Performance of Slag Cement with Portland-limestone Cement in Concrete

Reducing the CO_2 Footprint of Concrete

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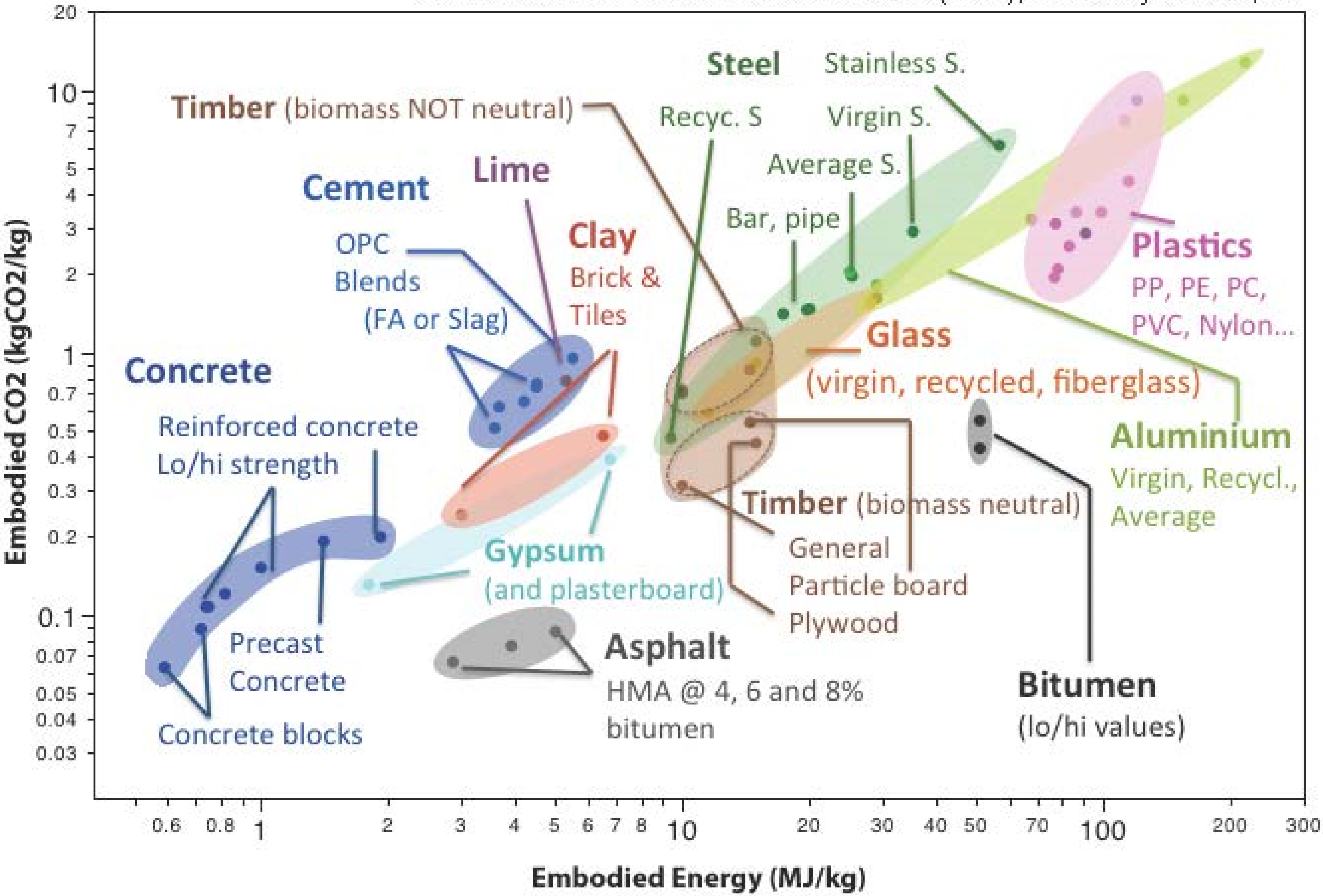
Concrete is a Sustainable Material

- Concrete has the lowest embodied carbon and energy footprint of any material (on a kg basis).

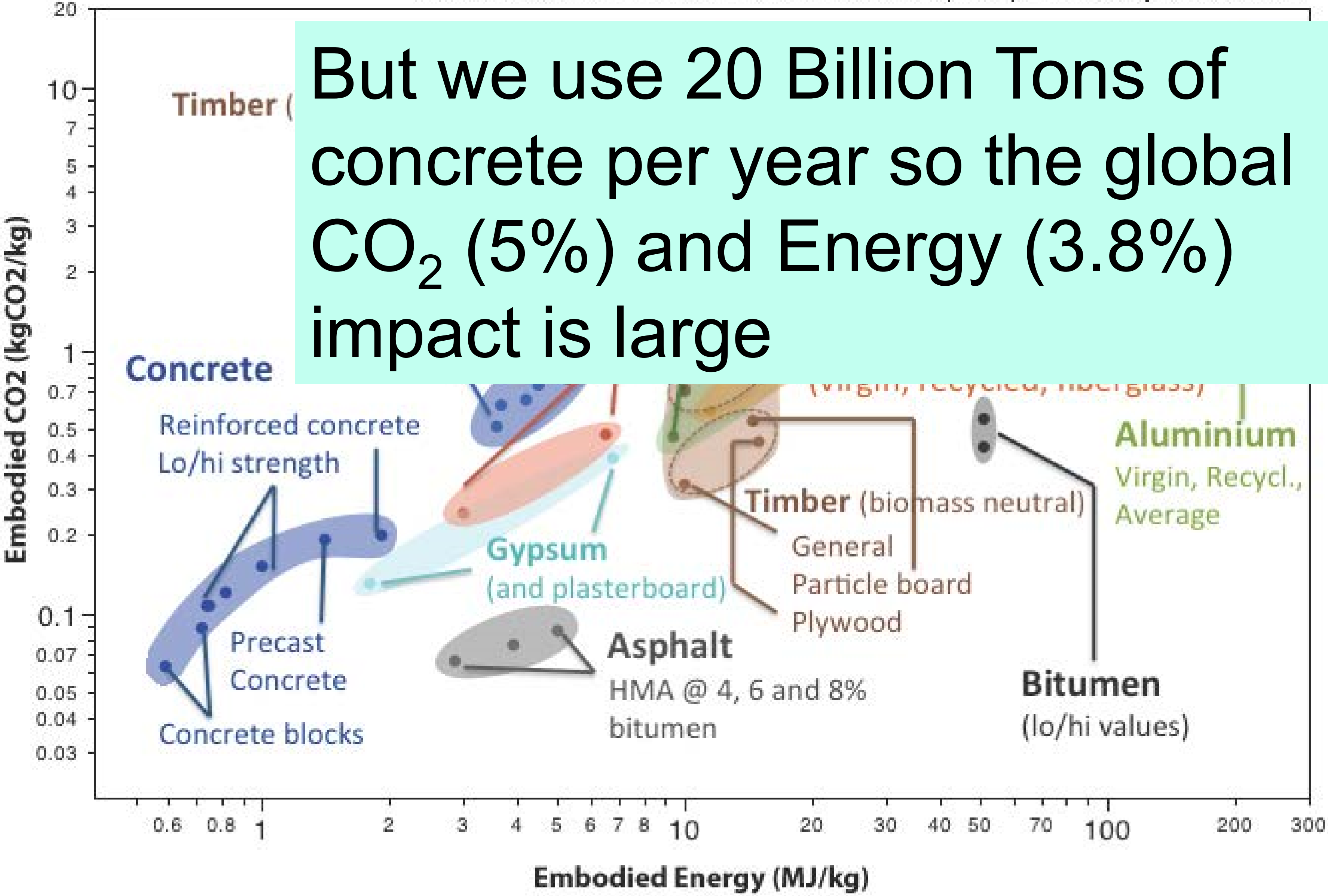
- It uses **local materials**, and if properly designed and executed, has a **long service life**, and is **recyclable**.

- If concrete structures are designed for durability, better life-cycle sustainability will be achieved due to longer service life and less repair.

data extracted from Hammond and Jones (2011), University of Bath, UK



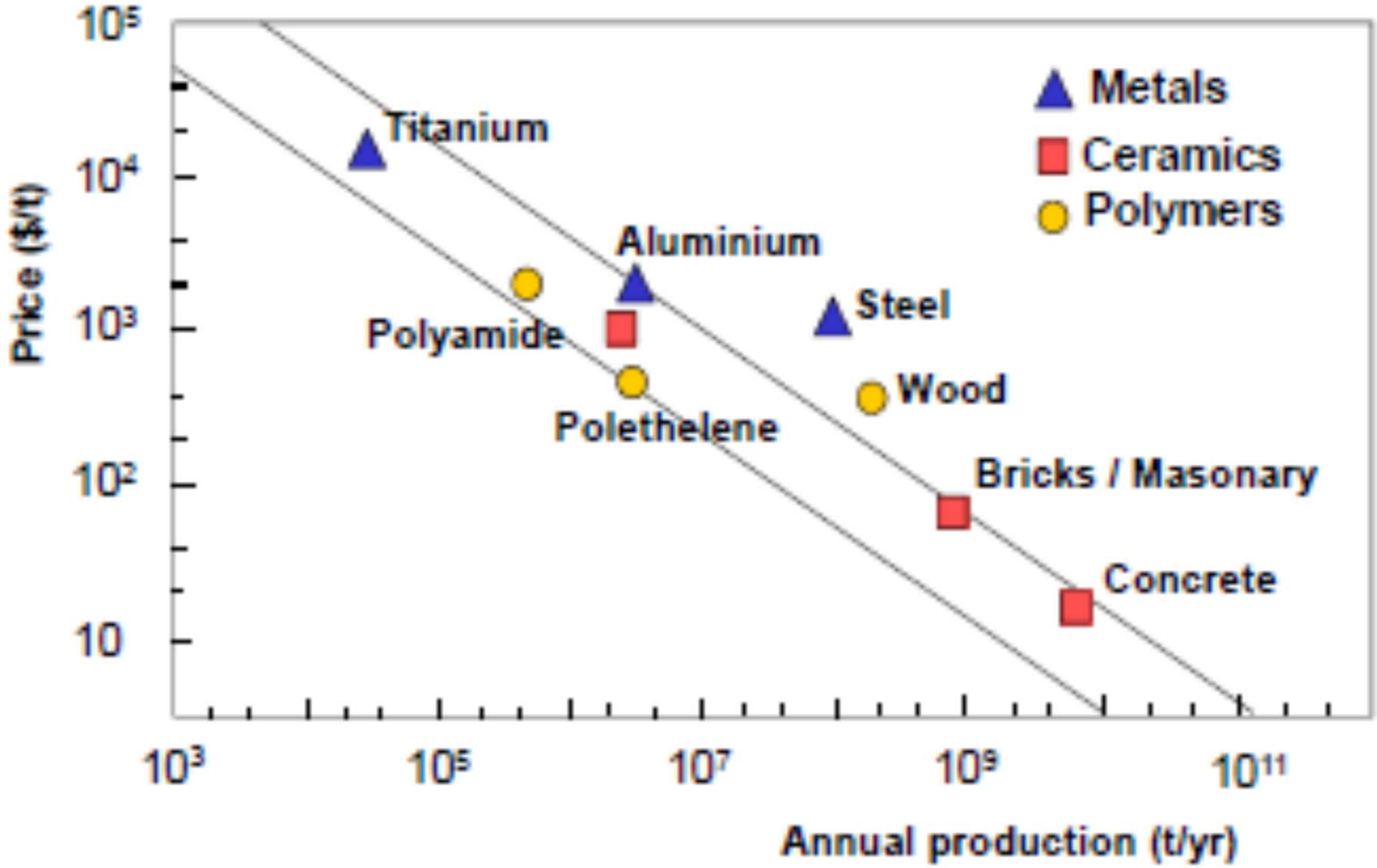
data extracted from Hammond and Jones (2011), University of Bath, UK



But we use 20 Billion Tons of concrete per year so the global CO_2 (5%) and Energy (3.8%) impact is large

