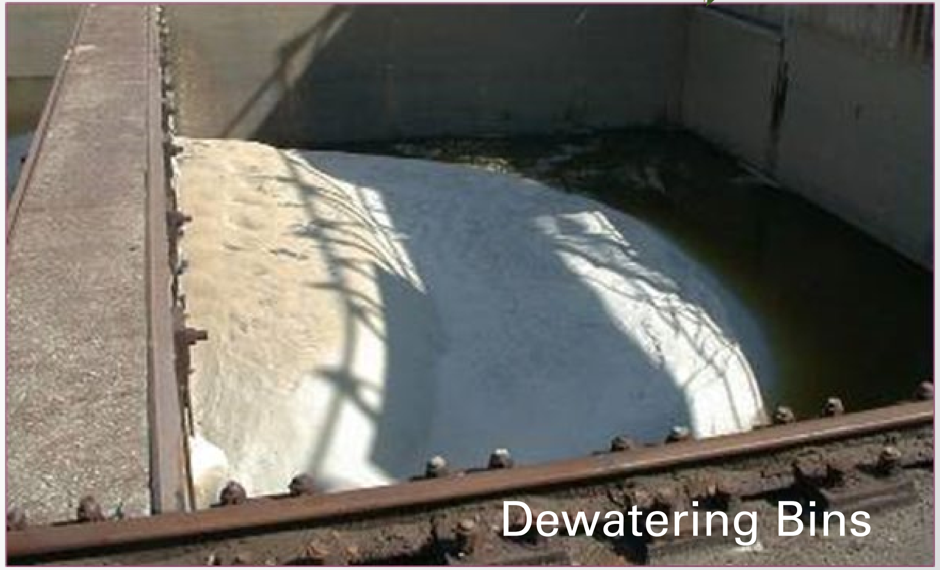
Waste stream of iron ore **blast furnace for steel manufacturing**

Slag

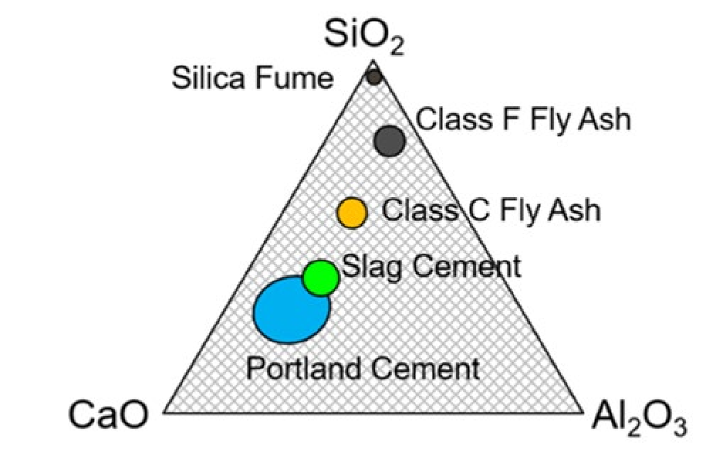


Granulation Process

Rapidly quenched to produce a glassy (non-crystalline) **granulated** product



Slag diverted to Granulator high pressure water 6 - 10 tons water/ton slag

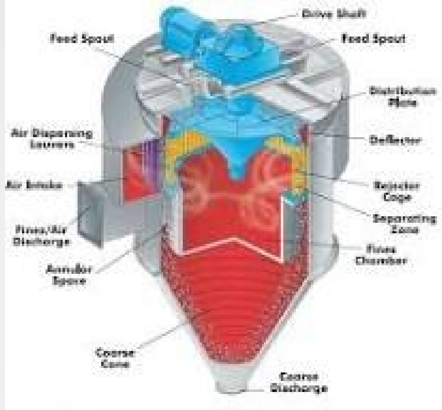


Slag Granules

Grinding Slag Cement

Slag cement plant

Separator



Oversized

Finished product Slag Cement / GGBFS

Granules

Ball Mill

Product	Blaine (m^2/kg)
Slag Cement	500 - 650
Type III	550 - 650
Fly Ash	400 - 450
Type I	350 - 400

Quality Control Lab

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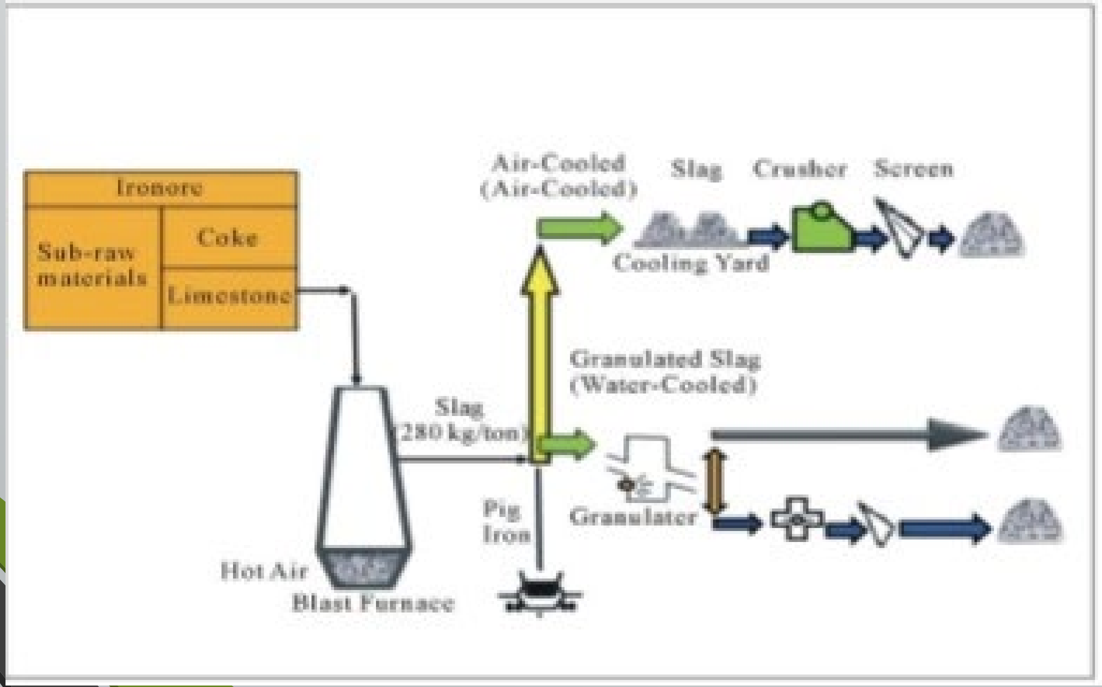
Distribution / Shipping Modes

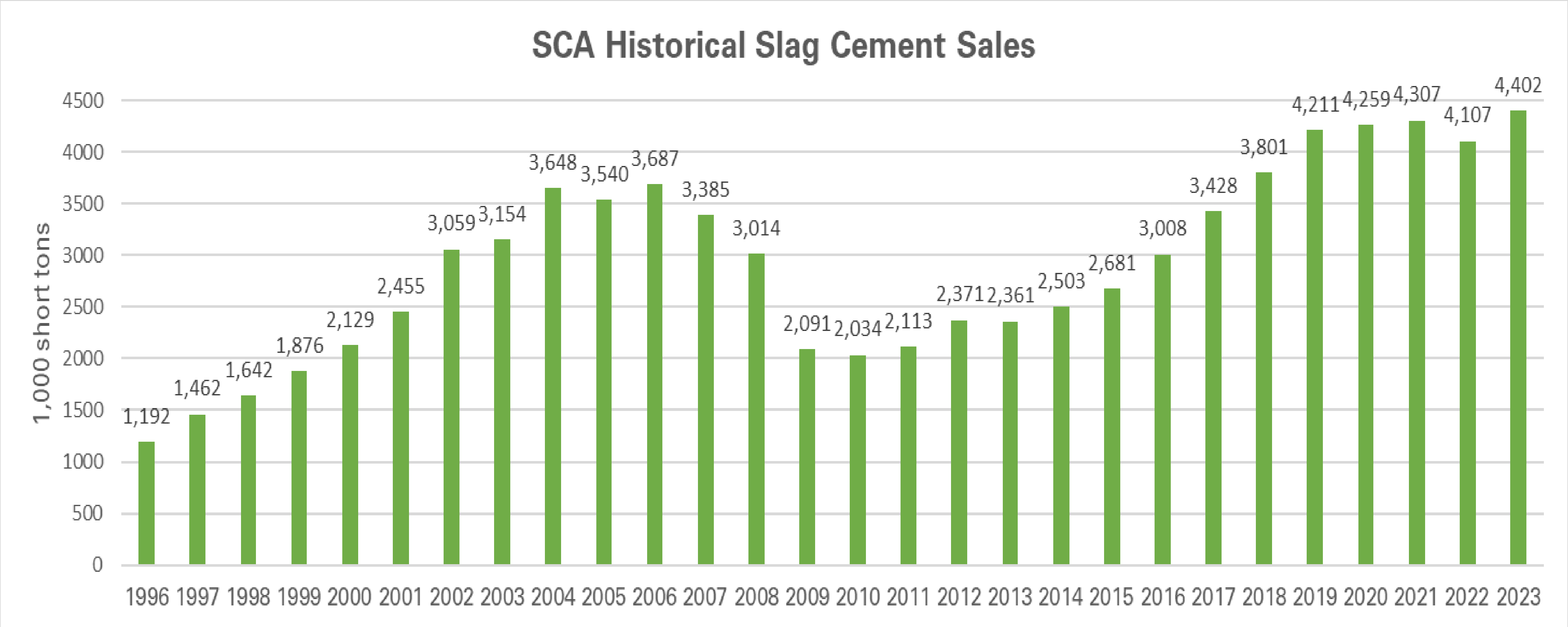
Barge

Air-Cooled Slag

- Slag is diverted to a pit
- Slowly cools
- Becomes crystalline, and is non cementitious even if ground fine
- Used as slag aggregate



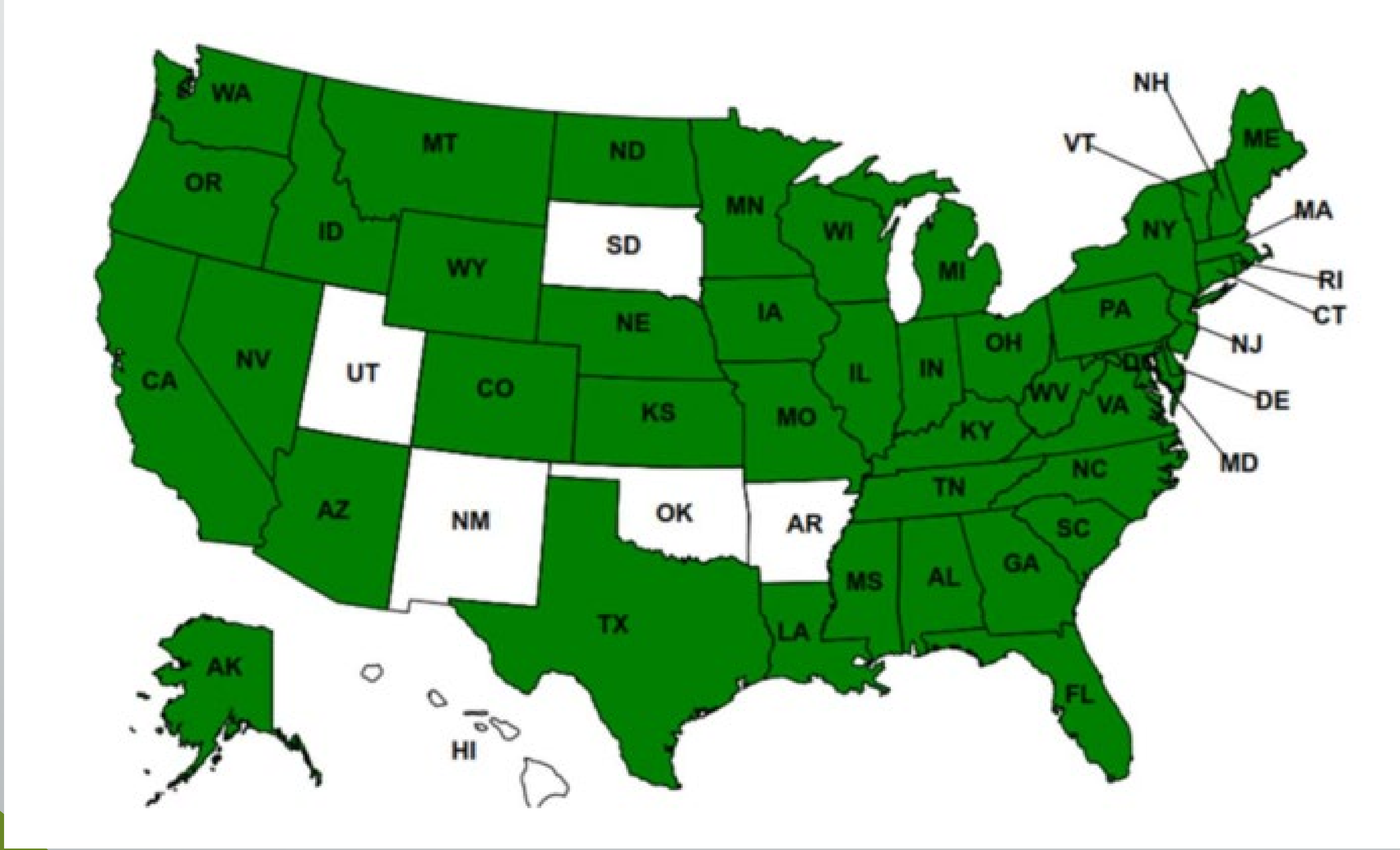
SCA Slag Cement Historic Shipments



Cement 2022: 120M tons (100M tons Domestic & 20M tons Imports)

Flyash 2022: 47M tons produced, 11M tons used in concrete, Harvested ash ~4M tons

States Approved for Use 2023



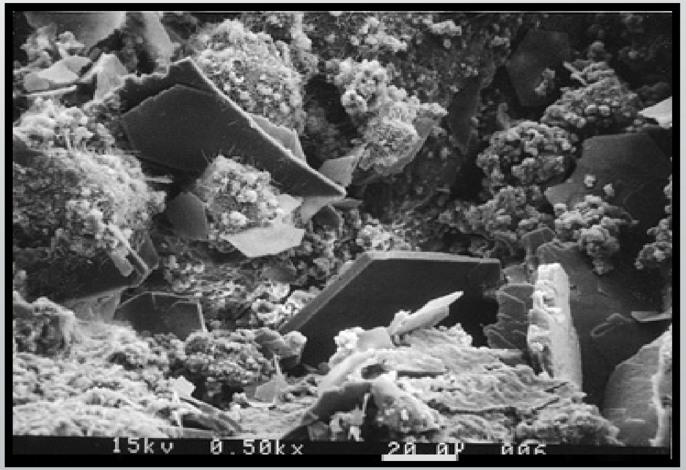
How Portland Cement Hydrates

Portland Cement
C_3S / C_2S / C_3A / C_4AF +
$CaSO_4.2H_2O$ (Gypsum)
+
Water

→

Hydraulic Reaction

Calcium-Silicate Hydrate (CSH)
+
Calcium Hydroxide
$Ca(OH)_2$



How Slag Cement Hydrates

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Slag Cement
+
Water

→

↑

Alkalies From Portland Cement

Hydraulic Reaction

More Calcium-Silicate Hydrate (CSH)

→

- Higher Strength
- Lower Permeability
- Greater Durability

Slag Cement + $Ca(OH)_2$
+
Water

↑

From Portland Cement

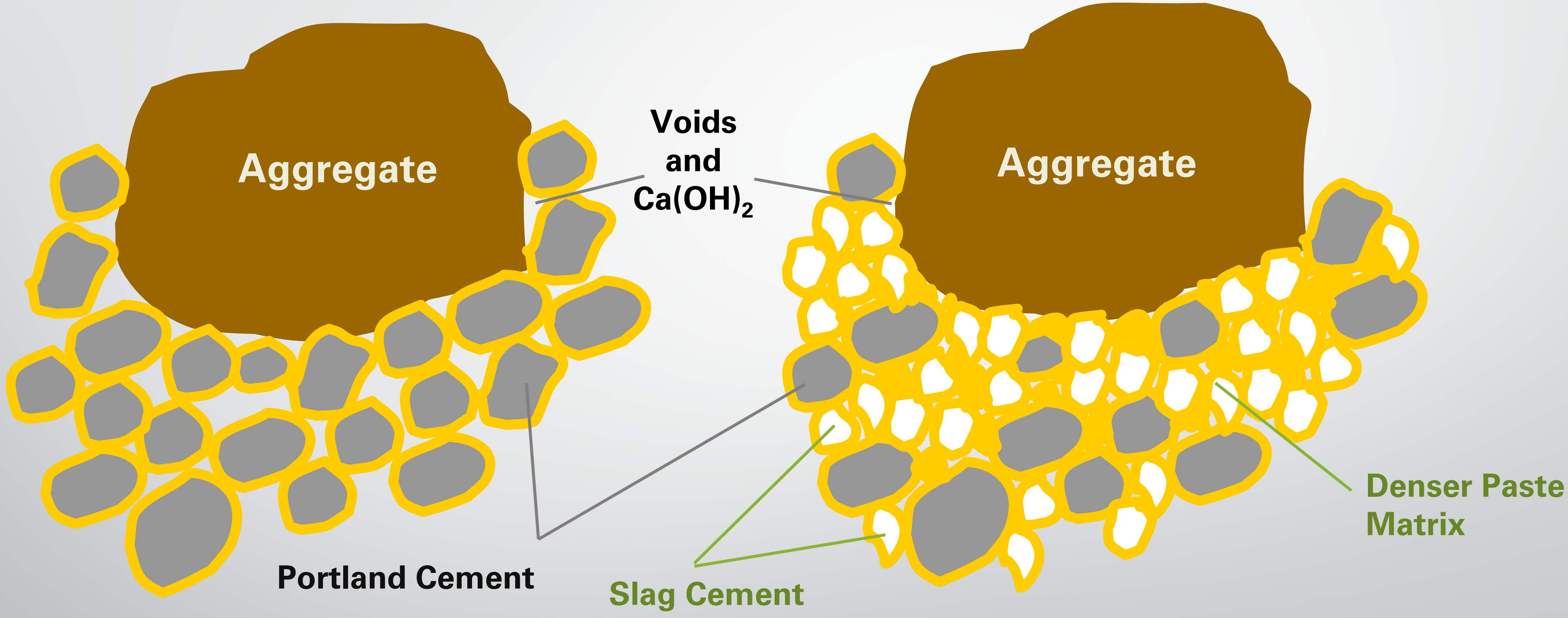
→

More Calcium-Silicate Hydrate (CSH)

→

- Higher Strength
- Lower Permeability
- Greater Durability

Paste Matrix Hydration



Portland Cement Concrete

Portland-Slag Cement Concrete

Designation: C989/C989M – 18

Standard Specification for
Slag Cement for Use in Concrete and Mortars[1]

Standard Specification for

Slag Cement for Use in Concrete and Mortars

AASHTO Designation: M 302-15
ASTM Designation: C989-14

	Min. 28-day SAI % of Reference
Grade 100	95
Grade 120	115

A 50% cement / 50% slag cement is compared to 100% reference cement at the various ages.

The reference cement used has a lot to do with determining the grade of slag cement (Alkalies: 0.60 – 0.90% & 5,000 psi @ 28 days).

Slag Cement Properties

Lower early strength but higher 28 & 56 day compressive and flexural strengths +1,000 - 2,000 psi

Lower permeability < 1,000 coulombs

Sulfate resistant T-II/T-V equivalent

Mitigate impact of ASR

Overall improved durability

Lower temperatures mass concrete

Very consistent quality

Mitigate efflorescence masonry products

Whiter concrete

Improved finishability & pumpability

Slower set times hotter temperatures

Cost savings – replace more cement (11 – 13 psi/lb)

No air issues as with fly ash

LEED credits / sustainability

Versatility – Use in many applications

Slag Cement's Effect on Concrete Properties

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General Concrete Properties*			
Fresh Concrete		**Hardened Concrete**	
Lower Water Demand (Slump + 1" to 2")	↓	Lower Early Strengths	↓
Workability	↑	Higher Later Age Strengths (28 & 56 Days)	↑
Slower Bleed Rate	↑	Much Lower Permeability	↓↓
Slight Decrease in Air Content	↓	Lower Chloride Ingress	↓
Mass Lower Heat of Hydration	↓	Much Better ASR Durability	↓↓
Longer Setting Time (30 to 60 mins)	↑	Much Better Sulfate Resistance	↑↑
Improves Finishability	↑	Freeze Thaw Resistance	←→
Improves Pumpability	↑	Abrasion Resistance	←→
Plastic Shrinkage	←→	Drying Shrinkage	←→

*General guidance properties, concrete making materials and mixture proportions will determine project specific properties of any given concrete mixture.

Proportioning

Application Dosage	Slag Cement
Concrete paving	25 – 50 %
Exterior flatwork not exposed to deicer salts	25 – 50 %
Exterior flatwork exposed to deicer salts with (w/cm < 0.45)	15 – 20 %
Interior flatwork	25 – 50 %
Footings	30 – 65 %
<u>Sulfate Resistance</u>	
Type II equivalence	25 – 50 %
Type V equivalence	50 – 65 %

Application	Slag Cement Dosage
Pre-stressed concrete	20 – 50 %
Pre-cast concrete	20 – 50 %
Concrete Pipe	20 – 50 %
Masonry/Pavers	20 – 50 %
ICF	25 – 60%
High strength	25 – 50 %
Tilt-up panels	25 – 50 %
ASR mitigation	25 – 70 %
Lower permeability	25 – 65 %
Mass concrete	50 – 70 %

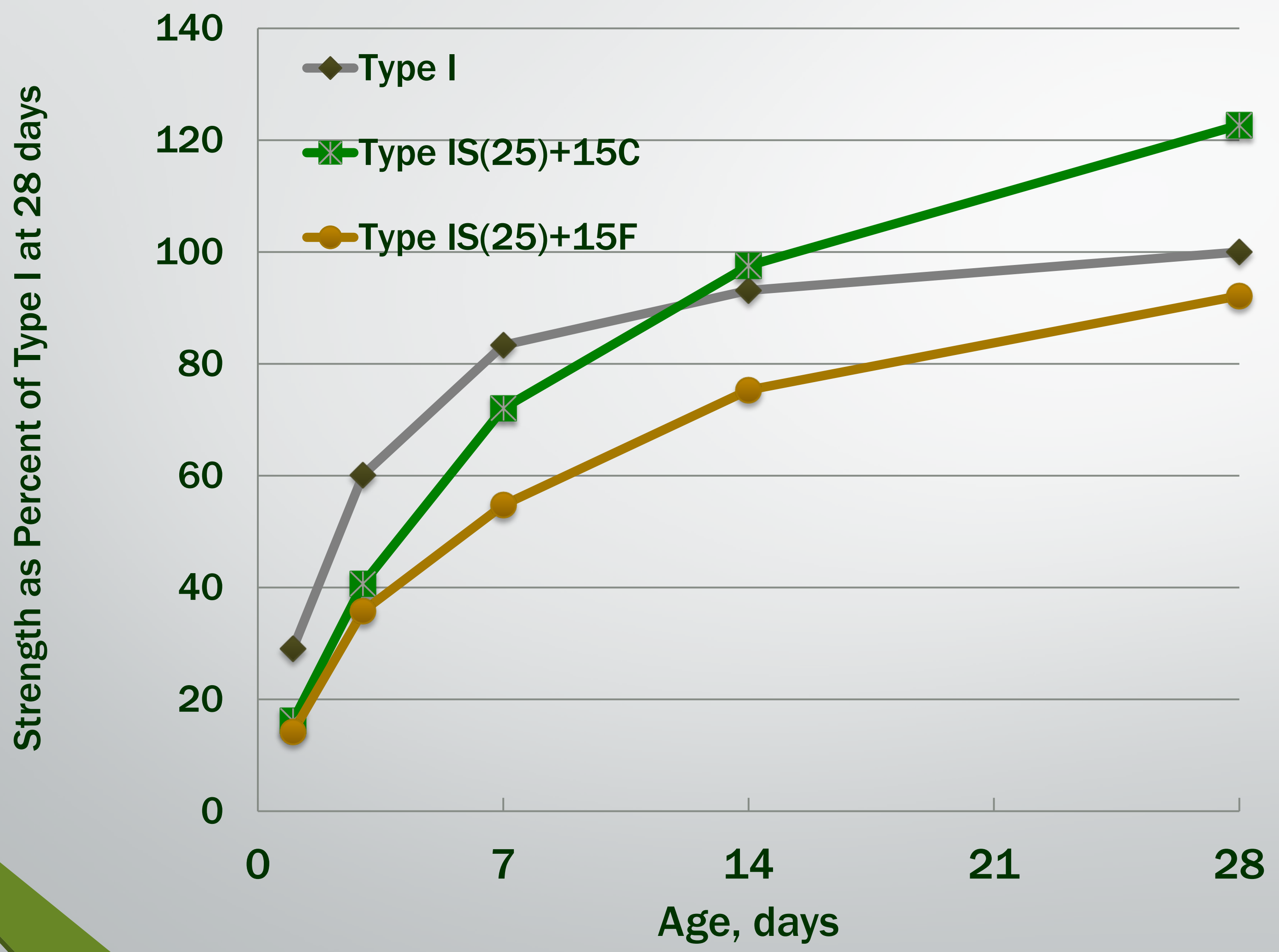
Ternary Mixes

- Cement (60-40%) / Slag Cement (25-35%) / C/F Fly Ash (15-25%)
- Cement (72-48%) / Slag Cement (25-45%) / Silica Fume (3-7%)

Ternary mixtures have been used in a wide range of concrete applications

- General Construction
- High Performance
- Shotcrete
- Paving
- Masonry Fill
- Mass Concrete