Economics also explain why concrete is widely used

Price versus consumption of materials



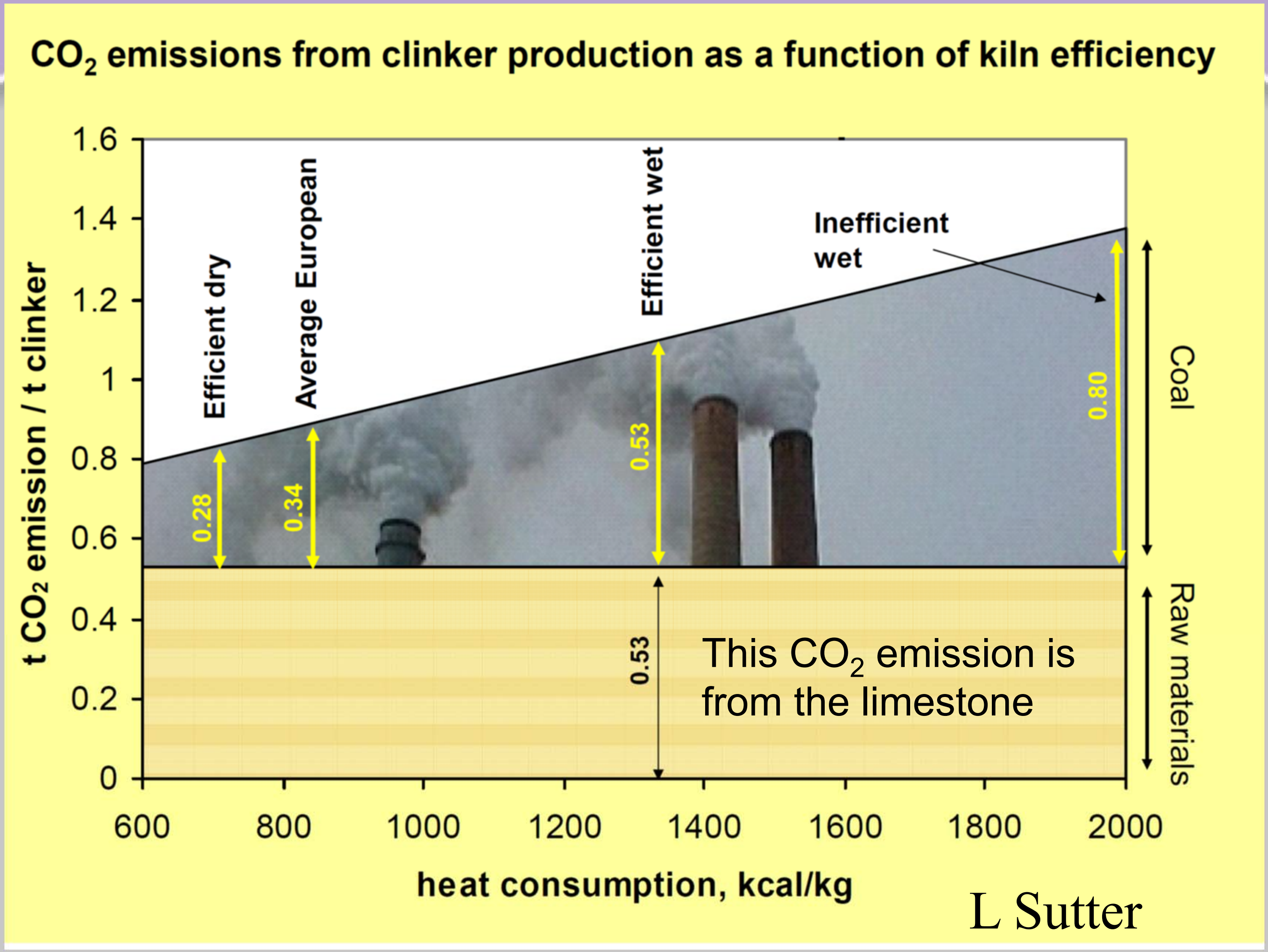
Source: *INTRODUCTION à LA SCIENCE DES MATÉRIAUX*, Mercier, Zambelli, Kurz

Portland cement is the primary binder in Concrete

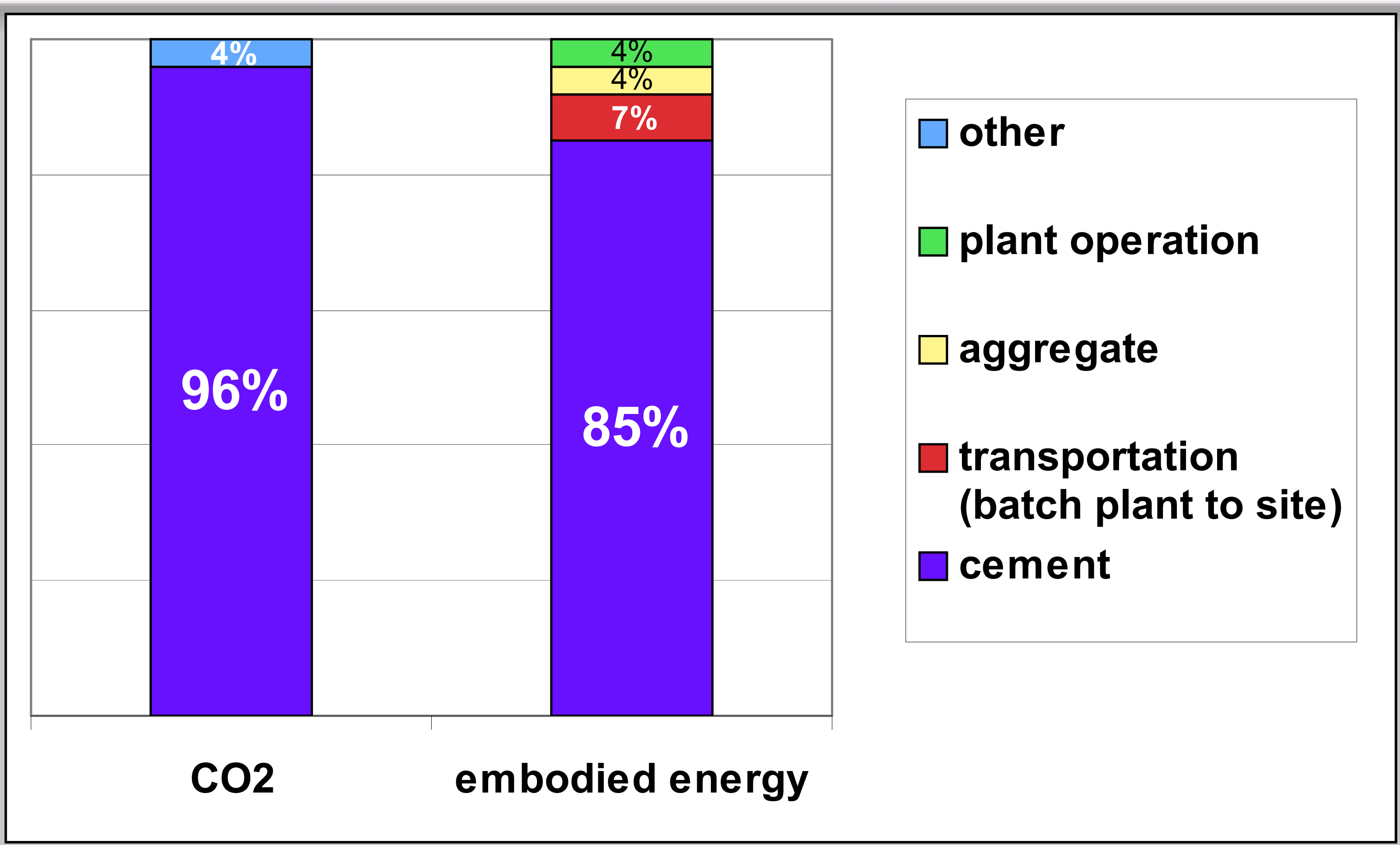
- Portland Cement is manufactured from limestone and shale rocks that have been fired at 1450 ^{o}C to form a synthetic rock called clinker. This clinker is then crushed to a powder.
- When limestone is heated in the kiln, it gives off CO_2.
  - $CaCO_3 \rightarrow CaO + CO_2 \uparrow$

- This reaction is unavoidable in the manufacture of cement clinker
- **So to reduce CO_2 the clinker fraction of cement has to be reduced.**

Cement Clinker Emissions



CO_2 emissions and embodied energy in Plain Portland Cement **Concrete**



Source: PCA, *Third Quarter 2006 Survey of Portland Cement by User Group*, PCA, November 2006

Future Trends: Emissions Regulations & Portland Cement

- Portland Cement manufacturing produces CO_2
  - From Limestone decomposition
  - From fuel consumption
- Cement plants have reduced CO_2 by 33% since 1972
- **Further cuts can only be obtained by reducing clinker content of cements**, such as with:
  - Blended cements
  - Portland-Limestone cements (PLC)
  - Increasing the use of supplementary cementitious materials in concrete

Summary

- Using both limestone and slag in combination can lead to significant reductions in the embodied CO_2 associated with concrete while providing excellent concrete.
- The early-age performance of slag cement concrete with Type IL cement has been found to be equal to or better than with Portland cement from the same source.
- The alumina in the slag cement can react with more of the finely divided limestone in Type IL cement to form additional carboaluminate hydrates that then results in reduced porosity and increased early-age strength of concrete.
- There is also reduced permeability, as indicated by ASTM C1202 test results.
- Field trials in pavements and highway structures have shown equivalent performance of Type IL-slag binders relative to Type I-slag binders in terms of both mechanical and durability properties.

Sulfate Attack

- While some early published papers indicated a potential concern for an increased risk of low-temperature thaumasite sulfate attack, extensive long-term tests on concretes have shown that Type IL cement- slag cement combinations are as resistant to sulfate attack as Type I cement-slag cement combinations and more resistant than equivalent w/cm concretes made with Type V cements to both the ettringite and thaumasite forms of degradation.

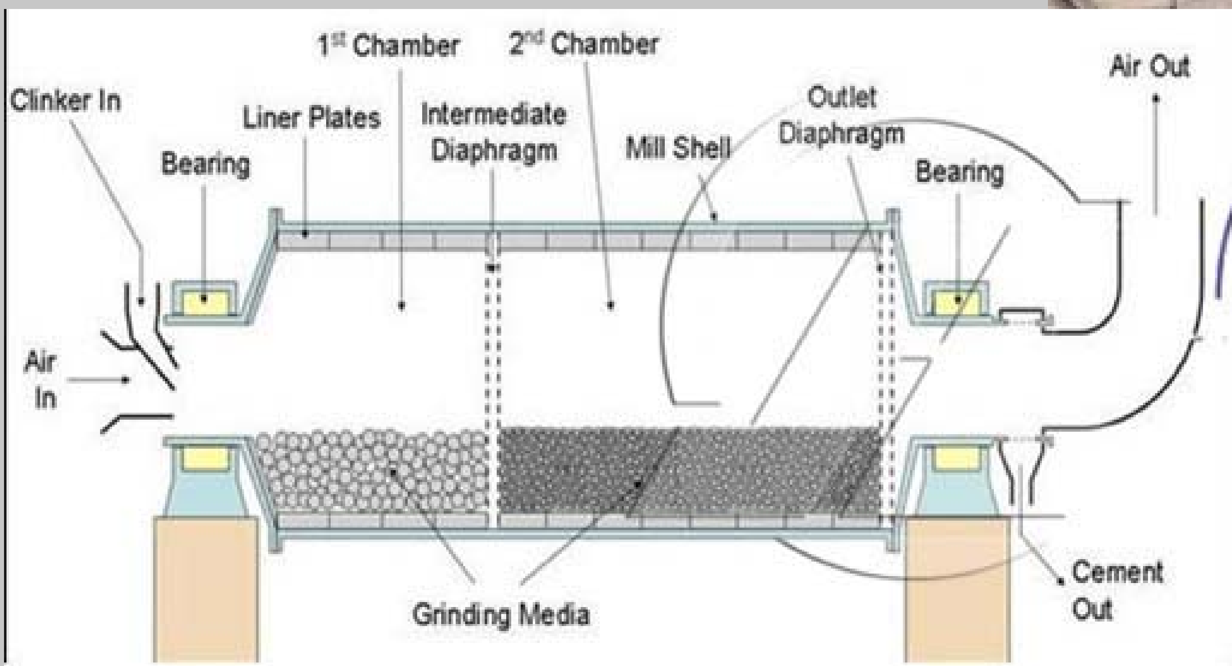
Outline

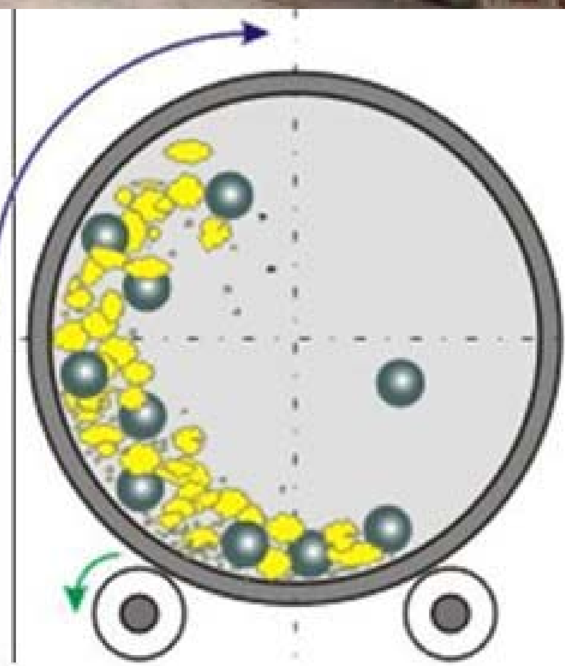
1. What is Portland-limestone cement (Type IL) and why use it?
2. The synergy of using slag cement – Type IL combinations
3. How do Type IL and slags impact concrete properties?
4. Sulfate Resistance
5. Example applications in buildings and infrastructure

Portland-limestone Cements (PLC) in North America

- Portland-limestone cements are made from the same components as Portland cements: Clinker, gypsum and limestone---but with about 10% additional limestone.
- Portland-limestone cements have been used under the ASTM C1157 Performance Specification for the last 20 years
- Portland-Limestone cements were added to CSA A3001 in 2008, with up to 15% interground limestone replacing cement clinker and to ASTM C595 in 2011 (CSA Type GUL and ASTM Type IL).
- PLC have to meet the same set times and strength development as portland cement of the same type (eg. GU = GUL; Type I = Type IL)
- In addition, fewer raw materials and less energy are used to produce PLC.
- When properly optimized, the limestone is not inert and contributes to the properties of the cement.