Compressive Strength – Ternary Mixes



565 lbs/cy

w/cm = 0.45

Slump 4″

Air content 6.5%

T-I @ 28 days = 6,120 psi

(IS)25+25C @28 days = 7,400 psi

(IS)+15F @ 28 days = 5,700 psi

PLC / IL Effects

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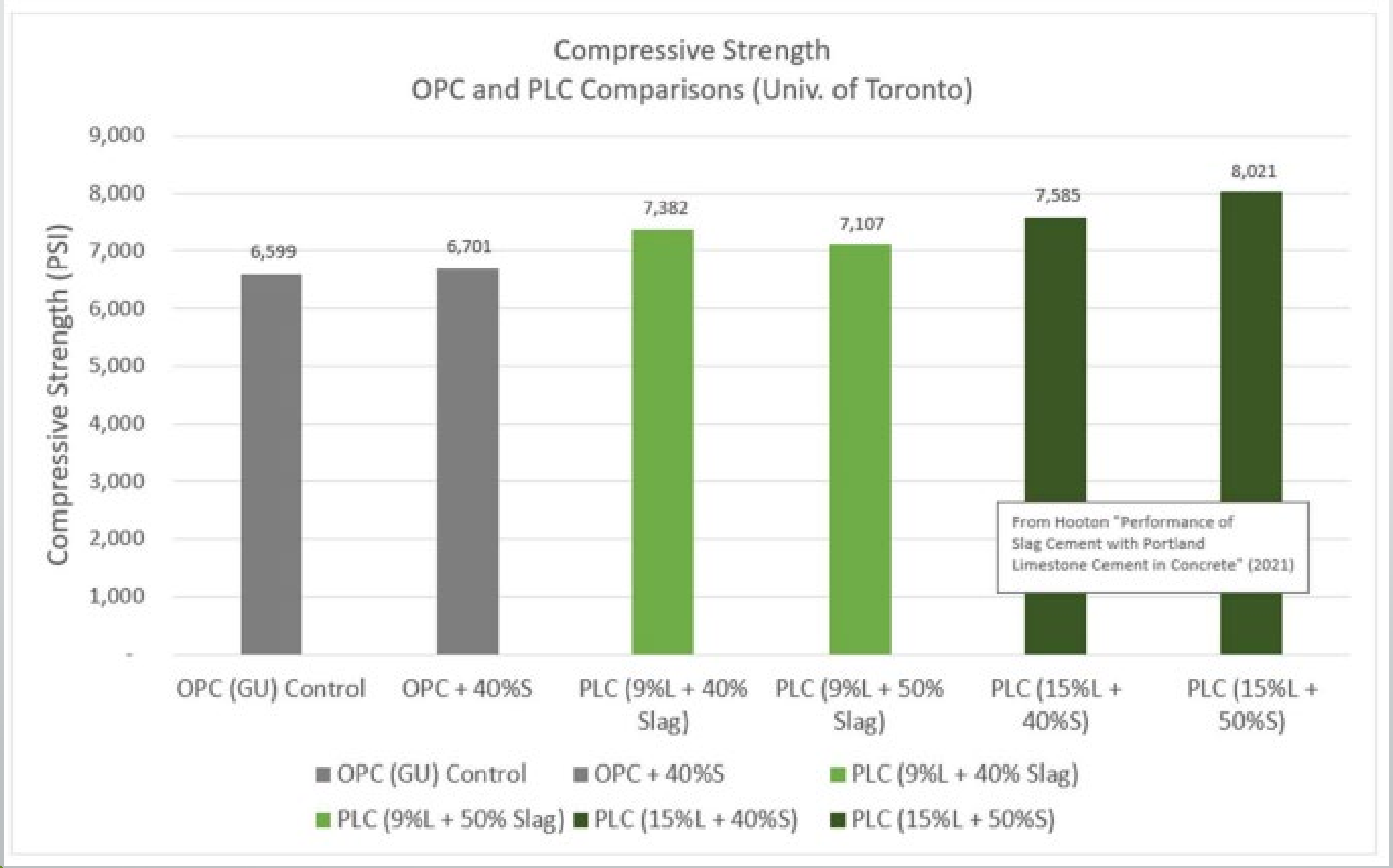
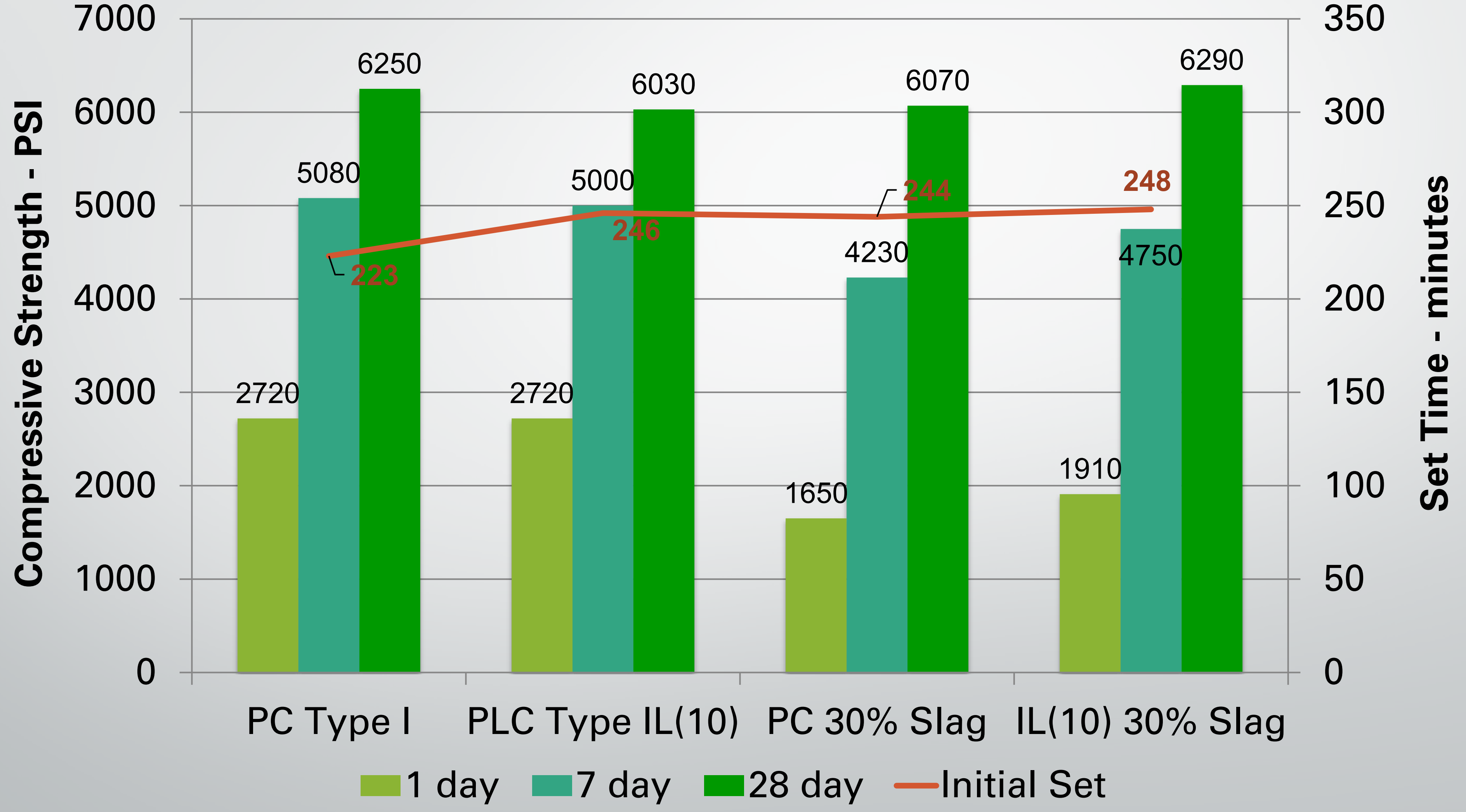
- Slag contains 8% - 14% alumina
- The aluminates in slag react with the calcium carbonate in the limestone
- When slag cement is included in a IL mixture, more carboaluminates are formed, contributing to a strength increase and decrease in porosity / permeability
- Synergistic effect: Slag cement with IL provides added strength/durability benefits in concrete beyond normal benefits of slag cement.

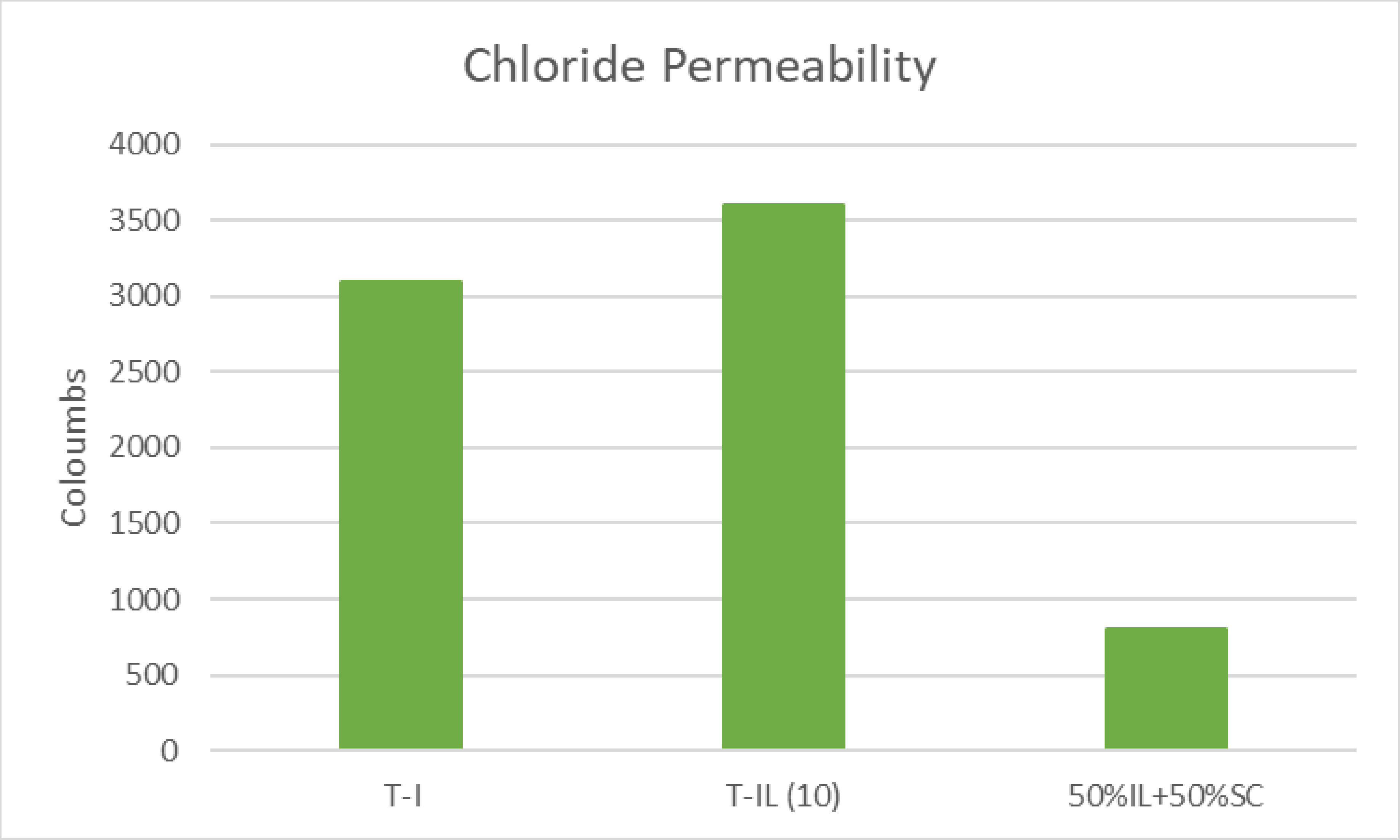
PLC Effects
Compressive Strength with Increasing Limestone



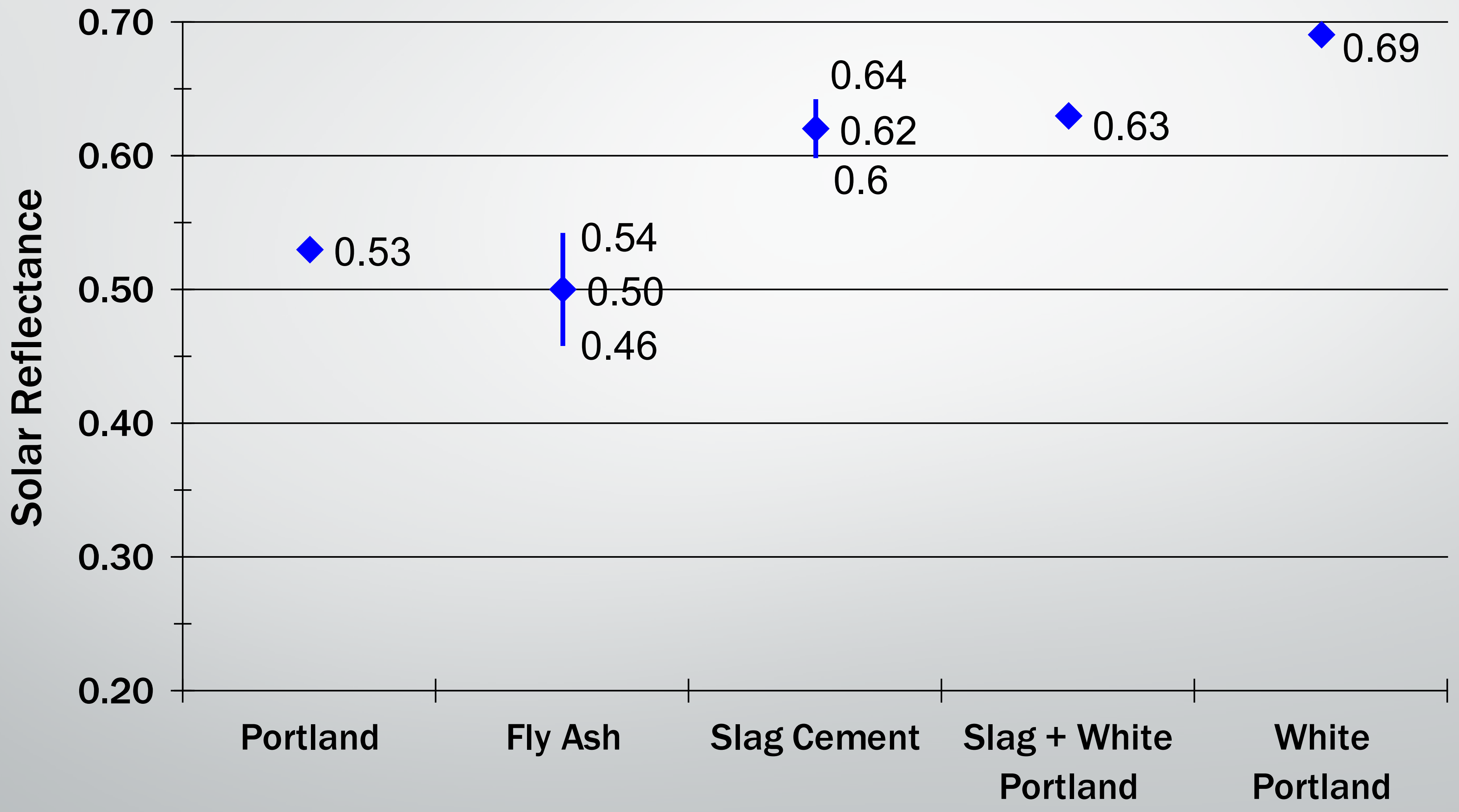
Compressive Strength and Set Time



Chloride Permeability



Improved Reflectivity



Concrete Solar Reflectance (SRI)

EPA LEED Bldg Cincinnati, OH

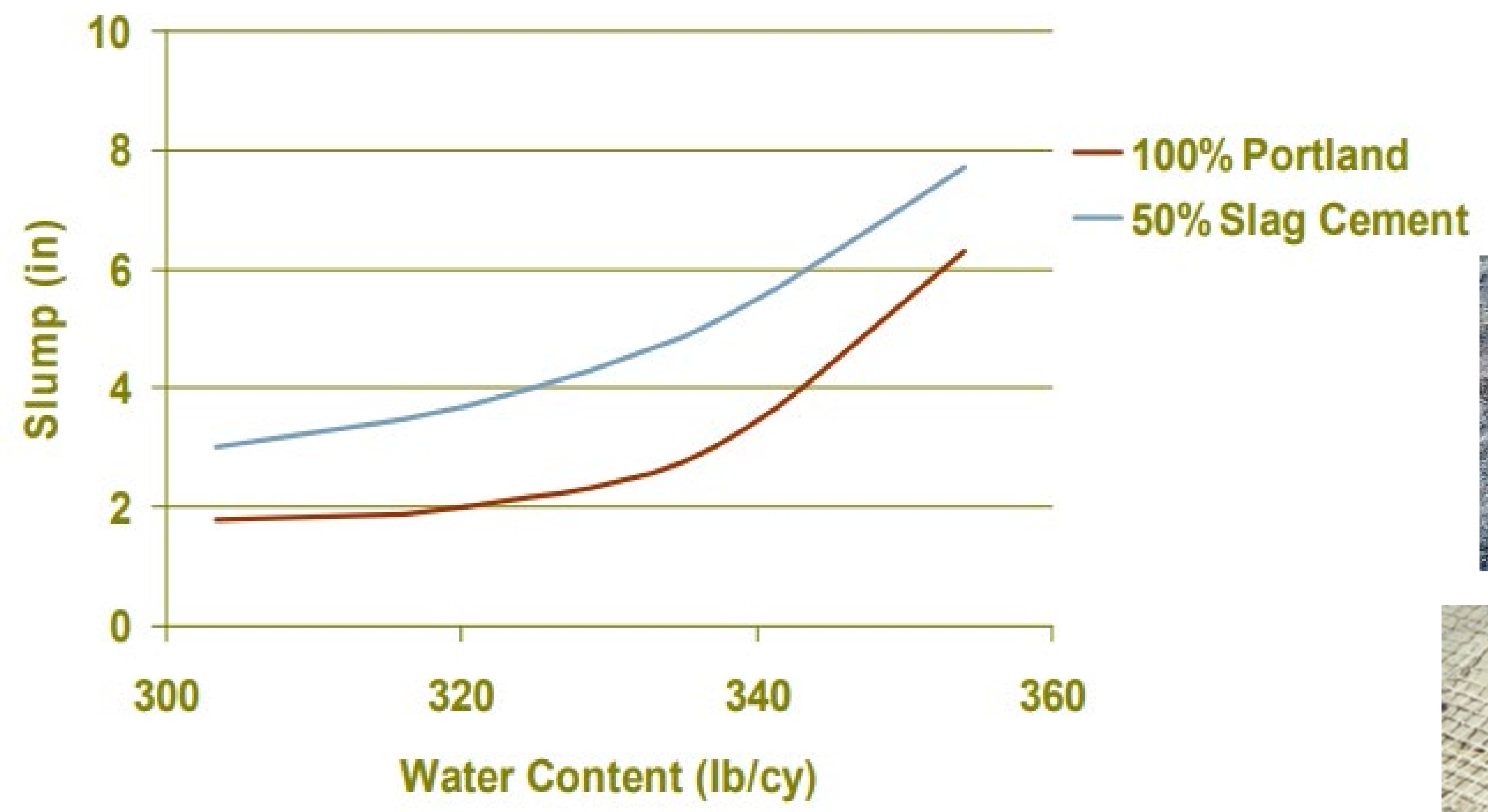
High albedo sidewalk 40% slag cement SRI > 29

Material surface	Solar Reflectance	Emittance	Solar Reflectance Index (SRI)
Black acrylic paint	0.05	0.9	0
New asphalt	0.05	0.9	0
Aged asphalt	0.1	0.9	6
White asphalt shingle	0.2	0.9	21
Aged concrete	0.2 to 0.3	0.9	19 to 32
New concrete (ordinary)	0.35 to 0.45	0.9	38 to 52
Concrete with slag cement &/or fly ash	0.4 to 0.7	0.9	40 to 70
New white Portland cement concrete	0.7 to 0.8	0.9	86 to 100
White acrylic paint	0.8	0.9	100

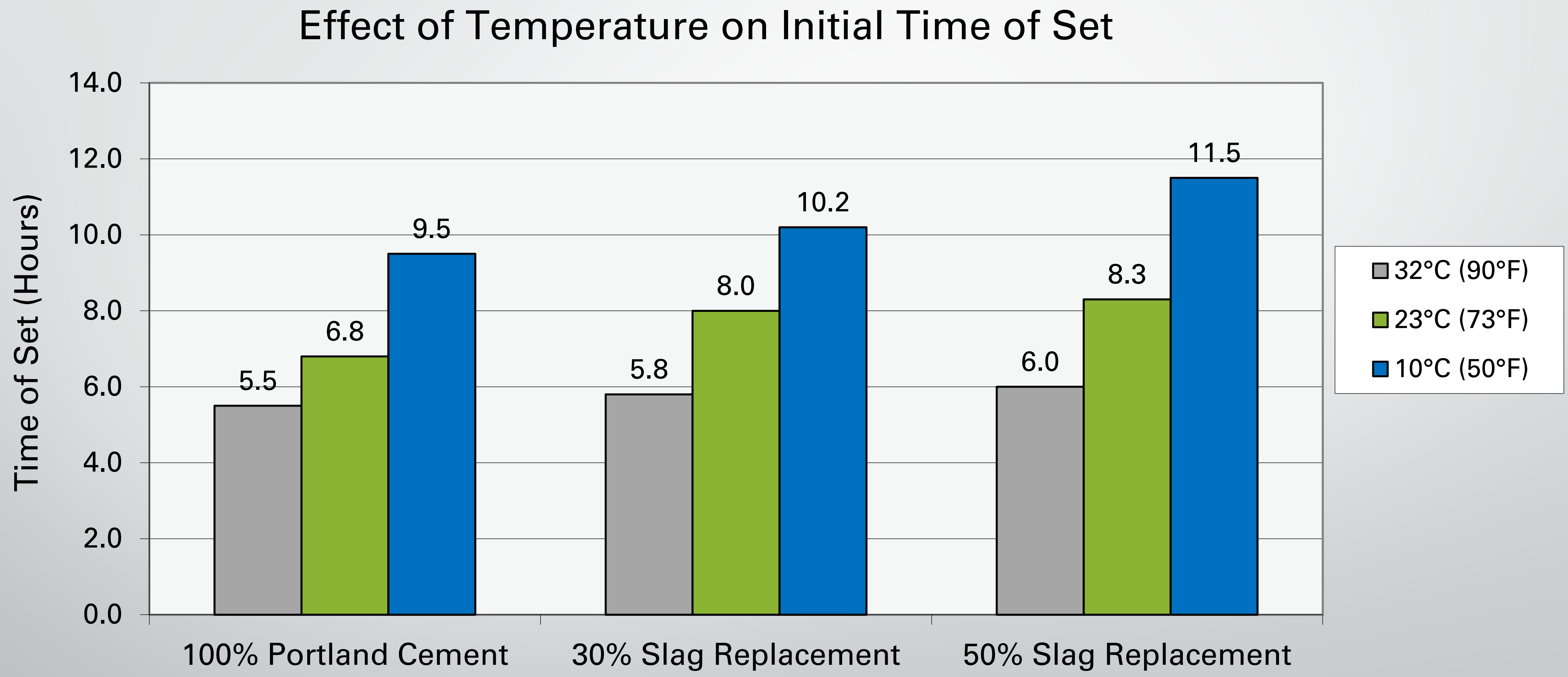
Color "Greening"

- "Greening" is a temporary blue-green color showing on the surface of concrete containing slag in the first few days after placement
- Occurs in small percentage of concrete made with slag cement from sulfides, disappearing within a days/week of exposure to air and sunlight (oxidizes)
- More prevalent with cements that burn waste fuels
- Spray white vinegar to remove