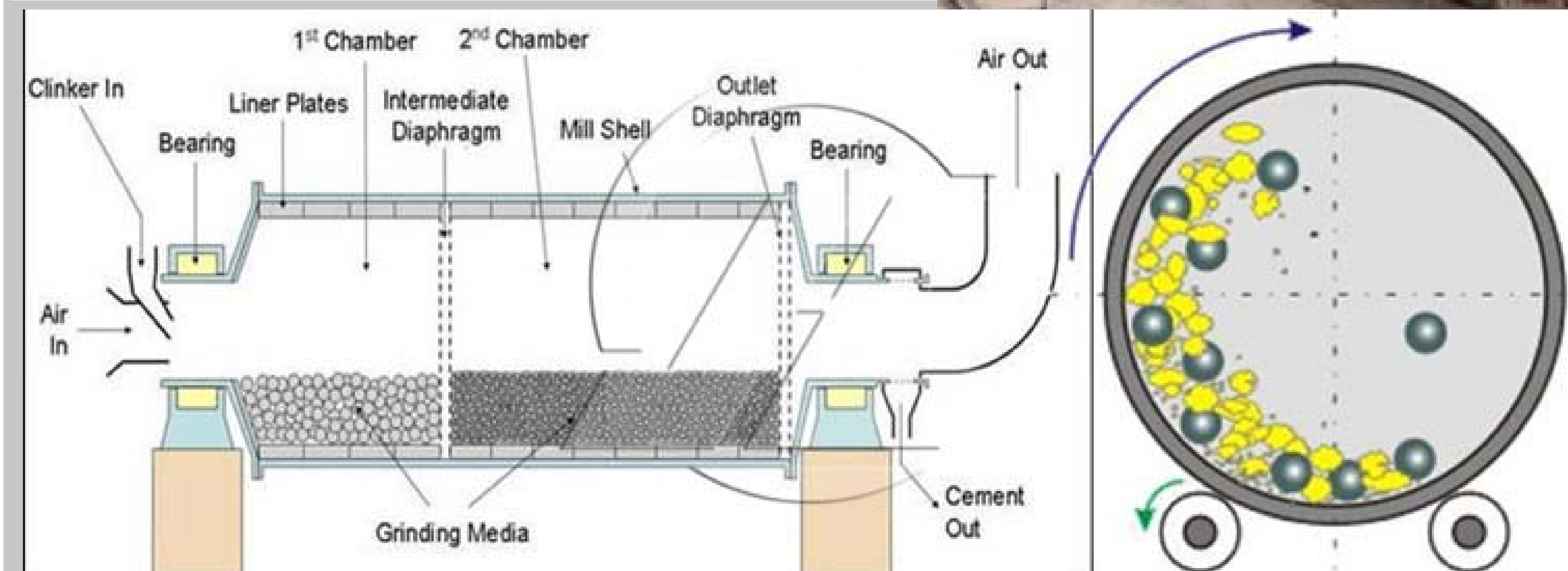
Type I/II: Portland Clinker is ground in ball mills together with ~8% gypsum and **~3 % raw limestone** to make the finished portland cement.





Type IL: Portland Clinker is ground in ball mills together with ~8% gypsum and **10-13% raw limestone** to make the finished cement.
(gypsum levels need to be optimized)

Because limestone is softer than clinker , it grinds preferentially, so the cement needs to be ground finer so the clinker component is of equal fineness to get the same strength performance.



Softer limestone gets ground finer than clinker in Type IL

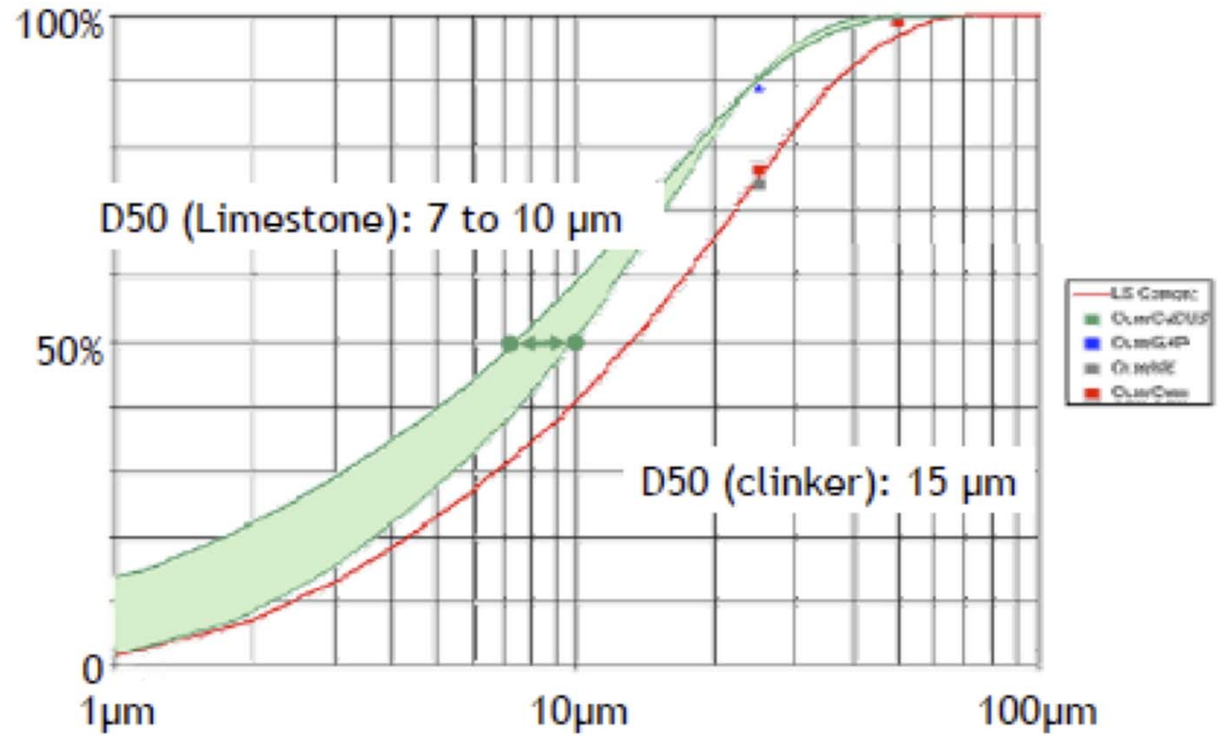


Figure 2.1 Particle size distributions for components of an interground cement. The limestone fraction is finer than ground clinker (Barcelo data as quoted in Hooton 2009).

So Blaine fineness of Type IL is ~100 m^2/kg higher than Type I

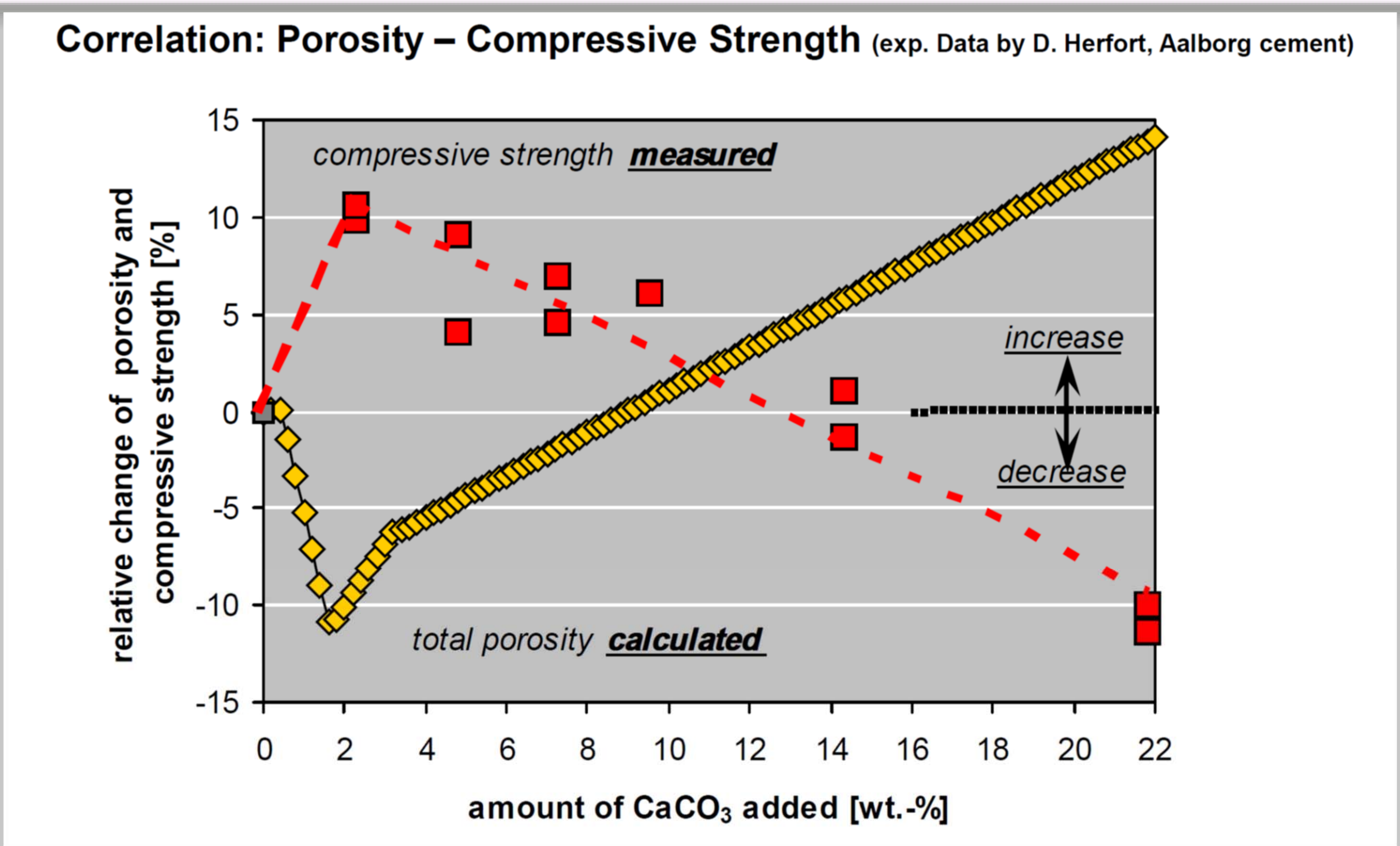
ASTM C595 / AASHTO M240/CSA A3001 Type IL (GUL) Performance

- In ASTM C595, setting times and strength development limits are the same for Type IL as for C150 portland cement of the same type.
- Heat of hydration limits are the same as for Portland cements.
- The only chemical difference is that LOI limits are higher for PLC to account for higher limestone contents.
- In concrete, PLC also performs well with slag or fly ash at normal replacement levels.
- In many cases, Type IL+SCM perform better at early age than Type I+SCM, due to nucleation effects of fine limestone particles and due to formation of additional carbo-aluminates.

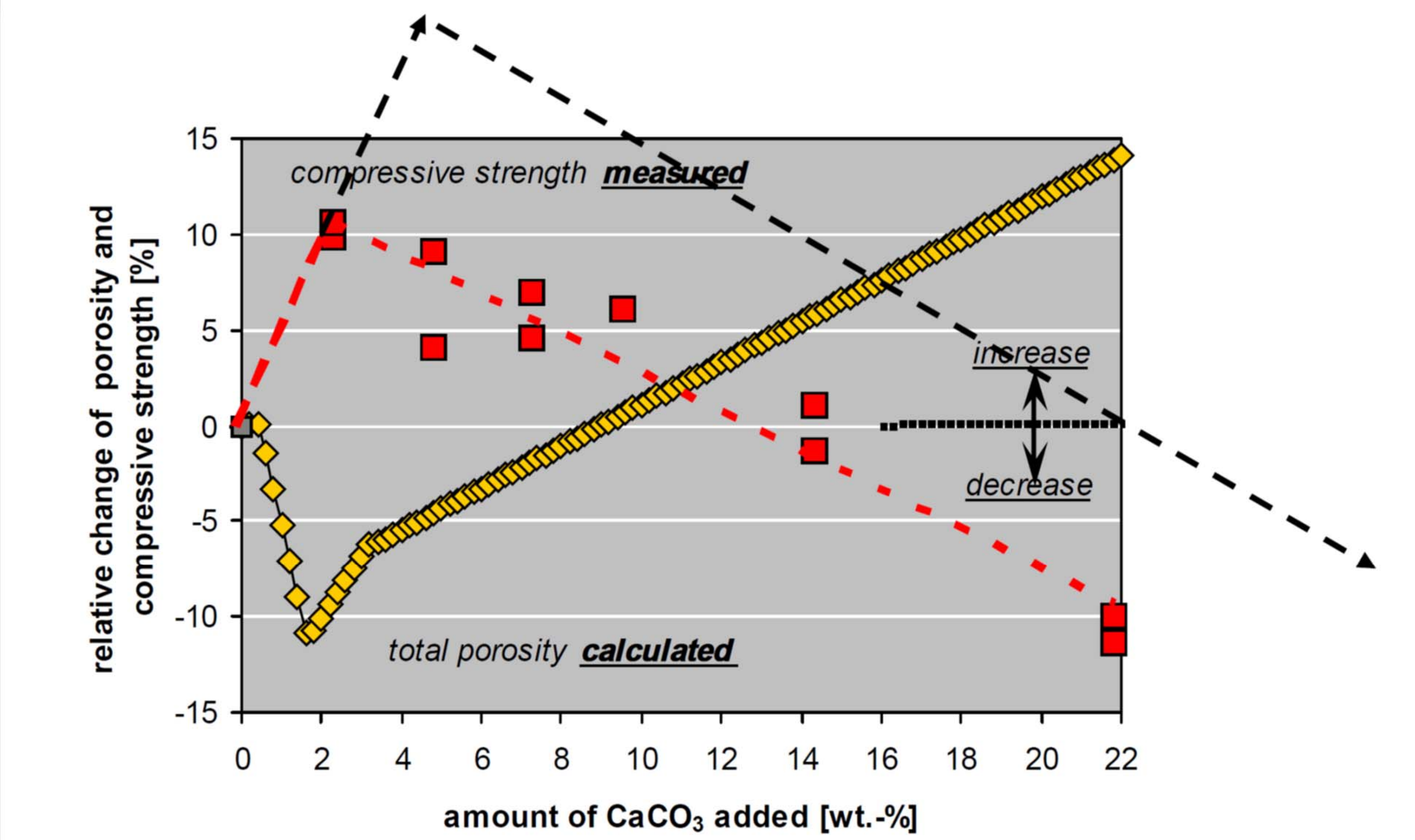
Background– Portland limestone cement in Europe

- The EN197 Cement standard has allowed up to 20% interground limestone in CEM IIA/L cements, and up to 35% in CEM IIB/L cements, in addition to 5% MAC (minor additional components) which also could be limestone.