Effect on Water Demand

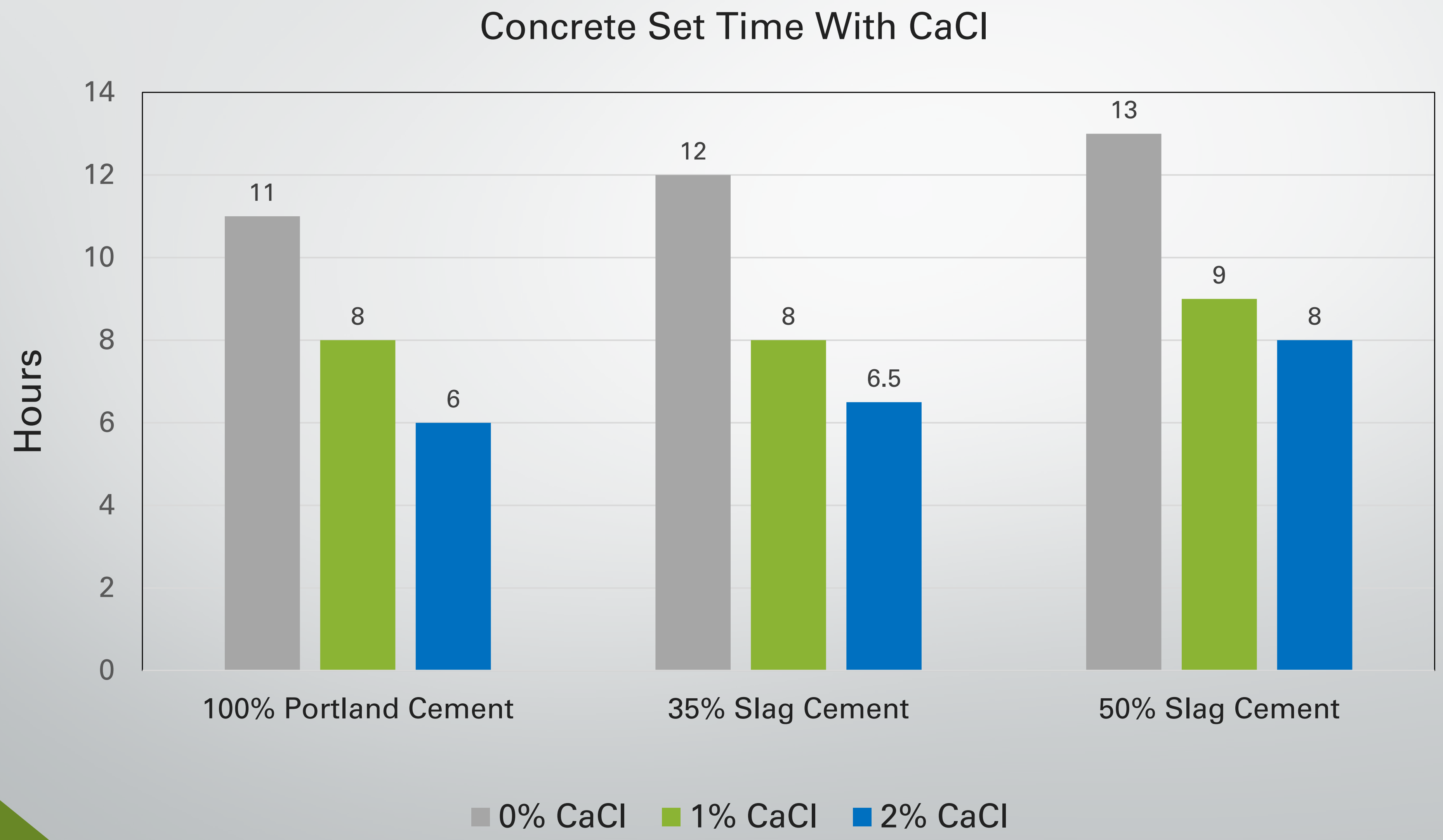


Set Time

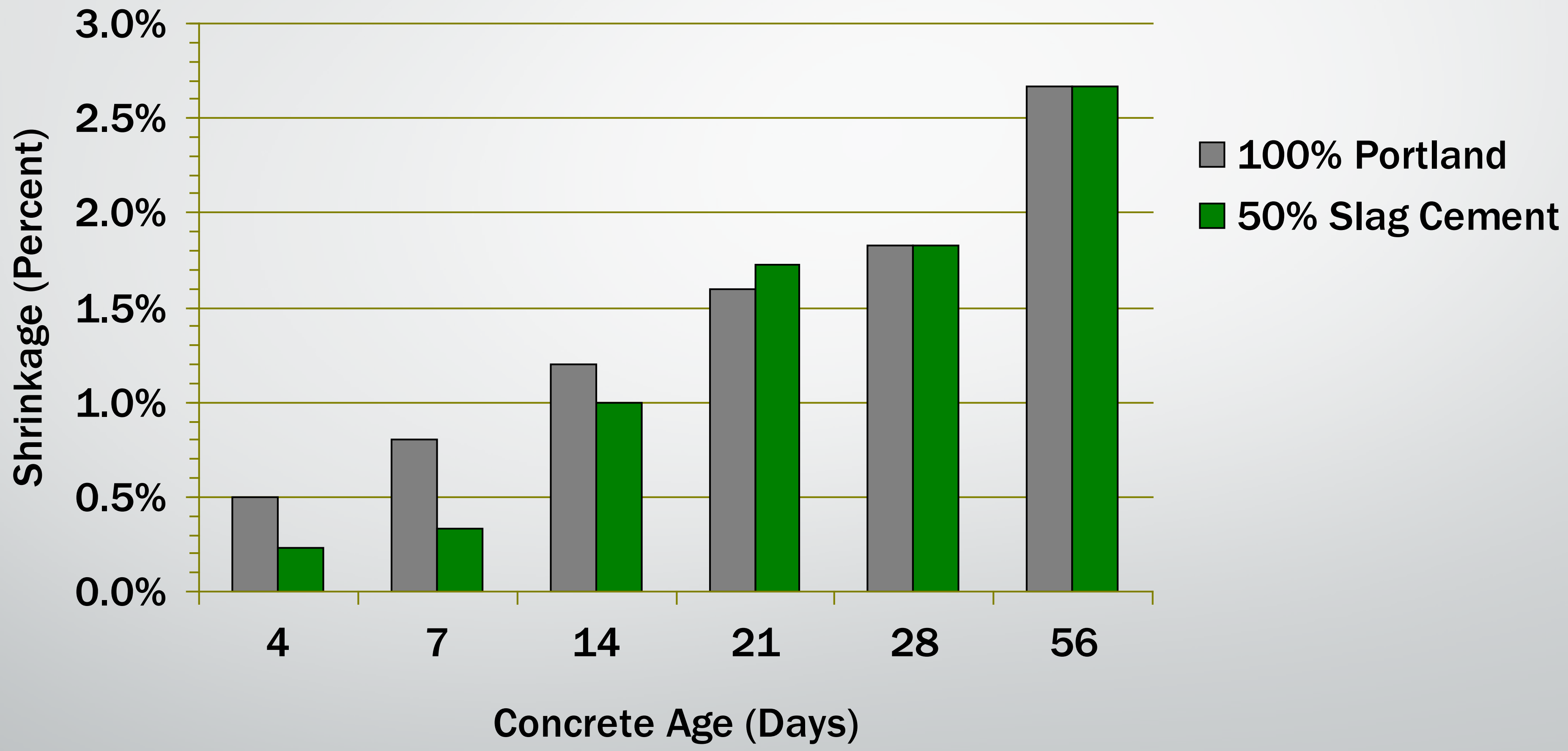


At higher cement replacements > 40% - 50% dose (admix) cement only

Set Time w/Accelerator

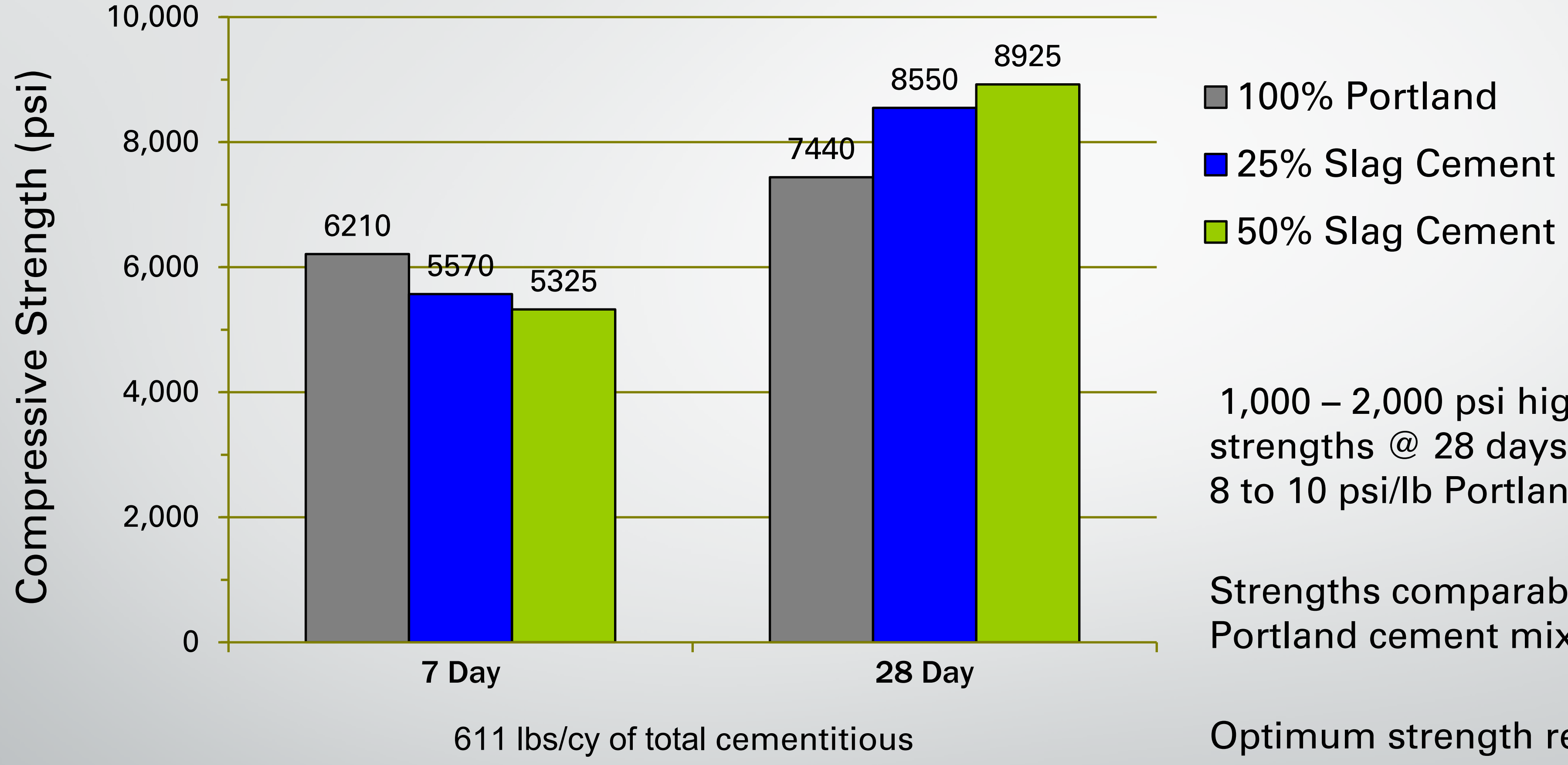


Drying Shrinkage



Slag cement has little or no effect on drying shrinkage

Compressive Strength



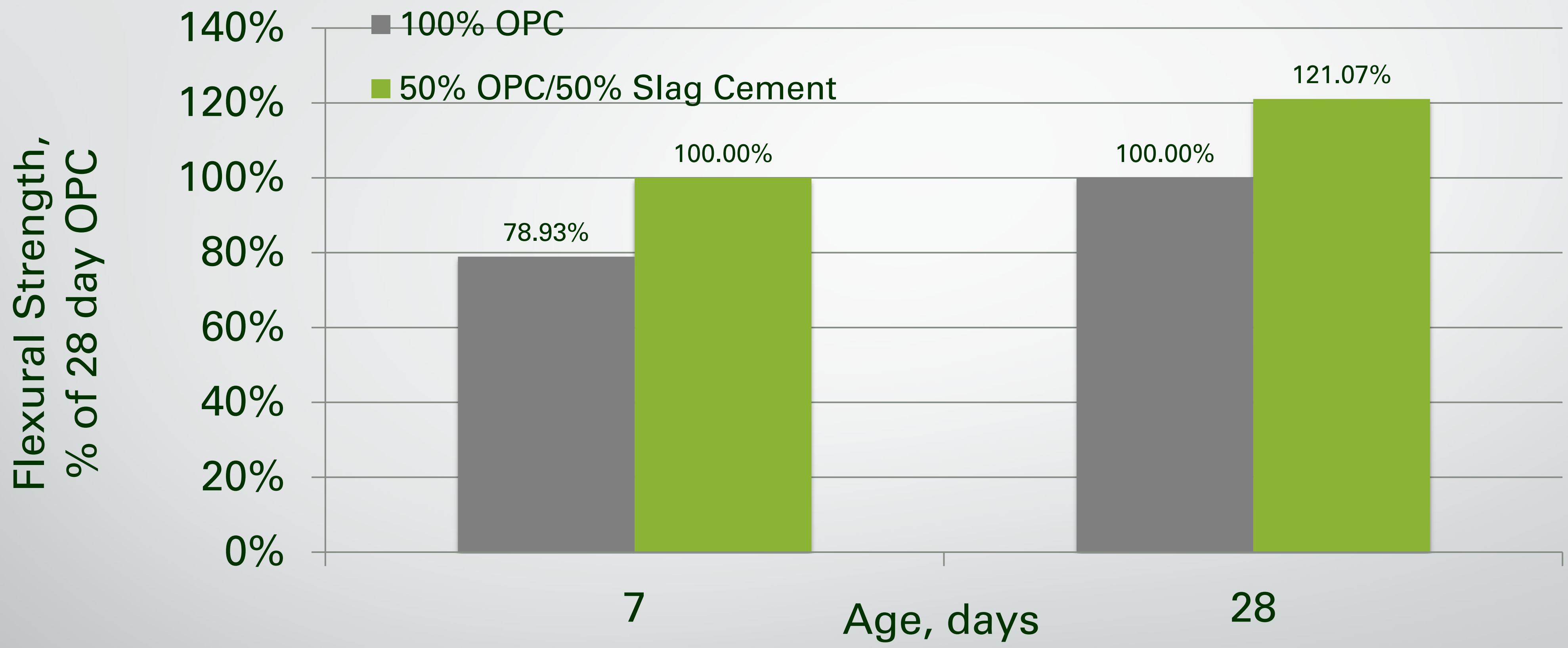
1,000 – 2,000 psi higher compressive strengths @ 28 days (11 to 14 psi/lb vs 8 to 10 psi/lb Portland or Flyash mix)

Strengths comparable to 100% Portland cement mix around 7 days

Optimum strength replacement approx. 35%

Cyls should sit for at least a couple of days when using > 40% replacement

Effect of Slag Cement on Flexural Strength

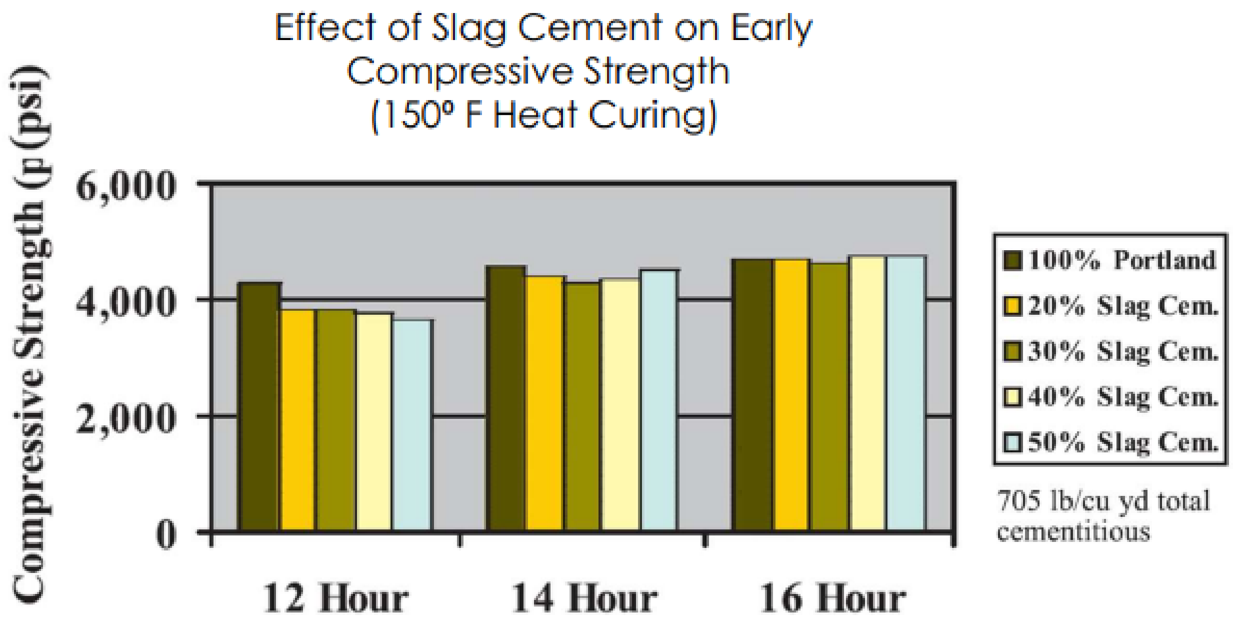


100% OPC 635 lbs/yd @ 28 days = 830 psi

50%/50% 583 lbs/yd @ 28 days = 1,000 psi

Precast/Prestressed Concrete

- Heat is an excellent activator for slag cement
- When heat is used, early-age strength is usually equivalent or superior to straight portland cement concrete
  - 3-4,500 psi achievable stripping str.
- At 28 days, strengths are superior,5-8,000 psi
- Precast manufacturers have used 20-50% replacement for portland,



One World Trade Center, NY

- Concrete performance requirements included:
  - Heat reduction in mass placements
  - High strength – 14,000 psi
  - Superior rheology – self consolidating SCC
  - Reduced environmental footprint
- Concrete included a quaternary mixture containing 32% portland cement, 52% slag cement with 8% fly ash and 8% silica fume
- Achieved 13,000 psi (14 psi/lb) to 16,000 psi (17 psi/lb) @ 56 days

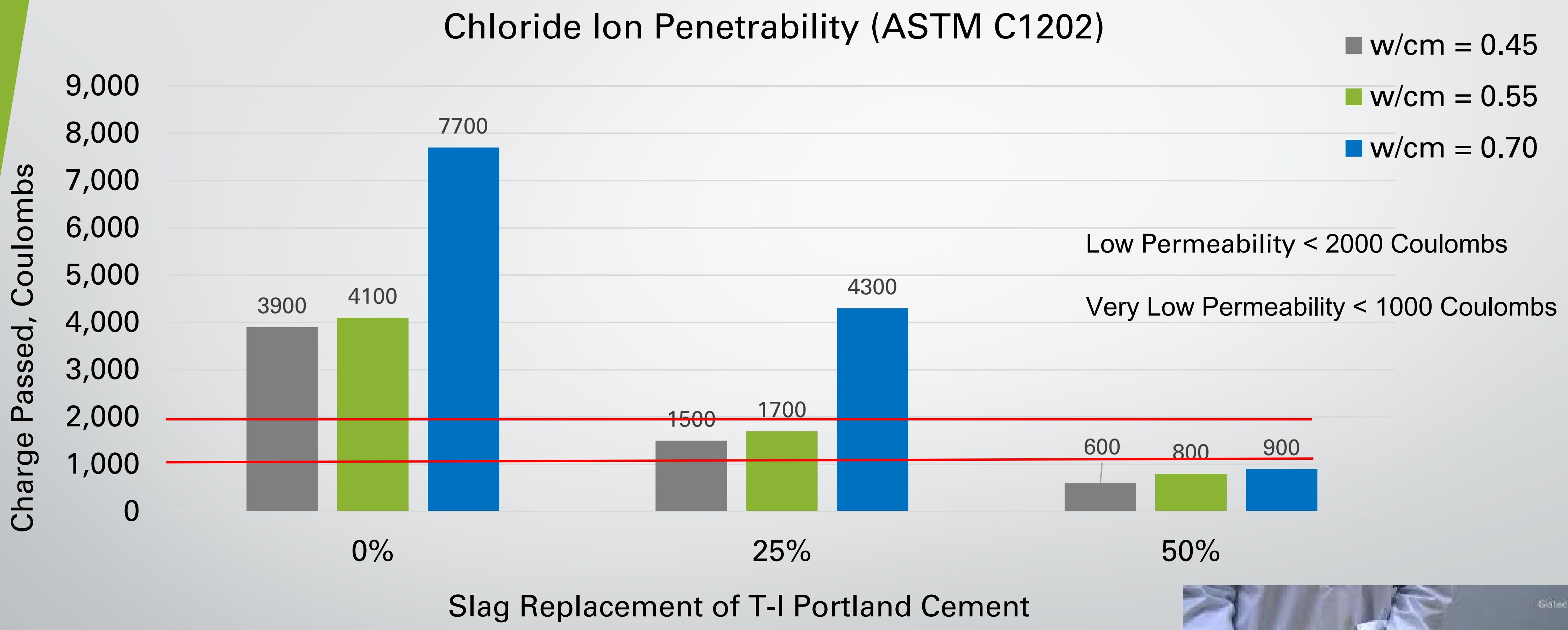
Ten Hudson Yards Tower, NJ

- 50 story 895-foot tall project consisted of 107,000 cubic yards of concrete.
- Design required high strength concrete of 14,000 psi in its foundation and lower shear walls. Slag cement was used to get the required strength while minimizing heat gain in mass concrete.
- The 14,000 psi mix design consisted of 350 lbs of portland cement, 700 lbs of slag cement, and 50 lbs of silica fume, and achieved over 16,000 psi.