Better particle packing and increased carbo-aluminate formation fills in pores and increases strength (Equal strength at ~12-14% limestone)



When Slag is blended with Type IL, more carbo-aluminates are formed (more alumina from the slag), so 28-day strengths should increase.



Strengths of Air-entrained Concretes cured at 23 ^oC with limestone and SCMs

Mix Identification (all 400 kg/m3 (666 pcy mixes)	% clinker in binder	w/cm	Compressive Strength (MPa)			
			7 day	28 day	56 day	182 day
GU Cement Control	89*	0.40	39.3	45.5	50.7	52.6
GU + 40% Slag	53	0.40	32.8	46.2	49.2	51.2
GUL9 + 40% Slag	50	0.40	36.1	50.9	53.6	50.7
GUL9 + 50% Slag	41	0.40	34.6	49.0	53.0	51.0
GUL15 + 40% Slag	46	0.40	37.1	52.3	57.5	59.2
GUL15 + 50% Slag	38	0.40	36.3	55.3	60.1	65.6
GUL15+ 6% Silica Fume + 25% Slag	53	0.40	46.0	65.0	70.1	76.0

* 3.5% limestone and 8% gypsum

U. of Toronto Field site data

RCPT Permeability Index of Air-entrained Concretes cured at 23 °C with GU/GUL cements and SCMs

Mix Identification (all 400 kg/m³ (666 pcy mixes)	% clinker in binder	w/cm	Rapid Chloride Permeability ASTM C1202 (Coulombs)		
			28 day	56 day	182 day
GU Cement Control	89	0.40	2384	2042	1192
GU + 40% Slag	53	0.40	800	766	510
GUL-9% + 40% Slag	50	0.40	867	693	499
GUL-9% + 50% Slag	41	0.40	625	553	419
GUL-15% + 40% Slag	46	0.40	749	581	441
GUL-15% + 50% Slag	38	0.40	525	438	347
GUL -5% + 6% Silica Fume + 25% Slag	53	0.40	357	296	300

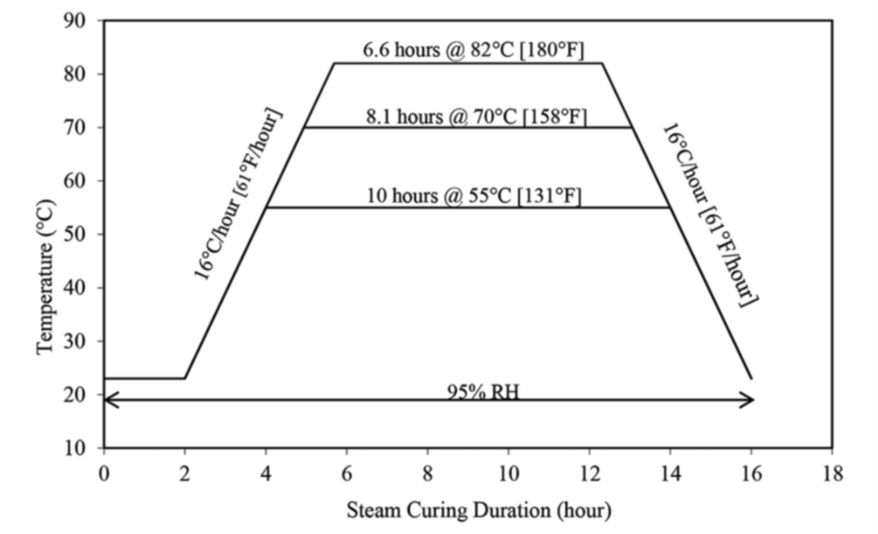
CSA A23.1 limit is 1500 coulombs @ 91d for C-1 Exposure

Type IL in Steam Cured Precast (M.Aqel, PhD U. Toronto thesis 2016)

Mixtures: W/C = 0.34, 450 kg/m^3 binder with 5% Silica Fume, Type IL = 12% limestone

	GU	GUL
Air (%)	5.2	5.7
Slump Flow (mm)	690	695

Age	Compressive Strength (MPa)			
	55 °C (131 °F)		70 °C (158 °F)	
	Type I	**Type IL**	**Type I**	**Type IL**
16h	**47.8**	**55.3**	**59.7**	**60.4**
3d	58.9	60.1	62.6	62.5
7d	64.5	65.7	66.0	66.2
28d	**72.5**	**71.1**	**70.1**	**70.4**
300d	89.3	84.9	82.9	81.1



28 day RCPT (Coulombs)			
55 °C		70 °C	
Type I	Type IL	Type I	Type IL
616	715	1050	1106

Freeze/Thaw Durability Factor (%)			
55 °C		70 °C	
Type I	Type IL	Type I	Type IL
98.0	97.1	68.4	83.1

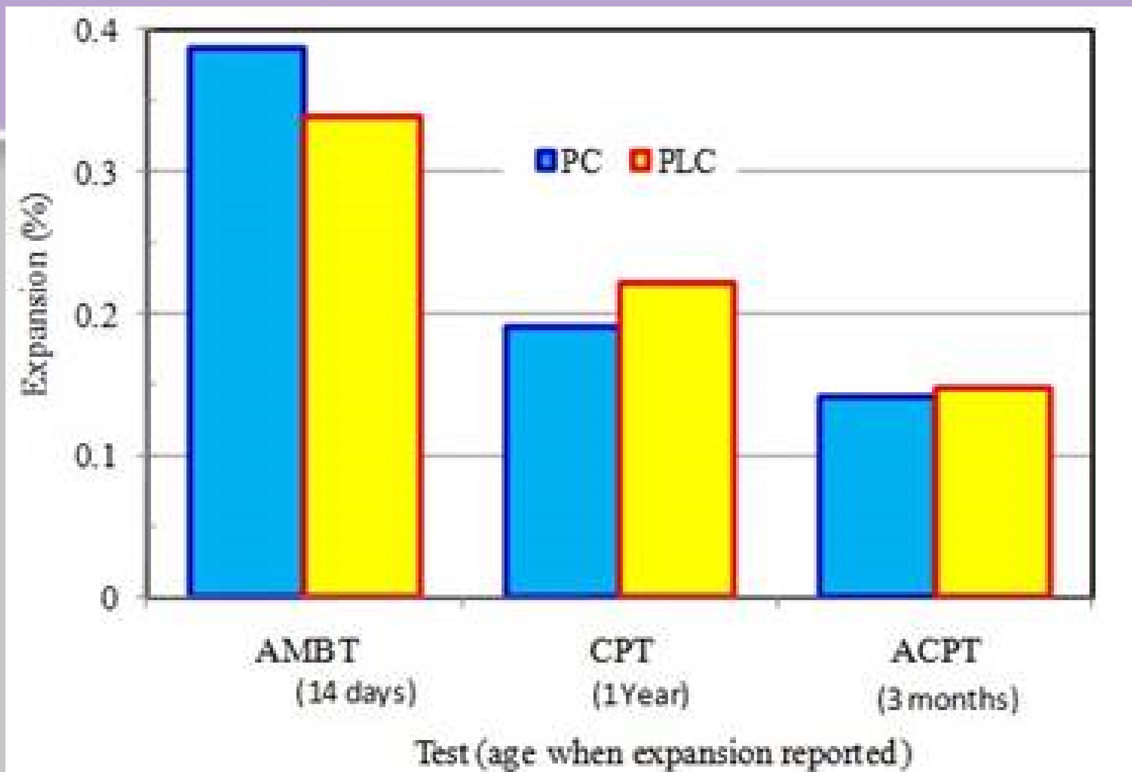
Drying Shrinkage
CSA A23.1 (ASTM C157)
w/cm = 0.40 mixtures

Length Change (%)	GU 100%	PLC10 100%	PLC15 100%	GU 70% SLAG 30%	PLC10 70% SLAG 30%	PLC15 70% SLAG 30%
28 days	**0.036**	**0.037**	**0.037**	**0.026**	**0.027**	**0.025**
1 year	**0.069**	**0.061**	**0.062**	**0.058**	**0.052**	**0.053**
2 years	**0.067**	**0.068**	**0.065**	**0.062**	**0.06**	**0.067**

- Shrinkage was unaffected by PLC (Type IL)
- Reduced 28-day shrinkage with slag mixes

Alkali-Silica Reaction

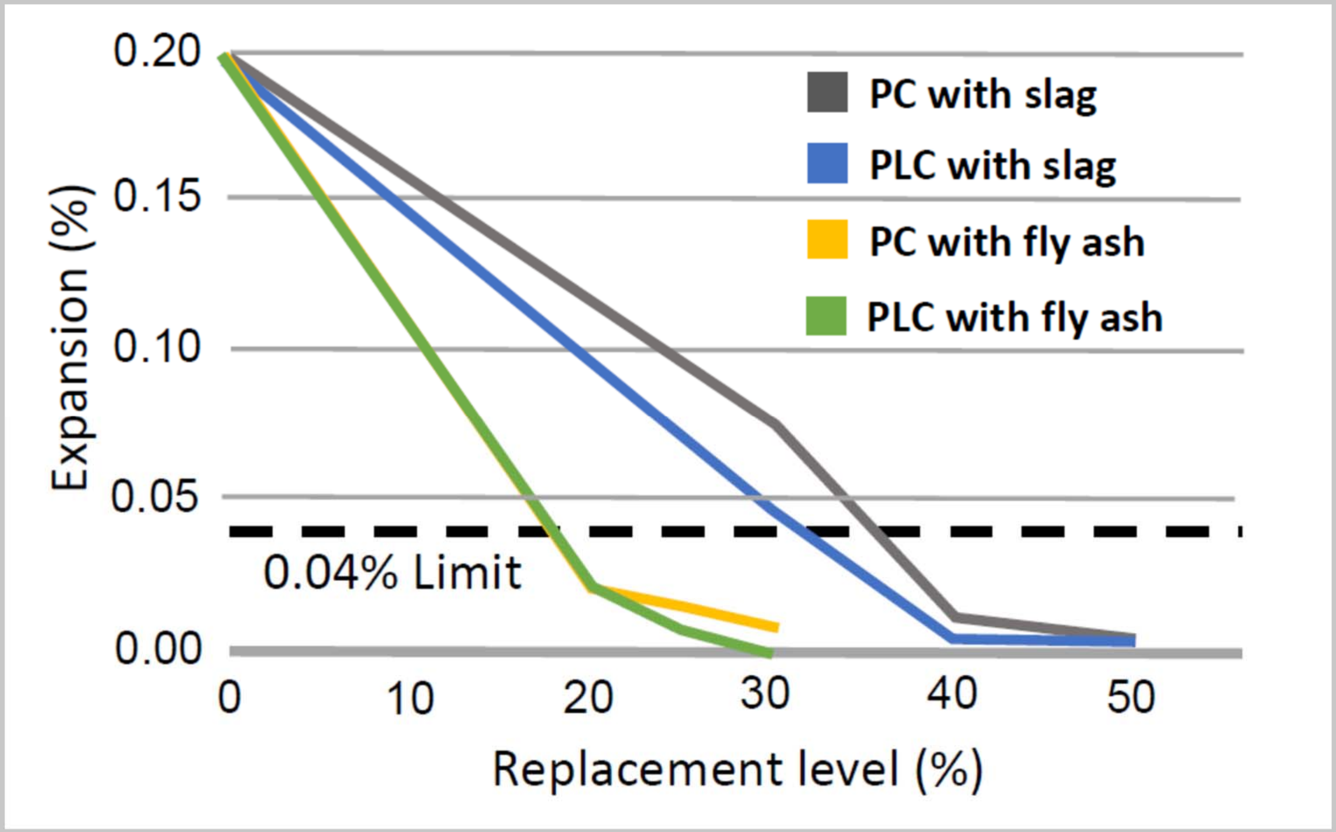
PCA SN3148 Weiss, Thomas & Tennis



Also no difference in the level of SCMs needed to mitigate ASR expansion. (M. Thomas)

Expansion of mortar bars and concrete prisms containing an alkali-silica reactive aggregate (siliceous limestone from the Spratt quarry in Ontario). (ACPT is similar to the CPT except specimens are stored at 60°C). The data show that there is **no consistent difference** between expansions produced with PC compared with PLC.