JFK International Airport – Runway 4L-22R Reconstruction

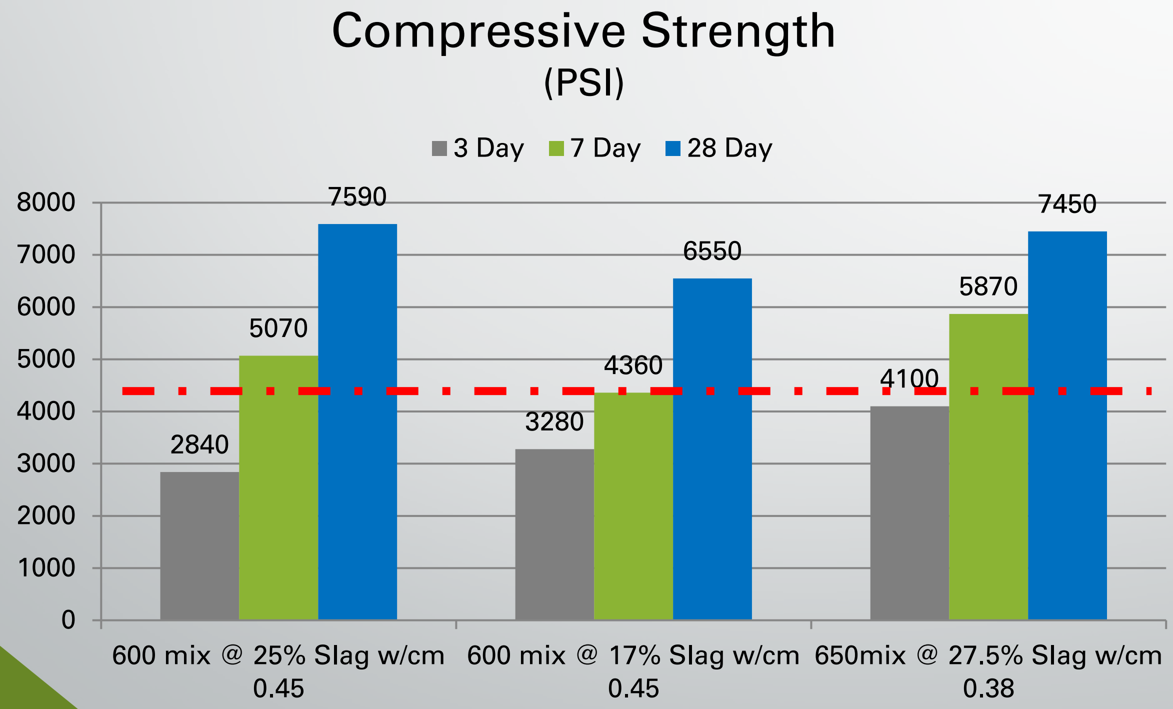
- Rehabilitated existing asphalt runway with 18-in concrete pavement overlay
- Concrete Specifications
  - 700 psi min 28-day flexural
  - 550 lb/cy max cementitious
- ASTM C595 Type IS (40) slag blended cement in 4-aggregate mixture yielded 1,300 psi flexural strength at 28-days
- Mixture provided constructability, strength, durability and smoothness, at a reduced environmental impact

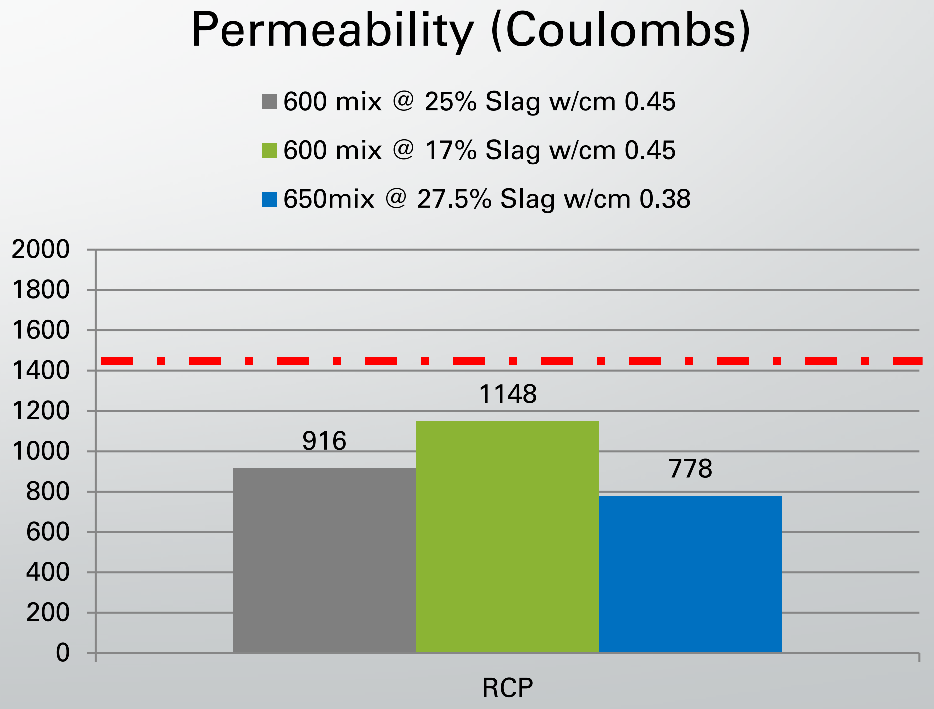
Effect of Slag Cement on Concrete Permeability



ODOT QC 2 Mix Examples

Requirements	4500 psi @ 28 days	RCP < 1500 coulombs
Mix A	- w/cm 0.45, 600 cementitious, 25% slag cement	
Mix B	-w/cm 0.45, 600 cementitious, 17% slag cement	
Mix C	-w/cm 0.38, 650 cementitious, 28% slag cement	





Roland Campo Bridge, Neenah, WI

SCA High Performance Award

- 6,000 cu.yds.
- 30% Replacement
- Rapid Chloride Permeability < 1,500 coulombs
- Concrete Temperature Range 60 to 80 oF
- Slump 2″ to 4″ (w/cm 0.42)
- Air Content 4.5% to 7.5%
- Strength spec 4,000 psi @ 28 Days
  - 7 Day strengths 4,000 to 5,000 psi
  - 28 Day strengths 5,200 to 6,200 psi

Effect of Slag Cement on Alkali – Silica Reactivity (ASR)

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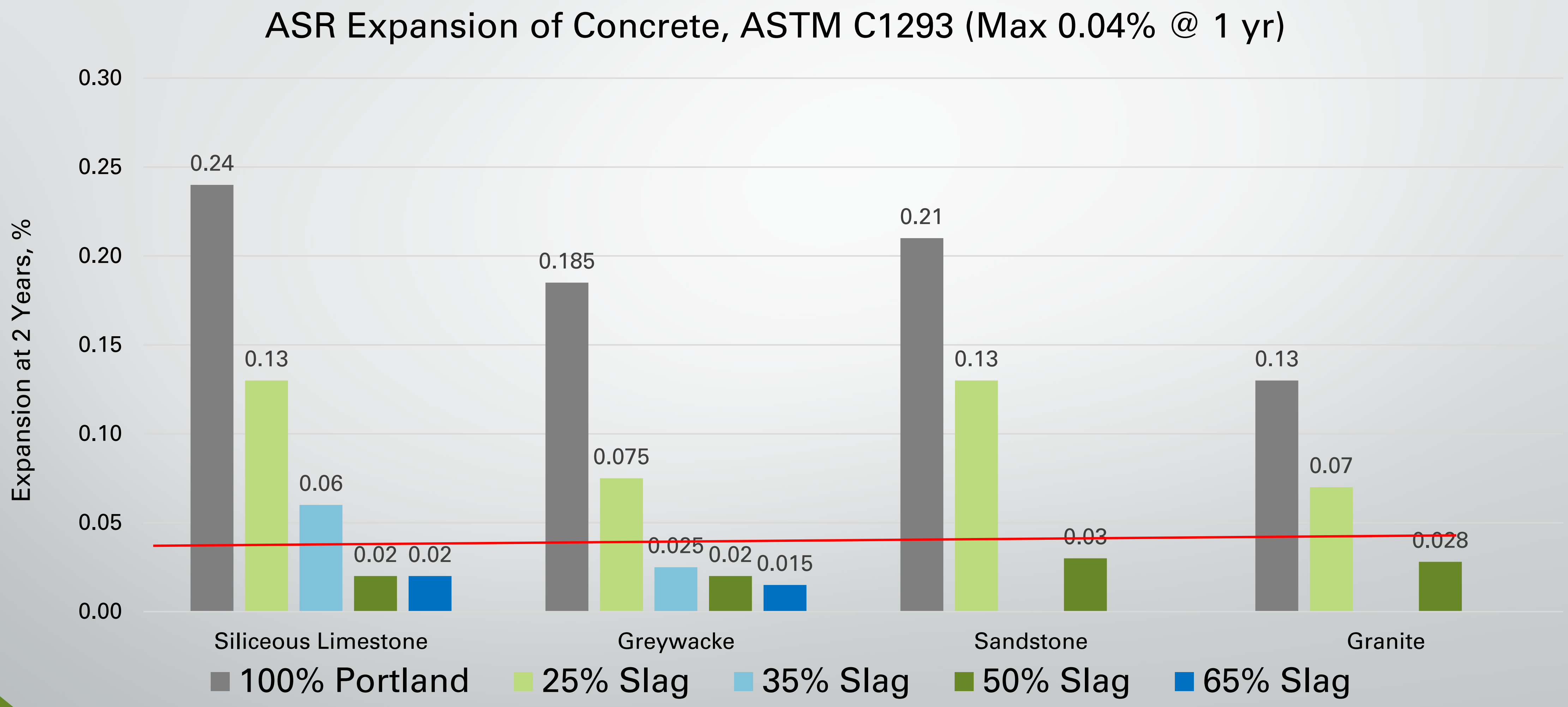
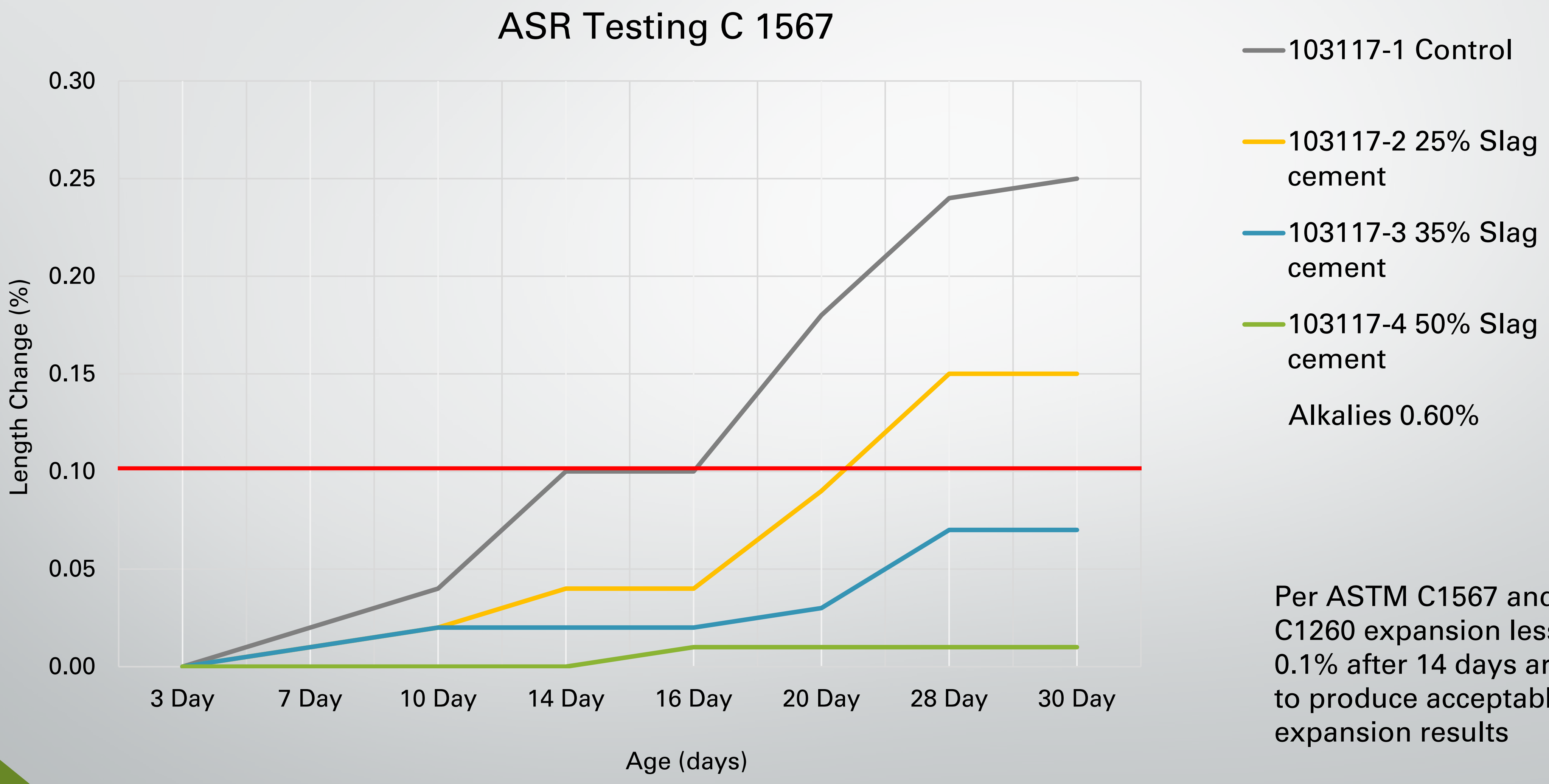


ASR Testing



Per ASTM C1567 and C1260 expansion less than 0.1% after 14 days are likely to produce acceptable expansion results

Indian Lake Spillway, OH

The Indian Lake Spillway is the second largest labyrinth style dam in the United States and the largest east of the Mississippi River, standing over 16 feet high and over 700 feet long. Indian Lake's storage capacity at principal elevation is 15 billion gallons of water spanning over 5,000 acres.

The project required over 7,300 cubic yards of mass concrete using of 50% slag cement for temperature control, ASR mitigation and to help reduce shrinkage.