ASR: 2-year ASTM C1293 Expansions



Thomas et al 2013

Freeze-Thaw and Scaling Resistance

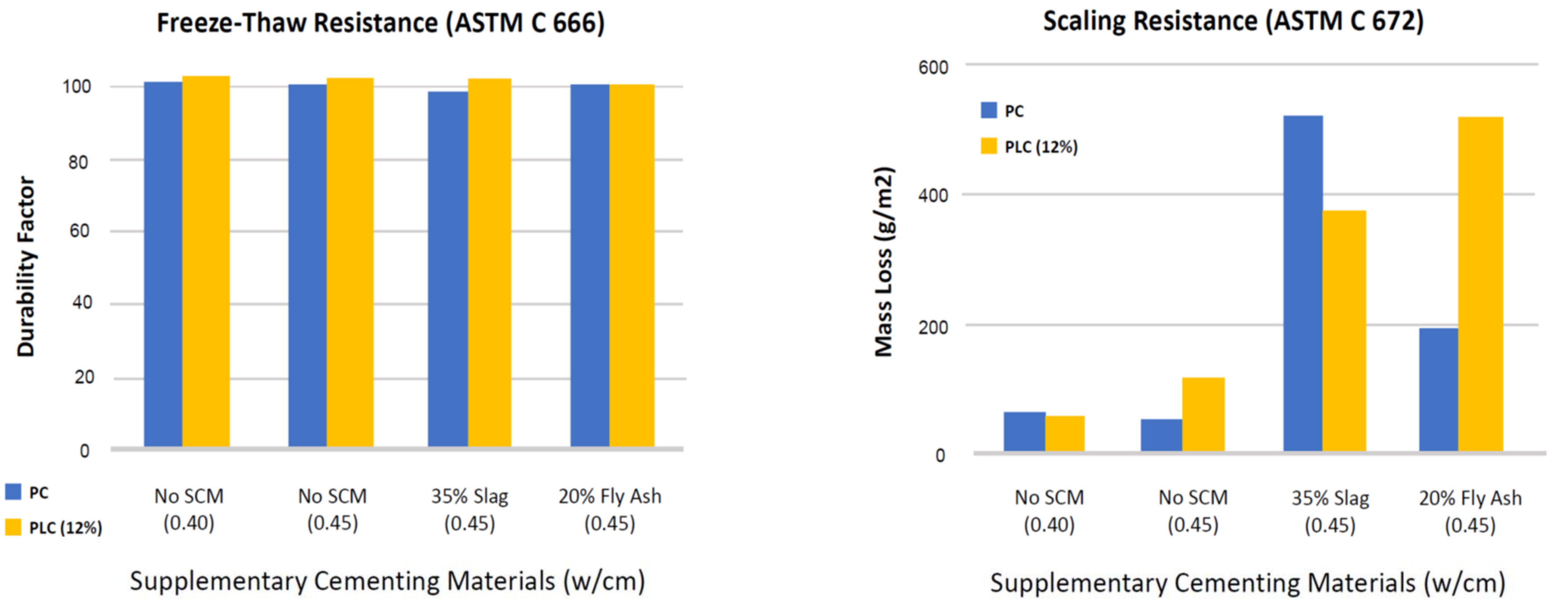


Figure 3: Results of freeze-thaw and de-icer salt scaling tests for PC and PLC concretes with and without SCM (Thomas and Hooton 2010)

ASTM C1202 Coulombs

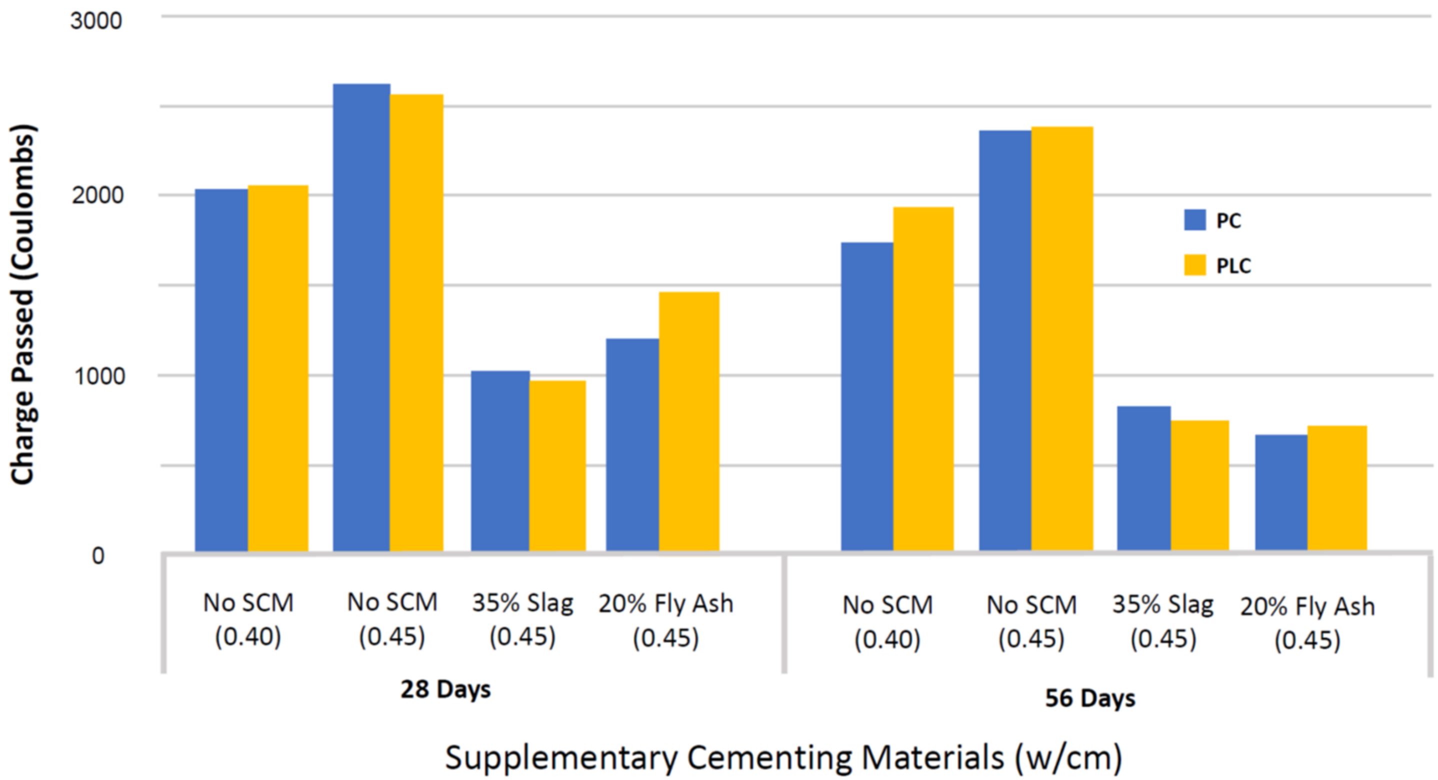
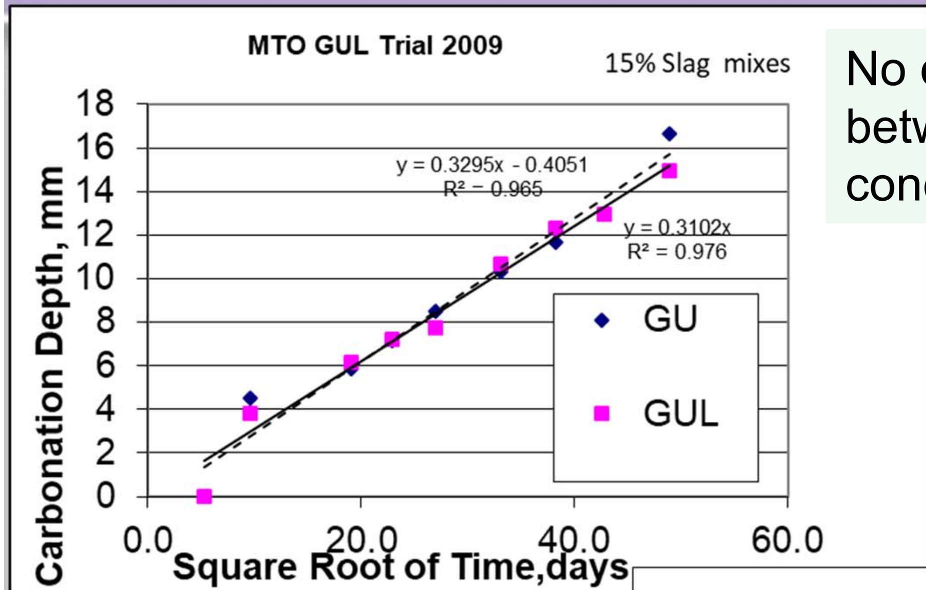


Figure 4: "Rapid Chloride Permeability Test" (ASTM C1202) data for PC and PLC concrete with and without SCM (Thomas and Hooton 2010)

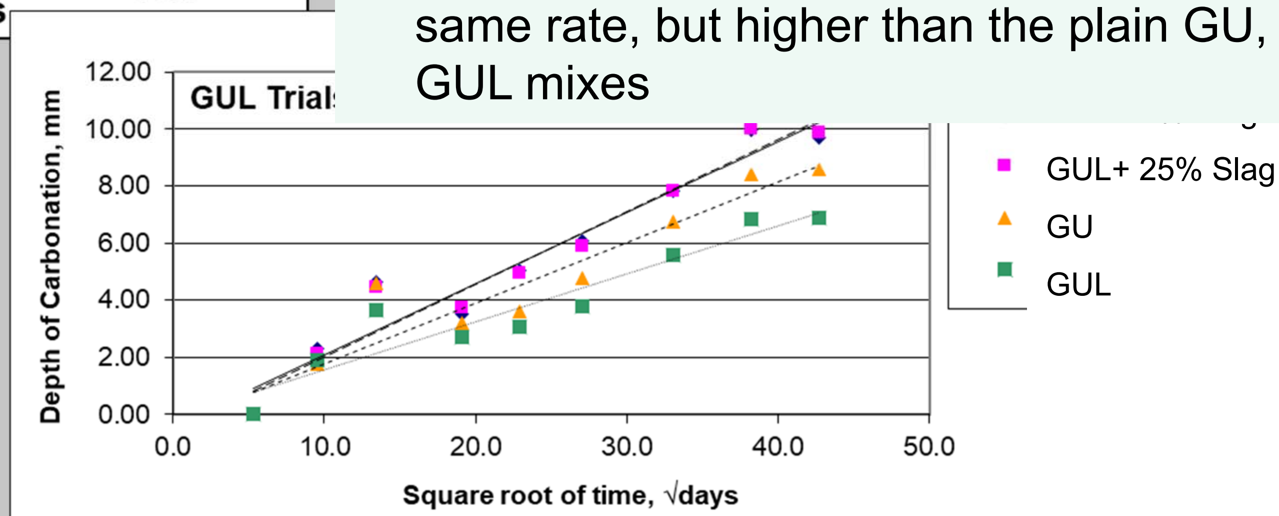
Two Carbonation Studies (UofT) 7-day moist cured concrete prisms (w/cm = 0.40) stored at 50% rh and 23 ^{o}C



No difference in carbonation between Type I & Type IL concretes with 15% Slag

- Type IL mix carbonated less than Type I mix.
- Both 25% slag mixes carbonated at the same rate, but higher than the plain GU, GUL mixes

Note: SQRT 50 days = 6.8 years



Type IL + SCMs in Sulfate Exposure

Sulfate Soils in Western USA

Reportedly, sulfate concentrations can exceed 20,000 ppm.