Design strength 3,000 psi

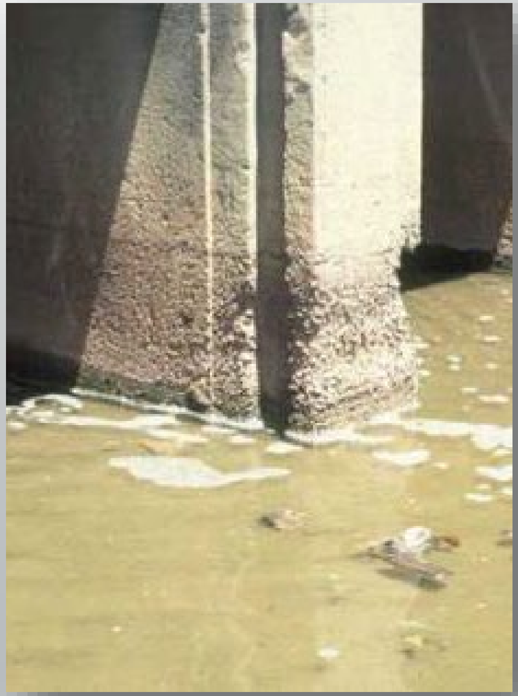
7 day strength 2,600 psi
28 day strength 5,800 psi

I 96 Reconstruction – Detroit, MI

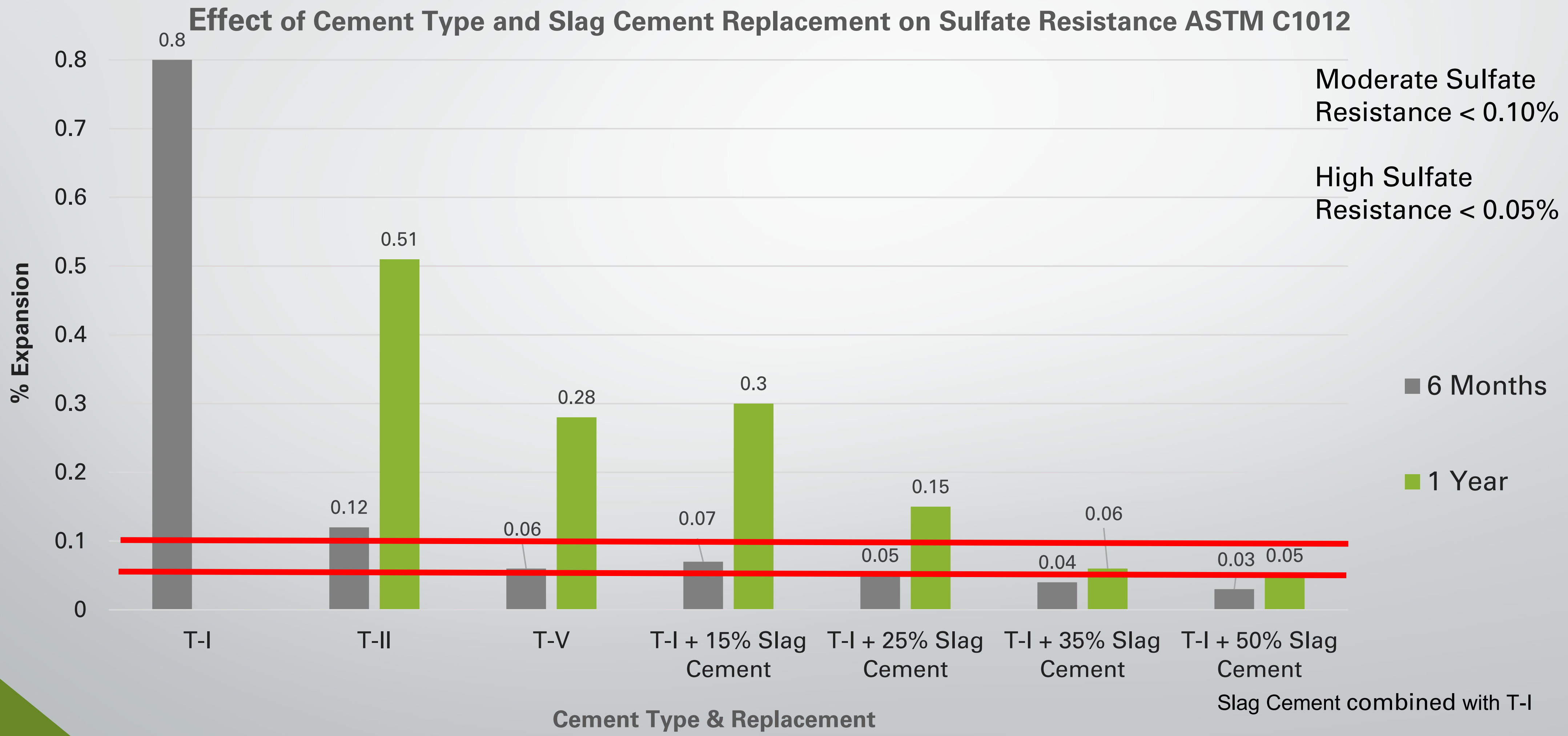
- Reconstructed 7 miles of 8-lane freeway, 6 interchanges w on/off ramps
- Slag cement used at over 30% to mitigate potential ASR and achieve specified flexural and compressive strengths
- Lighter color enhances night time visibility
- Consistent, reliable performance contributed to completion of project ahead of schedule

Improved Sulfate Resistance

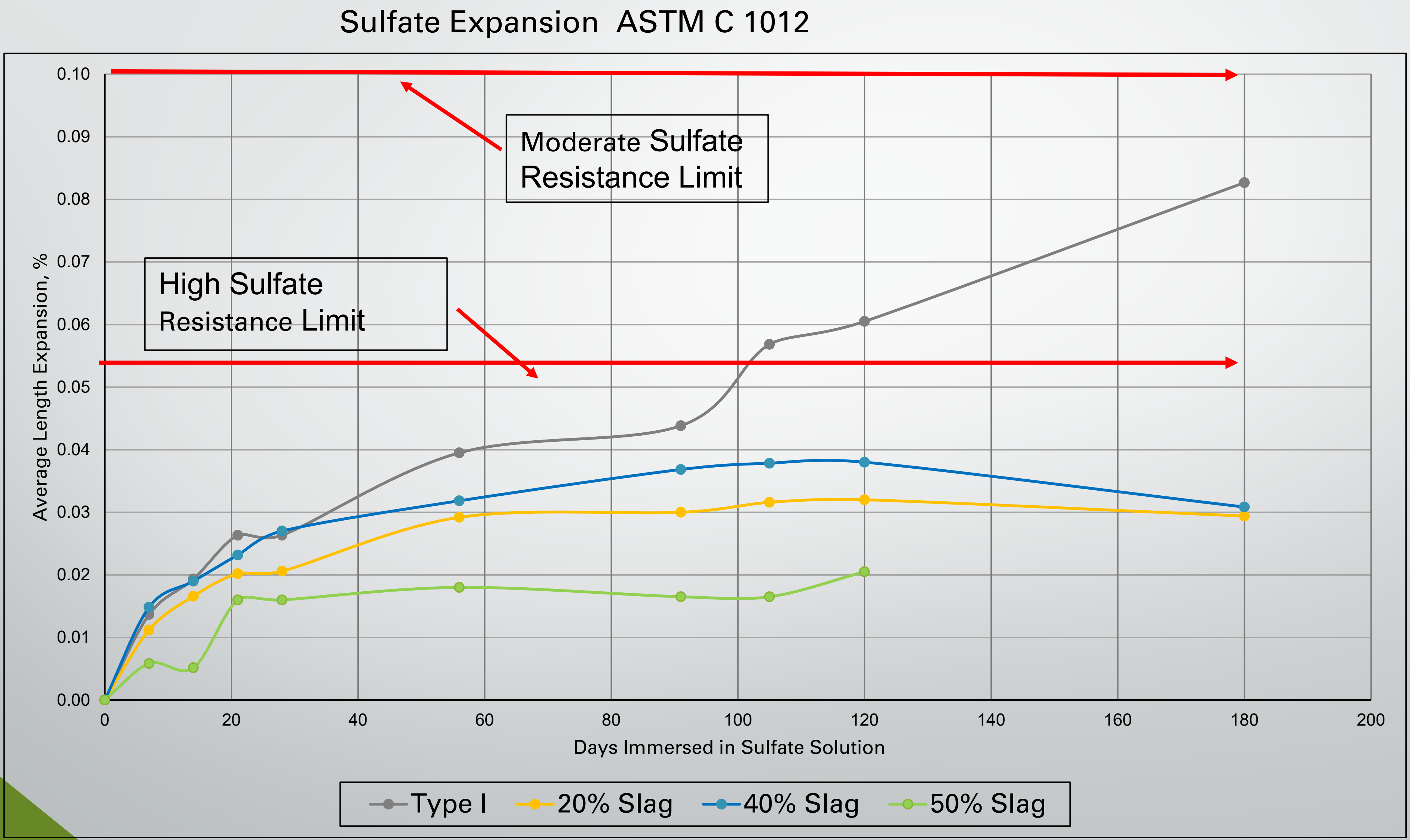
- 50% slag cement has been allowed by many agencies instead of Type V cement for severe sulfate exposure.
- T-I + 25% - 50% slag cement = T-II (Varies with C3A content)
- T-I + 50% - 65% slag cement = T-V (Varies with C3A content)
- T-II + 35% - 50% slag cement = T-V (Varies with C3A content)
- Certain types of Class F fly ashes can be effective at 20-30%
- Some can be detrimental due to the aluminates in the fly ash



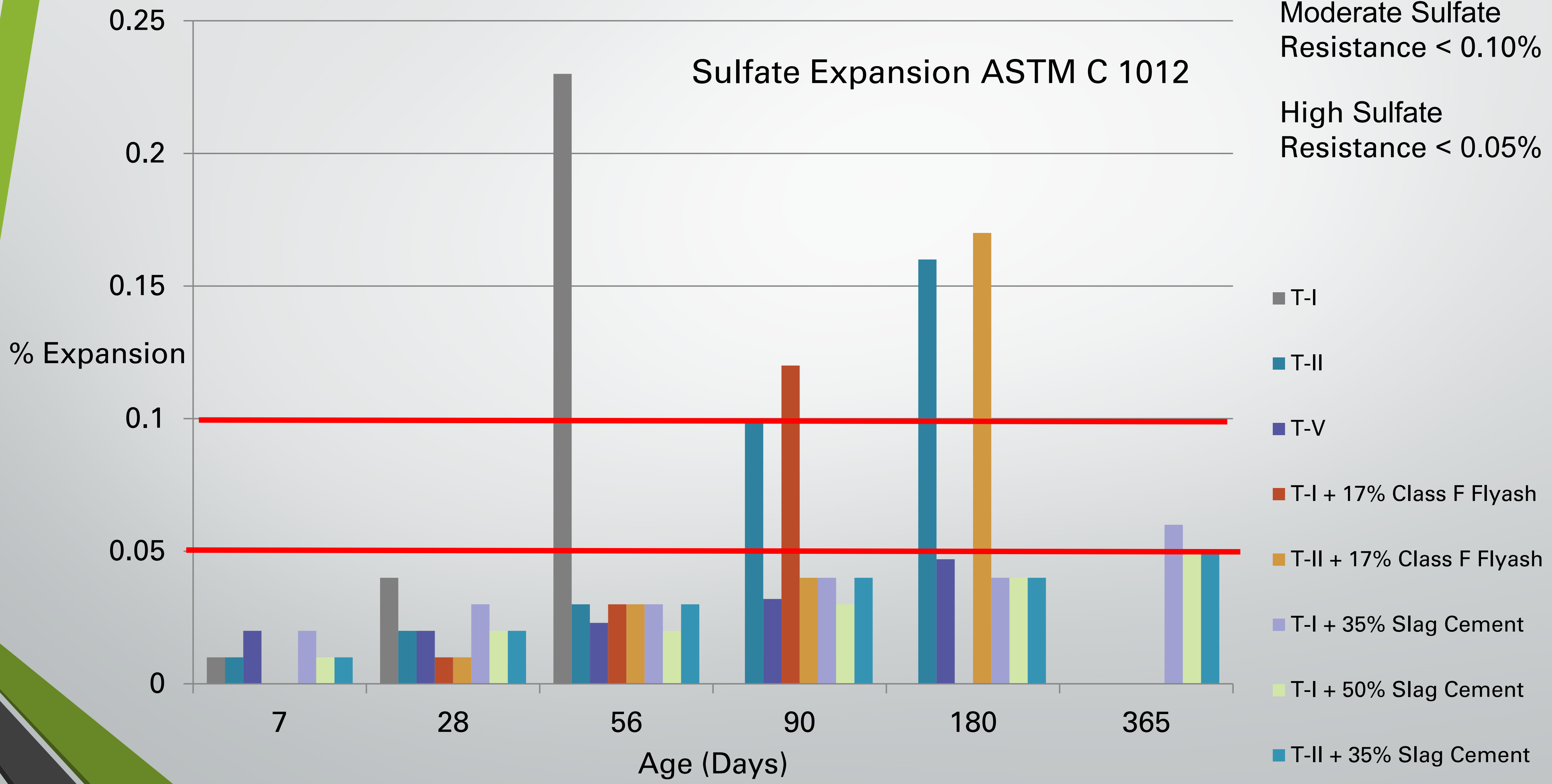
Sulfate Resistance
ASTM C1012



Slag Cement Sulfate Performance w/Type I



Sulfate Resistance



Moderate Sulfate Resistance < 0.10%

High Sulfate Resistance < 0.05%

Wastewater Treatment Plant Flow Equalization Basin Project, Clyde, OH

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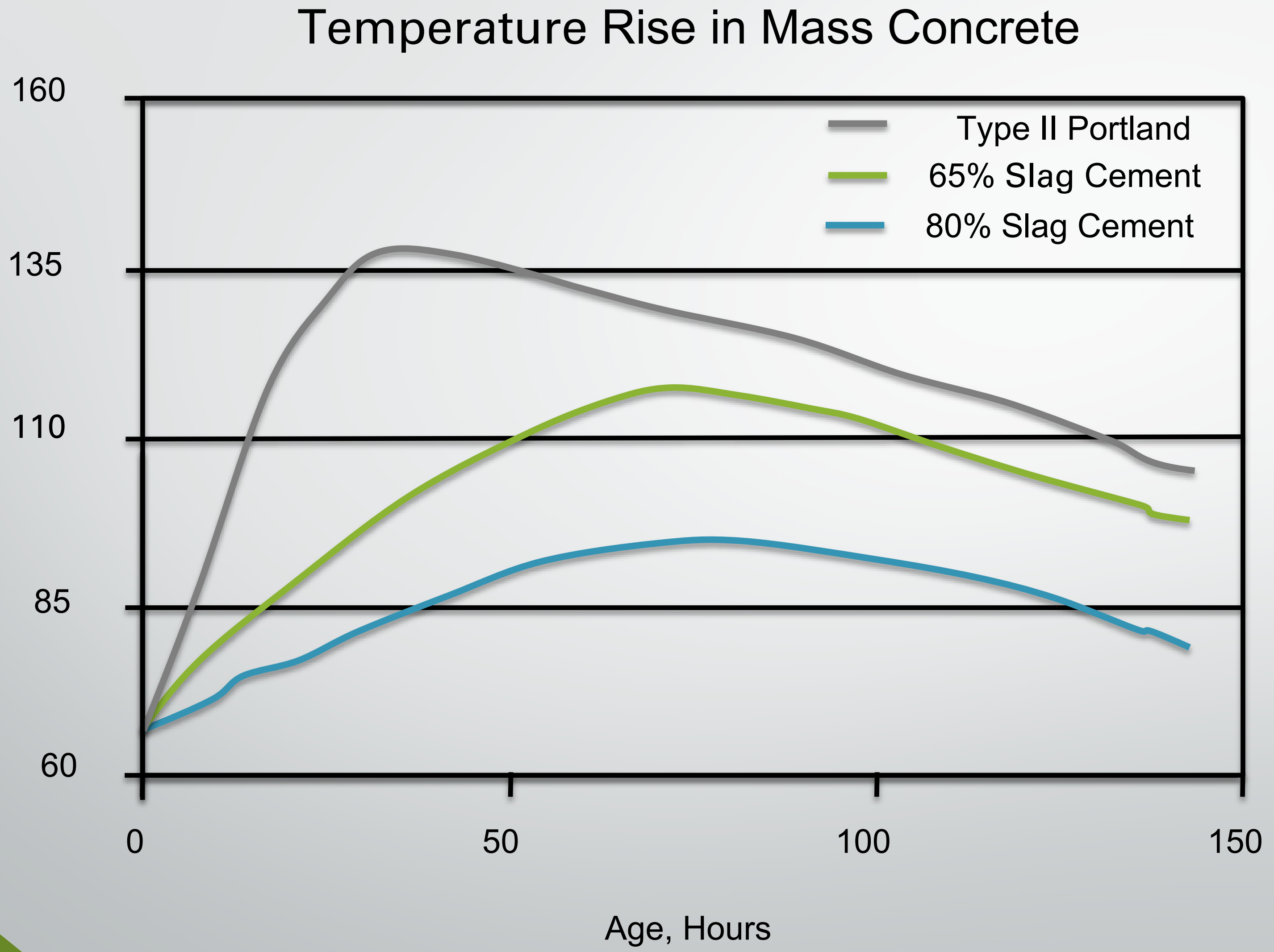
- One-million gallon flow equalization basin to meet Ohio EPA requirements
- Slag cement used at 40% replacement in mat foundation basin floor and at 25% in basin walls
- Use of slag cement provided desired sulfate resistance, reduced permeability and reduced susceptibility to ASR in this aggressive wastewater treatment environment