And the west is mostly arid, which concentrates salts

Ref: USBR soils map, where alkalinity = alkali sulfates

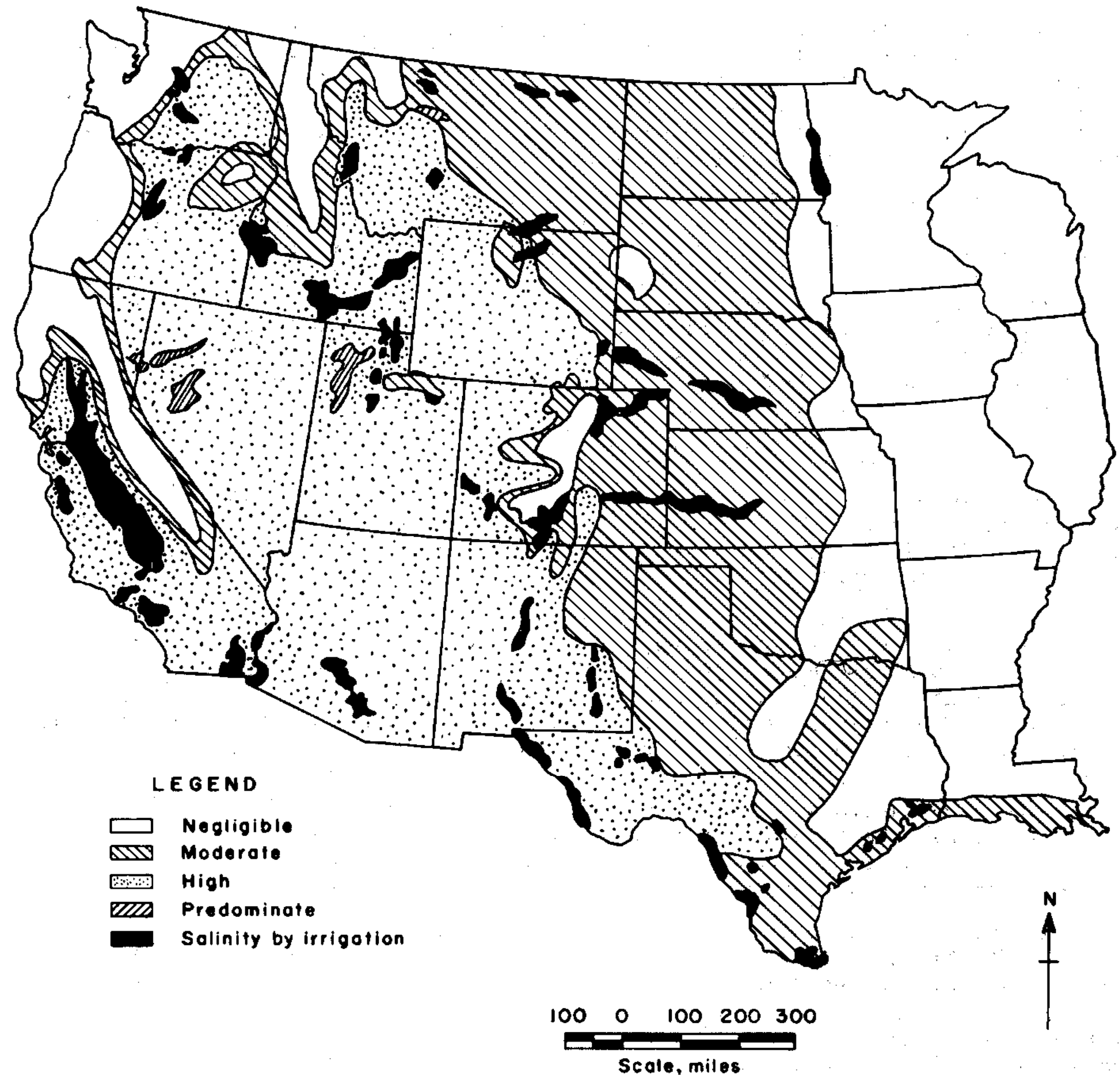
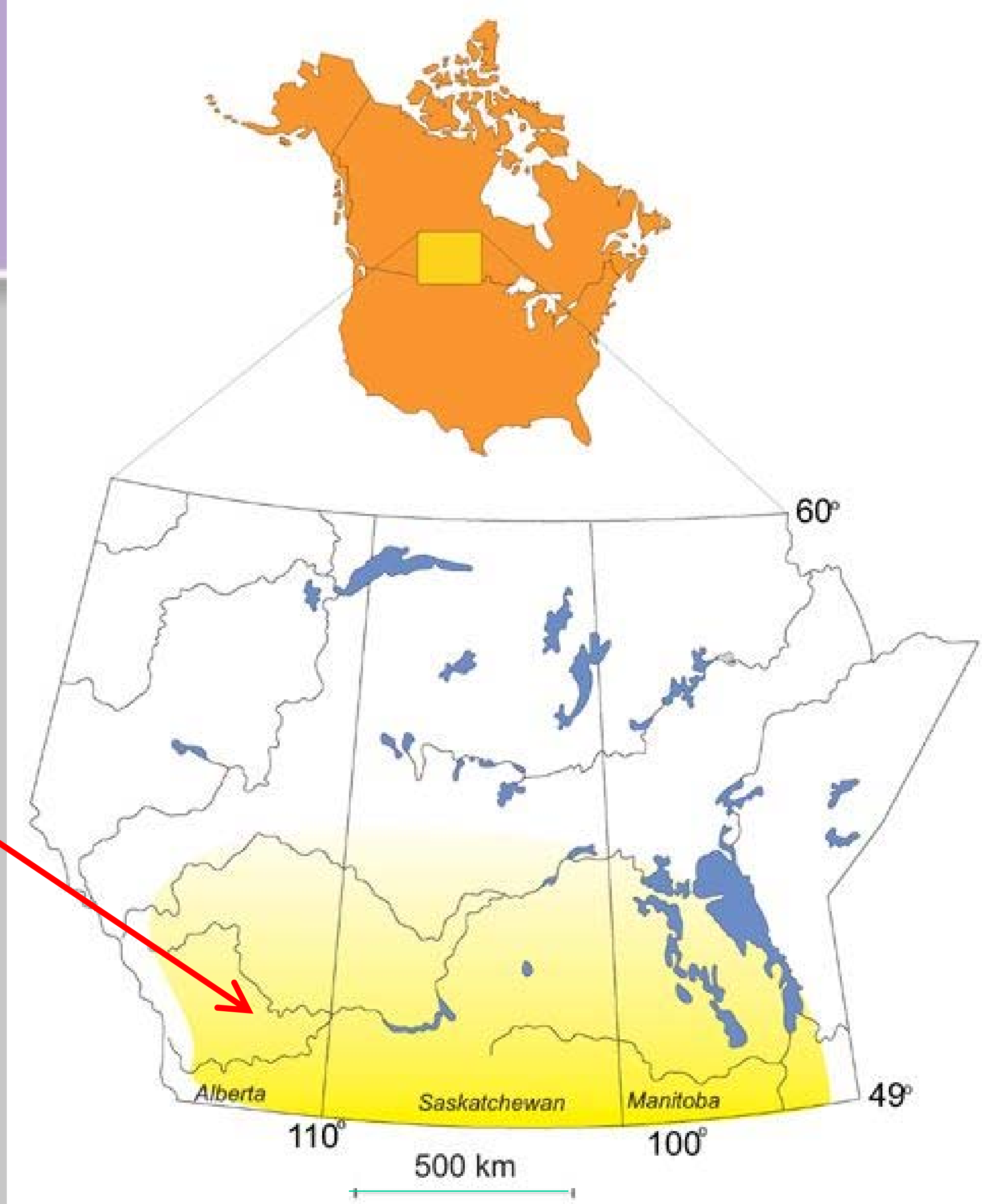


FIGURE 2. - Map of Alkali and High Salinity Soils in Western United States (2).

Sulfate soils in Western Canada

Up to 14,600 ppm SO_4 found in Alberta soils



Map: W. M. Last and F. M. Ginn, U. Manitoba

Thaumasite Form of Sulfate Attack

30-year-old bridge column exposed to cold, wet oxidized sulfide-bearing clay in England **(did not contain limestone cement)**

Thaumasite is not common, but when it occurs, it can attack the whole matrix.

Photos from UK Expert Panel Report

Thaumasite Sulfate Attack (TSA)

- A relatively unusual form of sulfate attack usually associated with low temperatures (0-10^{o}C) and very wet environments.

- Triggered by soluble carbonates and sulfates, and associated with low temperatures .
- The C-S-H and $Ca(OH)_2$ are converted to gypsum and thaumasite.

  $Ca_6[Si(OH)_6]\cdot(SO_4)_2\cdot(CO_3)_2\cdot 24H_2O$

  or: $CaSiO_3\cdot CaCO_3\cdot CaSO_4\cdot 15H_2O$

Sulfate Resistance: 2016 PCA Report based on 10 years of lab and field testing

1916-2016
Celebrating 100 Years of Excellence

PCA
America's Cement Manufacturers™

Research & Development Information

PCA R&D SN3285b

http://www.cement.org/pdf_files/sn3285b.pdf

Sulfate Resistance of Mortar and Concrete Produced with Portland-Limestone Cement and Supplementary Cementing Materials: Recommendation for CSA A3000

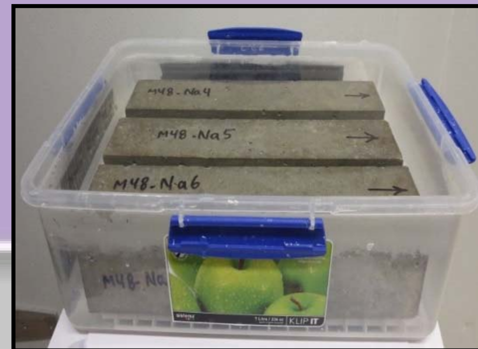
by R. D. Hooton and M. D. A. Thomas

U of T Concrete Sulfate Resistance Program

PhD of Reza Ahani, 2019

- **53 concrete mixtures (cast 2010, 2011, 2012): Still being monitored**
  - W/CM = 0.4, 0.5, and 0.7,
  - Cements: GU, PLC (9, 10.5, and 15), 3 HS, 2 HSL, 2 MS, and HSb,
  - SCMs: 40 & 50% slag, 8% silica fume, 15% metakaolin, and 25% fly ash.
- Evaluation of sulfate resistance:
  - Measurement of length and mass changes (Lab: every 1.5m / Field: annually),
  - Making visual inspections (Lab: every 1.5m / Field: annually),
  - Mineralogical analysis (X-Ray diffraction) on damaged concrete prisms,
  - Microstructural analysis (Micro X-ray fluorescence spectrometer and scanning electron microscope) on damaged concrete prisms.
- Other tests:
  - Compressive strength (7d, 28d, 56d, 6m, and 1y),
  - Rapid chloride permeability (28d, 56d, 6m, 1y, 2y, and 3y),
  - Bulk resistivity (6m, 1y, 2y, and 3y).

Uof T Laboratory sulfate exposure



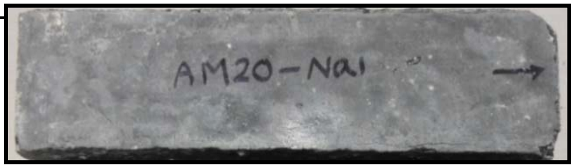
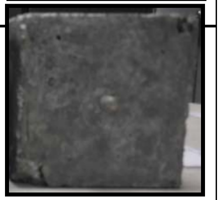
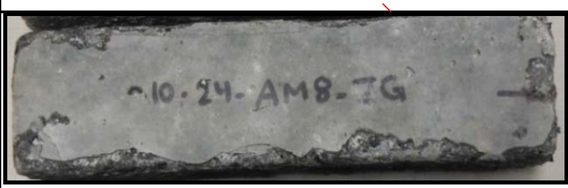
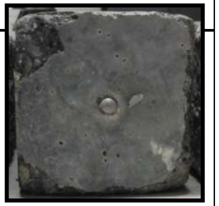
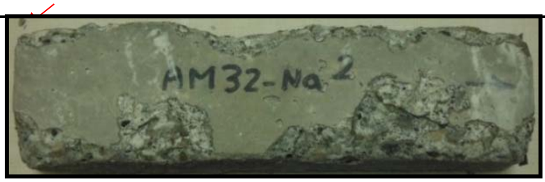
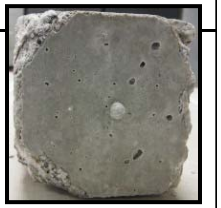
Constant temperature: 5 ± 1 °C

- Laboratory prisms:
- 50×50×285 mm
- From each concrete mixture:
  - 3 prisms in $Ca(OH)_2$,
  - 3 prisms in Na_2SO_4,
  - 3 prisms in $MgSO_4$.
- SO_4^{-2} concentration:
  - 0.40 & 0.50 mixtures:
    - 33,800 ppm until 19m,
    - 15,000 ppm afterwards
  - 0.70 mixtures: 1,500 ppm.

UofT Field sulfate exposure started in 2010

- A trench dug to 2.5m deep,
- Located in Toronto,
- Variable underground temperatures of 3-16 ^{o}C,
- Field prisms: 75×75×285 mm,
- For each concrete mixture:
  - 3 prisms in limewater,
  - 3 prisms in Na_2SO_4,
  - 3 prisms in $MgSO_4$.

- SO_4^{-2} concentration:
  - 0.40 mixtures: 15,000 ppm,
  - 0.50 & 0.70 mixtures: 1,500 ppm.

UofT Visual Condition Rating od Concrete	Label [Num. Rating]	Example Photos	
Excellent Condition – No visible damage	UND [0]		
Minor damage **<u>Slight</u>** mass loss and/or cracking at some corners and/or some longitudinal edges	MIN [1]		
Minor to Moderate damage **<u>Slight to moderate</u>** mass loss and cracking at some corners and/or longitudinal edges	MIN-MOD [2]		
Moderate damage **<u>Moderate</u>** mass loss and/or cracking at some corners and/or some faces Localized scaling at some faces	MOD [3]		
Moderate to Severe damage **<u>Moderate to severe</u>** mass loss and/or cracking at most of the faces and corners Widespread scaling at most of the faces	MOD-SEV [4]		
Severe damage **<u>Severe</u>** mass loss from all faces and ends. Complete peeling of surface paste from all faces and both ends	SEV [5]		

0.40 Type I (GU) prisms at 9 months at 5C in lab (50x50x300mm prisms)

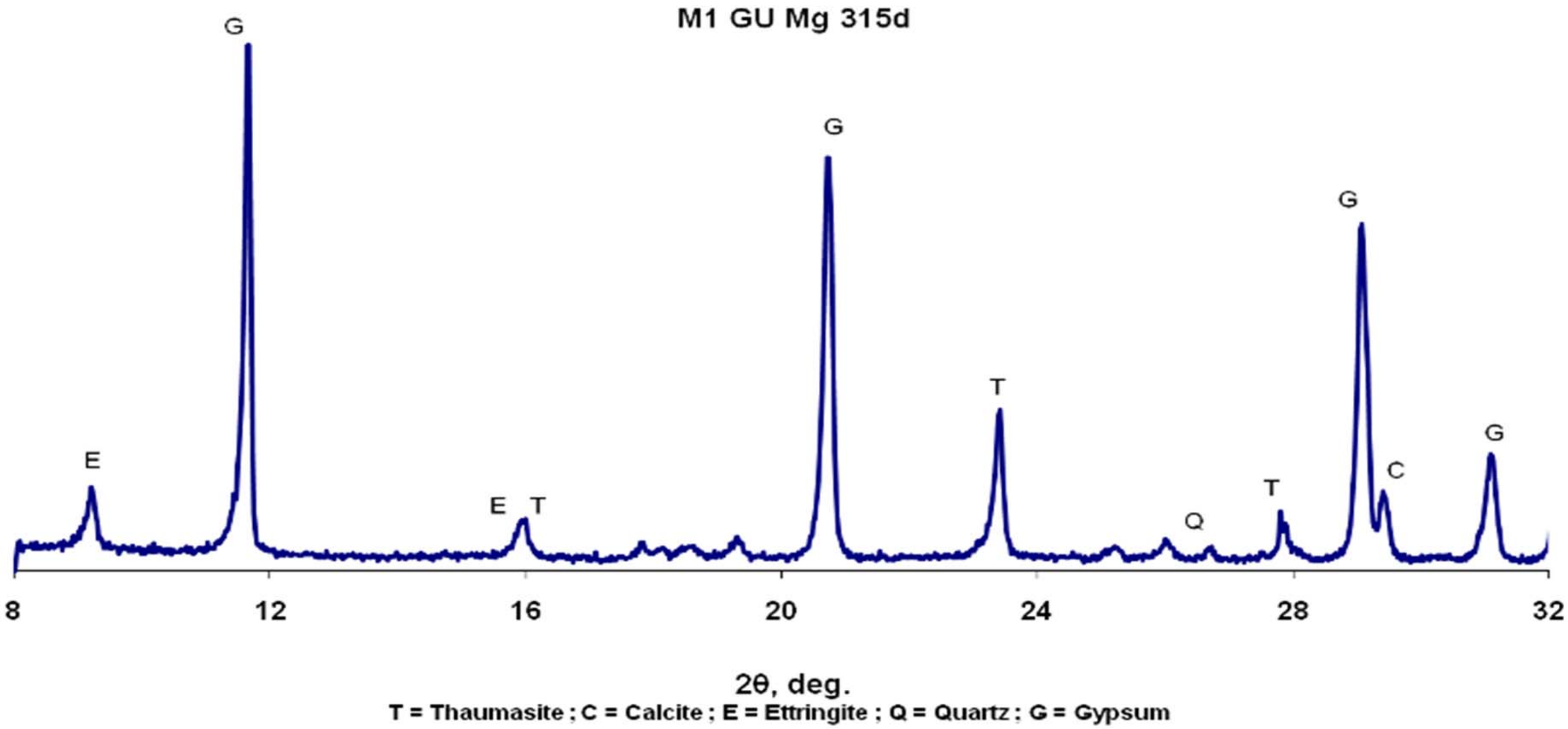
33,800 ppm Na_2SO_4

All surface paste is gone

33,800 ppm $MgSO_4$

Mass loss at corners of prisms

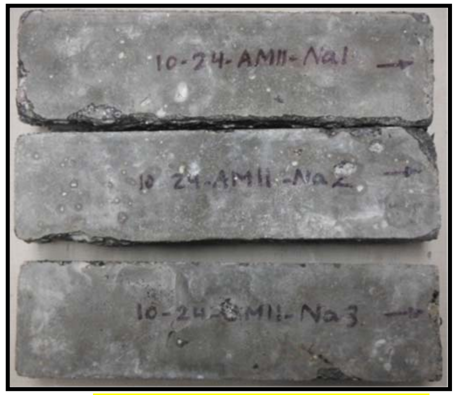
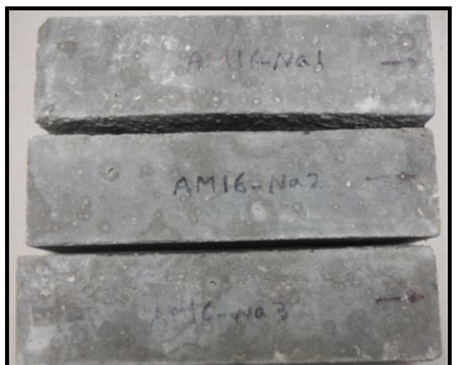
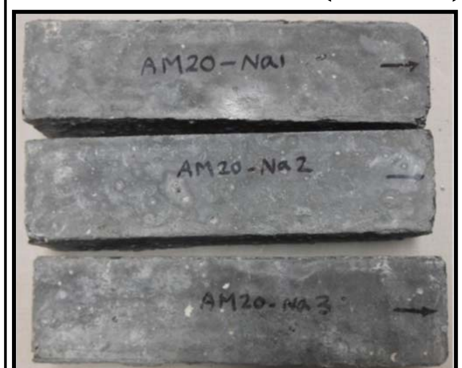
XRD analysis on Type I (GU) at 315 days in $MgSO_4$



More Thaumasite formed in MgSO4 than in Na2SO4

Thaumasite can form together with ettringite in non-sulfate resistant concretes without limestone.

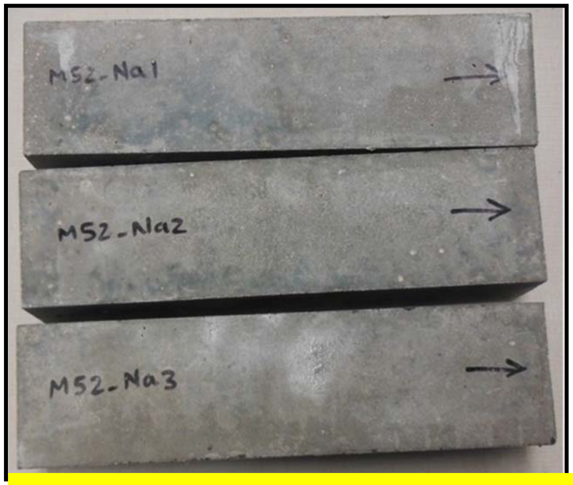
(PC/PLC)-Slag vs HS/HSb / w/cm=0.4 / 4.5 years (54 months) / 15,000 ppm Na_2SO_4

GU-40S	PLC15-40S	Type V/ HS (1)
 Minor damage	 Minor damage	 Severe damage
Field Site Prisms GU = Type I S = Slag cement	**PLC15-50S**  Excellent Condition	**HSb (30FA)**  Minor damage

PLC(10.5)-Slag vs HS / w/cm=0.4 / ~2.5 years (33 months) / 15,000 ppm Na_2SO_4

Field Site Prisms @ 2.5 years

PLC10.5-40S

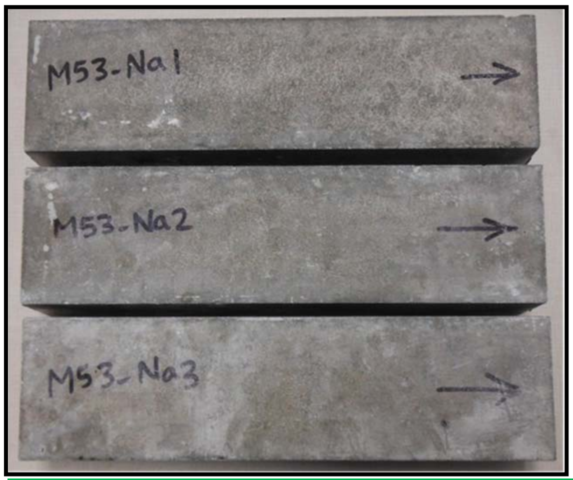


Minor damage

Type V/ HS (2)

Minor damage

PLC10.5-50S

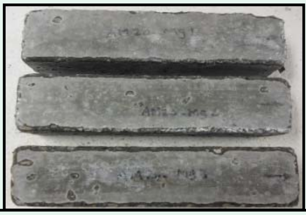
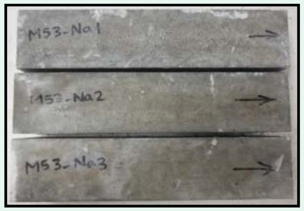


Excellent Condition

Type V/ HS (3)

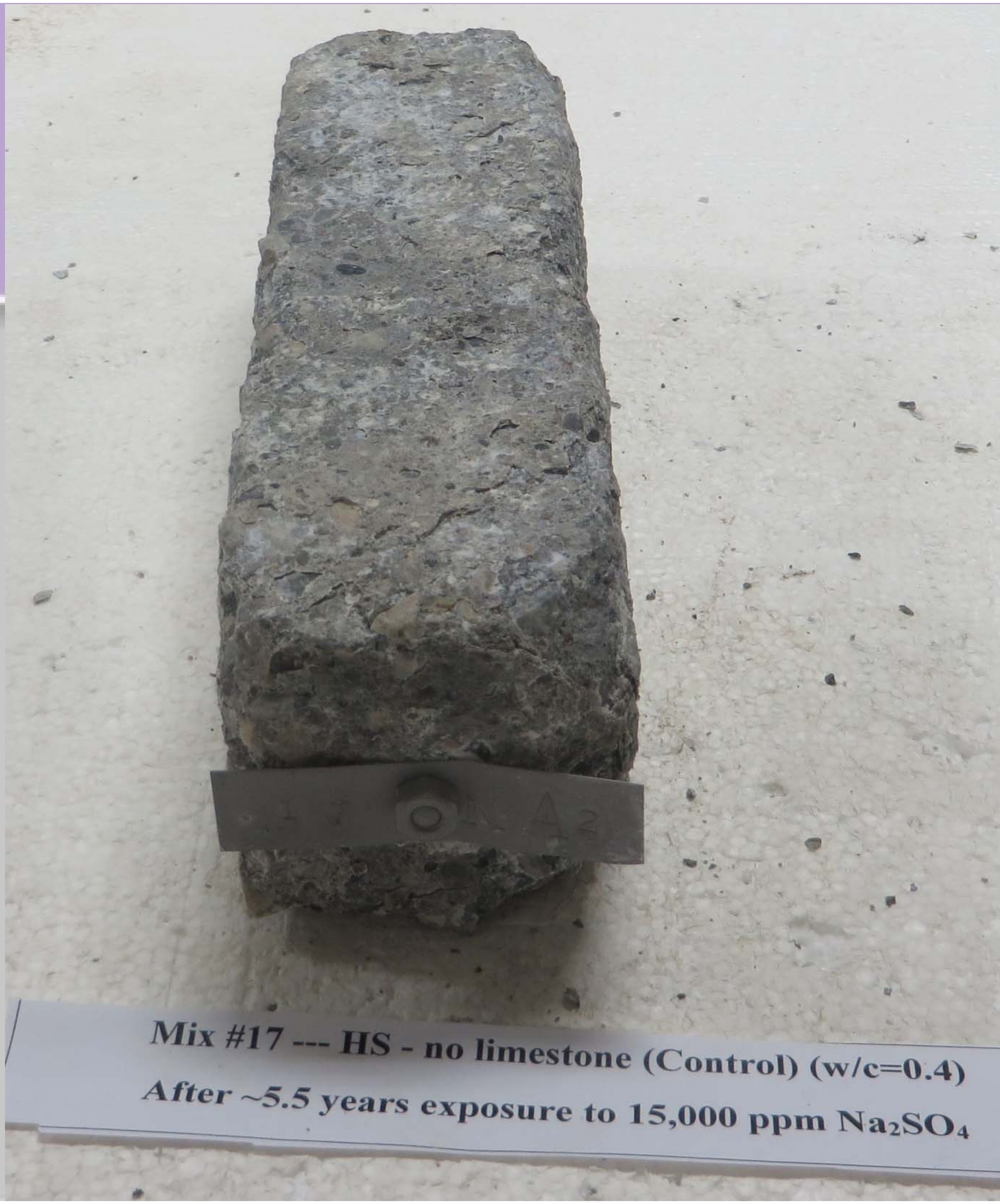
Minor damage

(PLC-Slag) vs (HS / HSb) --- W/CM=0.40
Na_2SO_4 vs $MgSO_4$ in field exposure (June 2016)

Field Prisms	~5.5 years 15,000ppm Na_2SO_4 (3-16 °C)	**PLC15% - 50%Slag**  UND [0]	**HS1**  SEV [5]	**HSb - 30%Fly Ash**  MIN [1]
	~5.5 years 15,000ppm $MgSO_4$ (3-16 °C)	**PLC15% - 50%Slag**  MIN-MOD [2]	**HS1**  SEV [5]	**HSb - 30%Fly Ash**  MIN-MOD [2]
	~4 years 15,000ppm Na_2SO_4 (3-16 °C)	**PLC10.5% - 50%Slag**  UND [0]	**HS2**  MIN-MOD [2]	**HS3**  MIN [1]
	~4 years 15,000ppm $MgSO_4$ (3-16 °C)	**PLC10.5% - 50%Slag**  MIN [1]	**HS2**  MOD [3]	**HS3**  MIN [1]

Slag/Silica Fume Mixes / w/c=0.4 / 4.5 years (54 months) / 15,000 ppm Na_2SO_4

GU-8SF	PLC15-8SF
 UND [0]	 UND [0]
GU-6SF-25S	**PLC15-6SF-25S**
 UND [0]	 UND [0]



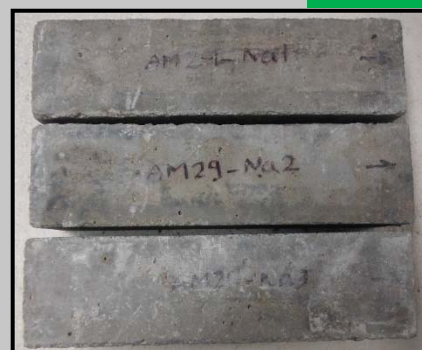
HS1: Type V Sulfate Resisting Cement, 0.40 w/c concrete after 5.5y in field site

15,000 ppm Na_2SO_4

Effect of w/c on 12% C_3A Type I cement concretes in field site, immersed in Na_2SO_4 after 4.5 or 5.5 years

(PC-Slag / PLC-Slag) vs (HS / MS) --- Field Exposure
After ~5.5 years exposure to Na_2SO_4 (3-16 °C)

W/CM = 0.40 (in 15,000 ppm) vs W/CM = 0.50 (in 1,500 ppm)

W/CM=0.40 15,000 ppm SO_4^{2-}	GU-40%Slag MIN-MOD [2] 	PLC15-40%Slag MIN- MOD [2] 	HS #1 SEV [5] 
W/CM=0.50 1,500 ppm SO_4^{2-}	GU-40%Slag UND [0] 	PLC15-40%Slag UND [0] 	Type II MS MOD-SEV [5] 

UofT Summary: Condition Survey after 5.5 years in Underground Exposure in Toronto (June 2016)

- Without SCMs All of the 100% high-C_3A cement concrete prisms (whether Type I, or Type IL with 9 or 15% limestone) showed severe surface damage in both Na_2SO_4 and $MgSO_4$ and at both 15,000 and 1500 ppm [SO_4].
- Traditional sulfate resistant binders: Type V (HS) and HSb (30% F-ash) cement prisms showed progressive surface damage.
- **The concrete prisms with SCMs that showed no signs of sulfate deterioration include 40 and 50% slag, 25slag+10MK, 25Slag+6SF, and 8% SF mixes made with either Type I or Type IL(15%) cements**
- Only 15%MK and 40%slag showed minor damage with Type I or Type IL(9%) cements (plus Type IL(15%) with 15% MK): but were the same or better than HS and HSb prisms
- The effect of w/cm (0.40 vs 0.50) was no different for Type IL-SCM concretes than for Type I-SCM concretes

Field data to be updated in 2021—Covid19 issues permitting

Conclusions from UofT and UNB (M. Thomas) Concrete Sulfate Resistance Tests

1. The addition of supplementary cementitious materials to the concrete greatly improves resistance to external sulfate attack.
2. Many SCM-blend concretes with GU and GUL cements are out-performing Type HS concretes
3. No consistent trend noted as a function of limestone content; concretes with GU or GUL and the same SCM contents show similar performance.
4. CSA A3004-C8 Procedure B (5 ^{o}C ASTM C1012 mortar bar test adopted in 2010—and deleted in 2018) does not reliably predict field performance and should not be used to evaluate acceptability of cementing materials.