Effect of Slag Cement on Mass Concrete



Let cylinders sit for 5 to 7 days

Mass Concrete Maximum In-Place Concrete Temperature Estimator

						Example					
	Project:	Example with SCA cal/gm						Date:	02/20/18		
	Location:							By:	MVK		
			Meters	1.53		Thickness	5.0	Feet			
			Meters	1.53		Length	5.0	Feet			
			Meters	1.53		Width	5.0	Feet			
			Meters³	3.55		Volume	125	Feet³			
Metric Units	Senerio #1	Senerio #2	Senerio #3	Senerio #4			Senerio #1	Senerio #2	Senerio #3	Senerio #4	Inch-Pound Units
ºC	21	24	21	24	T_i	Initial Concrete Temp.	70	75	70	75	ºF
kg/m3	192.8	192.8	178.0	178.0	P	Mass of Portland Cement	325	325	300	300	Lb/Cu.Yd.
kg/m3	192.8	192.8	178.0	178.0	S	Mass of Slag Cement	325	325	300	300	Lb/Cu.Yd.
kg/m3	0.0	0.0	0.0	0.0	F	Mass of Fly Ash	0	0	0	0	Lb/Cu.Yd.
kg/m3	2333	2333	2333	2333	W	Unit Weight of Concrete	3933	3933	3933	3933	Lb/Cu.Yd.
kj/kg	272	272	251	251	H_1	Heat of Hydration -	65.0	65.0	60.0	60.0	Cal/G
kj/kg	272	272	251	251	H_2	Heat of Hydration -	65.0	65.0	60.0	60.0	Cal/G
kj/kg	272	272	251	251	H_3	Heat of Hydration -	65.0	65.0	60.0	60.0	Cal/G
	Senerio #1	Senerio #2	Senerio #3	Senerio #4			Senerio #1	Senerio #2	Senerio #3	Senerio #4	
ºC	21.1	23.9	21.1	23.9	T_i	Initial Temperature	70.0	75.0	70.0	75.0	ºF
ºC	44.71	44.71	38.09	38.09	ΔT	Temperature Gain	80.47	80.47	68.57	68.57	ºF
ºC	65.8	68.6	59.2	62.0	T_{max}	Maximum Temperature	150.5	155.5	138.6	143.6	ºF

Buzzi Unicem USA Spreadsheet

Cinergy, Cayuga, IN Mass Concrete
Placed 10/05 – 12/05

SCA
SLAG CEMENT ASSOCIATION

Specification

4,000 psi @ 56 Days

W/Cm 0.44

Slump 4′ – 6″

Air 4% - 6%

Max internal temp 160^{o}F

Max temp gradient 30^{o}F

Mix Design

540 total cementitious

T I-II/Slag Cement 30% / 70% & 40% / 60%

7 day strengths: 2,800 – 3,200 psi

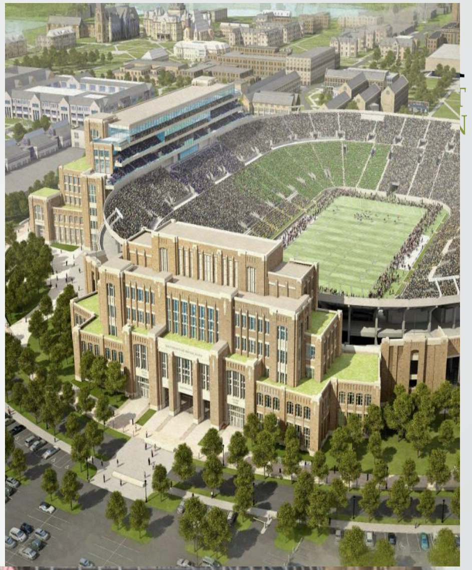
28 day strengths: 4,000 – 4,700 psi

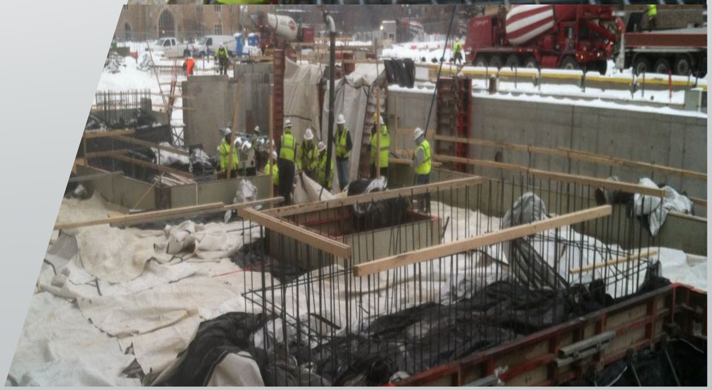
56 day strengths: 4,900 – 5,300 psi

Internal temps: 100^{o}F – 140^{o}F

University of Notre Dame Campus Crossroads Project

- $400 million, LEED Silver, project consisted of attaching three new buildings onto the existing iconic Football Stadium increasing capacity by 750,000 sq. feet.
- Total project entails 58,000 cubic yards of concrete, with over 13,000 yd3 of mass concrete.
- Mass concrete could not exceed 158 °F at its core. Mass concrete contained 70% slag to control temperature rise.
- No foundation exceeded 130°F.
- The 28-day design strengths were typically obtained in only 7 days.
- Slag was also used as a SCM in lightweight and general concrete.





National Veterans Memorial and Museum Columbus, OH

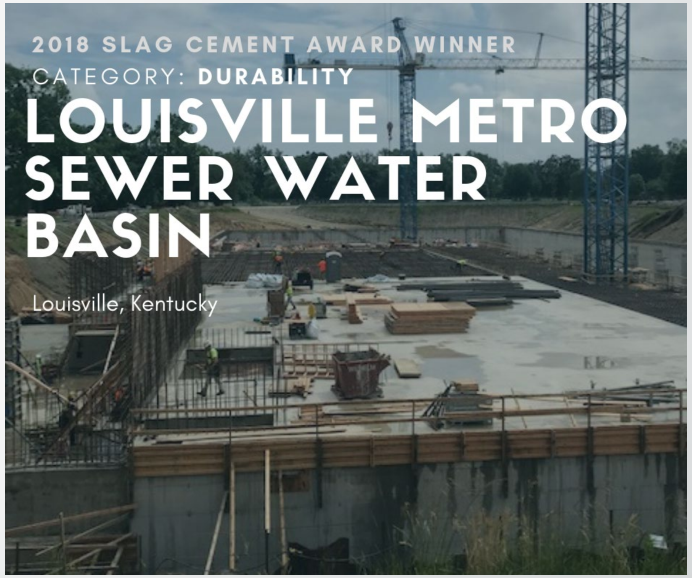
With over 8,000 cubic yards of concrete, the building's frame is one of the most complex concrete structures to ever be built in Ohio.

All mixes on this project utilized slag cement, varying between 35%-65% replacement. Slag cement was used for its aesthetically pleasing finish, lighter color, strength, lower permeability and mass concrete.

The mass concrete placements were successful due to using slag cement to lower initial heat of hydration. Almost all mixes made design strength within 7 days.

Metropolitan Sewer District Northwest Basin Louisville, KY 8/17

- Spec 5,000 psi @ 28 days
- Internal core max temp: 150°F max
- Mix Design
- 600 lbs total cementitious
- 50%/50% cement/slag cement
- Slump: 7-9”
- Admixture: hrwr, vma
- 1D: 700 psi
- 3D: 2,000 psi
- 7D: 4,500 psi
- 28D: Avg 7,500 psi (13 psi/lb)
- Core temp range: 105 - 115°F



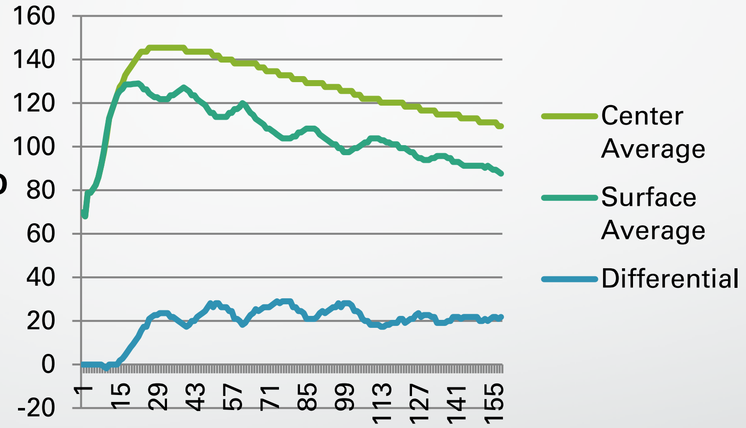
Dublin Pedestrian Bridge, Columbus, OH

- 6,000 psi SCC Mix Design
- 730 lbs/yd Cementitious
- 65% Slag Cement to Meet Permeability and Heat of Hydration Requirements
- Achieved 28 Day Strength in 7 Days Most Pours

Bluff Point Wind Farm Richmond, IN 6/17 – 8/17

- Base Mix Spec 5,000 psi @ 28 days, 3,000 psi @ 3 days
- Internal core max temp: 150°F max

- Mix Design
- 611 lbs total cementitious
- Cement/slag cement 60%/40%
- No air
- Slump: 8"   w/cm: 0.40
- Admixture: HRWR
- 3D: 3,000 – 4,800 psi
- 7D: 4,000 – 9,000 (7 – 15 psi/lb)
- 28D Avg: 6,500 psi (11 psi/lb)
- Core temp range: 130 - 149°F
- Ambient temps range: 70's – mid 90's



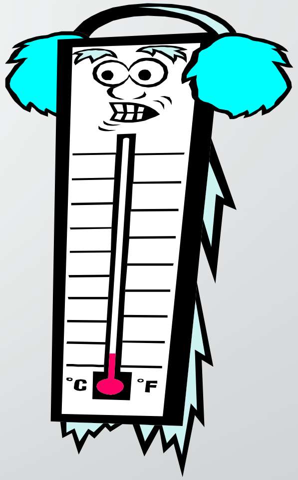
Brattleboro Bridge, VT

- Slag cement used for durability concerns/design requirements for a 100-year life from Vermont AOT
- Mass concrete 60% slag cement replacement met heat and strength requirements, exceeding the 4,000 psi & 8,000 psi requirements
- Ternary mixes ranging from 20-60% used improved workability of the low water/cement ratio with the emphasis of reducing permeability/durability concerns

Deicer Salt Scaling / Freeze -Thaw Resistance

- For exterior concrete flatwork that will be exposed to deicing chemicals, scaling resistance is dependent upon:

1. Good finishing practices (No premature finishing)
2. Adequate curing essential
3. Adequate air entrainment 4.5% to 7.5%
4. w/cm Ratio ≤ 0.45
5. Minimum compressive Strength ≥ 4,500 psi



- Any concrete will be susceptible to deicer scaling if the surface is not finished and cured properly

Exterior Residential Flatwork - Scaling

- 15% - 20% cement replacement max
- Max w/cm ratio (0.45) – Use WRDA, MRWR, HRWR for water reduction, accelerators for faster set times
- Mixes with cement replacements of 30+% can exhibit more bleeding which could cause scaling if water is left at the surface
- Not finishing too soon trapping in bleedwater
- WRDA/MRWR (retarder) – Dose cement only > 40% Replacement
- Proper curing !!!

Bleed Rate vs Time

Bleed rate (mls/cm^2)	100/0/0	82/0/18	75/25/0	71/11/18	70/20/10	63/19/18	53/29/18
50 mins		0.001	0.003	0.009			0.003
70 mins	0.015	0.015	0.008	0.009	0.019	0.006	0.024
100 mins	0.015	0.012	0.014	0.017	0.014	0.031	0.021
130 mins	0.015	0.021	0.019	0.017	0.019	0.015	0.027
160 mins	0.015	0.018	0.016	0.02	0.019	0.027	0.024
190 mins	0.012	0.018	0.016	0.017	0.014	0.018	0.012
220 mins	0.005	0.012	0.016	0.019	0.016	0.027	0.024
250 mins		0.008	0.011	0.02	0.011	0.027	0.024
270 mins		0.004	0.014	0.006	0.016	0.011	0.015
315 mins			0.008	0.003	0.003	0.009	0.006
350 mins			0.003				0.003
Total water collected	**0.077**	**0.109**	**0.128**	**0.137**	**0.131**	**0.171**	**0.183**
Slump (in.)	5.25	6.0	7.25	6.0	6.25	8.0	7.5
Air (%)	5.9	4.6	7	5	7	6.6	6.4

Questions?...