Recommendations from UNB and UofT Research (PCA Report SN3285, 2016)

- The data presented shows that the CSA A3004-C8, Procedure B conducted at 5°C is **overly aggressive** compared to performance in concrete.
- CSA should reconsider the more onerous testing and proportioning requirements imposed on GUL-SCM blends for sulfate exposure conditions, including some or all of the following:
  1. **removing the requirement for testing at 5°C,**
  2. **removing the requirement to extend the mortar bar test to 18 months, and**
  3. **removing the prescriptive requirements for minimum levels of specific SCMs.**
  4. **Changing to same w/cm limits for different exposures as for other concretes**

CSA A3000 made all these recommended changes in 2018 and CSA A23.1 adopted these changes in 2019

Type IL & Sulfate Resistance in ASTM, AASHTO, and ACI

- PLC (up to 15% limestone) was included in ASTM C595 & AASHTO M 240 in **2012** as Type IL.
- Based on results of this sulfate research, in **2016** ASTM & AASHTO balloted to permit Type IL+SCM in sulfate exposures. The only requirement is that ASTM C1012 expansion limits be passed---using the same limits as for blended cements without limestone.
- **ACI 318-19** removed previous restrictions on use of Type IL in sulfate exposures.

Examples of Concrete Performance with GUL (IL) + Slag

Concrete Performance Data from:

MTO Highway projects

&

Other Building Projects in Ontario

Note: in Canada, Slag is only widely available in Ontario

MTO Field Trial A
Type IL+25% Slag

Precast Tall Wall Median Barrier,

- November 2012
- Hwy 401 near Trenton, Glen Miller Road to Hillaire Road
- 35 MPa (5,000 psi) specified
- HE (Type III) and GUL (Type IL)
  With 25% slag

	28 day Strength (MPa)		28 day RCPT (Coulombs)		% Air and Spacing Factor (mm)		F/T Durability Factor (%)		Scaling Loss (kg/m^2)		Shrinkage (%)		Chloride Diffusion 10^{-12} m^2/s	
	25% slag		25% slag		25% slag		25% slag		25% slag		25% slag		25% slag	
	HE	GUL	HE	GUL	HE	GUL	HE	GUL	HE	GUL	HE	GUL	HE	GUL
Cylinders	54.5	46.6	1426	1518	5.5	6.8	99	97	0.45	0.71	0.04	0.04	2.48	2.46
			1460	1528	0.20	0.187								
Cores	48.1	43.3	1338	1266	8.0	7.8								
					0.15	0.144								

Trial 1: Ontario Highway Field Barrier Wall Nov. 4, 2009

- Dufferin Construction Barrier Wall Test sections 23m^3 of PLC+15% Slag vs GU+15% Slag (CM = 355 kg/m^3)
- On Queen Elizabeth Expressway in Burlington
- First MTO trial of PLC
- Testing performed by Dufferin and University of Toronto, with scaling slabs also tested by MTO.

PLC Barrier Walls on QEW
Nov. 4, 2009

GU Cement + 25% Slag

GUL Cement + 25% Slag

23 m^3 of each mix placed, 30 MPa, 60-100 mm (2.5-4 in.) slump

Nov. 2009 Barrier Wall

2009 Barrier Wall	PC +15% SLAG	PLC + 15% SLAG
Shrinkage (28d)	**0.038%**	**0.038%**
Strength (MPa)		
1	**9.5**	**10.3**
3	**19.3**	**19.4**
7	**25.6**	**26.8**
28	**36.9**	**37.9**
56	**38.9**	**38.0**
91	**40.7**	**40.2**
Freeze/Thaw Durability	**94%**	**94%**
MTO LS-412 Scaling	**0.24 kg/m^2**	**0.24 kg/m^2**
RCP (Coulombs)		
28 days	**2070**	**1490**
56 days	**1930**	**1340**

Field Trials Cylinders vs Cores ASTM C1202 (Coulombs)

Coulombs	GU + 15% Slag	GUL + 15% Slag
28 Day Cylinders	2071	1929
28 Day Cores	2127	2445
61 Day Cylinders	1488	1342
61 Day Cores	1417	1647

Trial 2: PLC Paving on Highway 401 Off Ramps at Hwy 10, Sept 27, 2010

Cooperation between MTO, Dufferin Construction, Holcim and University of Toronto

PLC Paving Trial

- New Highway 401 East bound exit to #10 from collector lanes.
- 100 m of paving was done with PLC+25% Slag as binder, otherwise identical to GU+25% Slag control mixture.   37 mm Aggregate
- Pavement was 4.25 m wide x 280 mm thick with pre-placed dowel baskets
- ~8m was wet-cured and rest used normal curing compound

PLC (GUL) Test Section

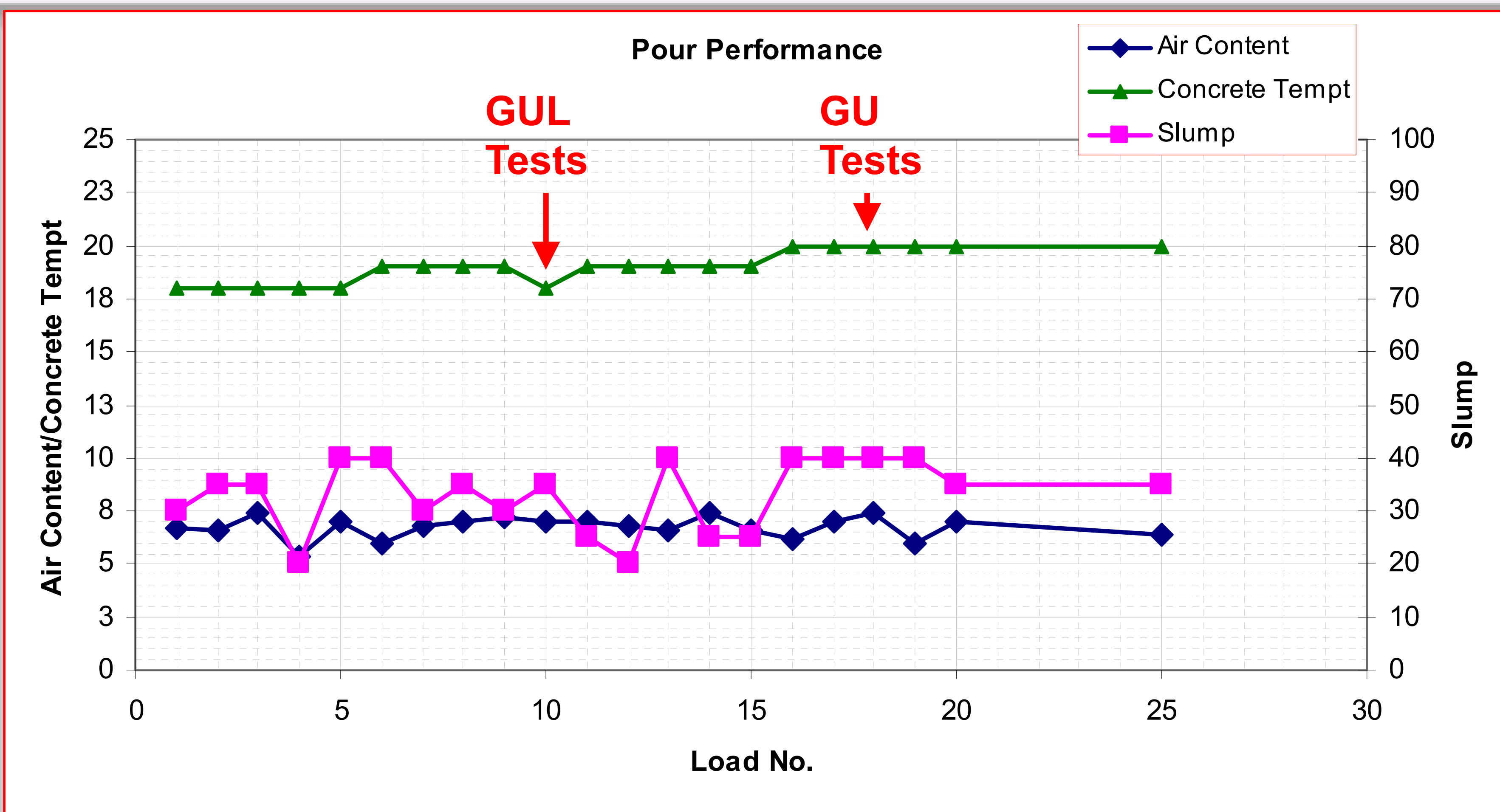
Floating and Tyning

Portable Central Mix Plant

GUL on left and GU on right in Paver (note segregation in GU Mix)

GUL on Left and GU on Right
(after tyning but before curing compound)

Test Data by Truck Load



Hardened Test specimens taken from Indicated Loads

Tested Loads	GU Control + 25% Slag	GUL + 25% Slag
Slump (mm)	**35**	**20**
Air (%)	**5.4**	**4.6**
Temp.	**18**	**19**
w/cm	**0.42**	**0.435**
Strength (MPa)		
7 day	**35.0**	**31.9**
28 day	**50.4**	**48.9**
56 day	**52.3**	**49.3**
91 day	**55.8**	**55.6**
Split Tensile (MPa)		
7 day	**3.3**	**3.0**
28 day	**4.3**	**4.0**
Flexural (MPa)		
7 day	**5.8**	**5.2**
28 day	**7.4**	**6.8**

Paving Data

	GU Control + 25% Slag	GUL + 25% Slag
Air (%)	**5.4**	**4.6**
Hardened Air (%)	**5.3**	**3.4**
Spacing Factor (um)	**0.135**	**0.123**
RCP (coulombs)		
(100x200 mm cyl.) 28d	**835**	**985**
56d	**702**	**770**
99d	**660**	**677**
(cored 150x300mm cyl.)		
28d	**1215**	**1254**
56d	**812**	**794**
Cores from Pavement 28d	**2009**	**2261**
99d	**972**	**983**
LS-435 28d shrinkage (%)	**0.023**	**0.022**

Paving Mixes: Chloride Bulk Diffusion ASTM C1556 (10^{-12} m^2/s)

	GU Control + 25% Slag	GUL + 25% Slag
28 days	4.8	6.2
56 days	5.0	6.6
91 days	5.4	3.4

Paving mixes: Freeze/Thaw and Scaling

	GU Control + 25% Slag	GUL + 25% Slag
ASTM C666 F/T		
Durability Factor (%)	94.3	91.8
Mass Loss (%)	0.096	0.114
LS-412 Scaling Mass Loss (kg/m^2)	0.88	1.37

Trial 3: Slip Formed Barrier Wall (Highway 402 near Sarnia Ont.)

- Cement/Concrete supplied by St. Marys Cement/CBM, with private paving contractor working on MTO project.
- A test section and a control section of barrier wall were slip formed on **Nov. 3, 2011.**
- Both sections had **25% slag** and the portland-limestone cement (GUL) had ~11% limestone
- The highway was opened shortly afterwards and was exposed to salt splash.

Highway 402 Sarnia Barrier Wall Data

	GU + 25% Slag	GUL + 25% Slag
ASTM C1202 56d cores (coulombs)	1212	894
Bulk Resistivity 56d cores (Kohm-cm)	141	189
ASTM C666-A Durability Factor (%)	93.9 (300 cycles)	90.2 (300 cycles)
Scaling Mass Loss ASTM C672 (kg/m^2)	0.32 (50 cycles)	0.27 (50 cycles)

Other Ontario Examples: GUL+ Slag in Bayshore Mall Parking Garage, Ottawa, 2016

Project Details	Location
Bayshore Shopping Centre, Redeveloped Parking Garage ▪ **GUL with 40% to 60% Slag** and 40mm Limestone ▪ Low Heat requirement, ▪ <0.04% Linear Shrinkage, Salt Scaling requirements, RCP <1000 Coulombs ▪ 3' thick raft slabs, 4 Parkades with 35 MPa-C1 up to 55 MPa concrete	Ottawa, ON **Volume** ~ 64,000 m3 **Date** 2011 - 2016

GUL+ Slag in PanAm Games Soccer Stadium, Hamilton 2014

Project Details	Location
Pan AM Soccer Stadium • **Strengths ranging from 10 MPa for mud slab to 35 MPa- Class C1 structural walls** • Specialty mixes including SCC, Early Strength, and Cold Weather Setting • LEED Silver	Hamilton, ON **Volume** ~ 11,000 m3 **Date** 2013 - 2014

PLC in Hamilton Trunk Sewer Rehabilitation 2017-2019 GUL+ 25% slag

- A large cast-in place concrete arch box sewer extending for several kilometers and containing two active sanitary sewers encased in concrete curbs.
- The 50 year old structure was extensively cracked due to rock squeeze and about 600 meters of the sewer was lined with 2000 m^3 of semi-self-compacting reinforced concrete using HRWR, viscosity modifying admixture, shrinkage reducing admixture and GUL cement.

- Pumped 600 m at 200 ±50 mm slump
- 35 MPa C-1 concrete (6-10 MPa @ 12h)
- 14 mm aggregate; maximum drying shrinkage of 0.040%.

Dufferin Concrete & Technicore Underground Inc.

Use of GUL+ 25% Slag in Precast in Ontario

(as reported by 1 cement supplier)

- Septic/ Industrial Tanks
- Hydro Vaults
- Burial Vaults
- Concrete Block
- Concrete Pipe (only recently started using GUL)
- Smaller precasters: lintels/ sills, manhole grade rings, wet cast paving stones (small quantity, not an automated plant)

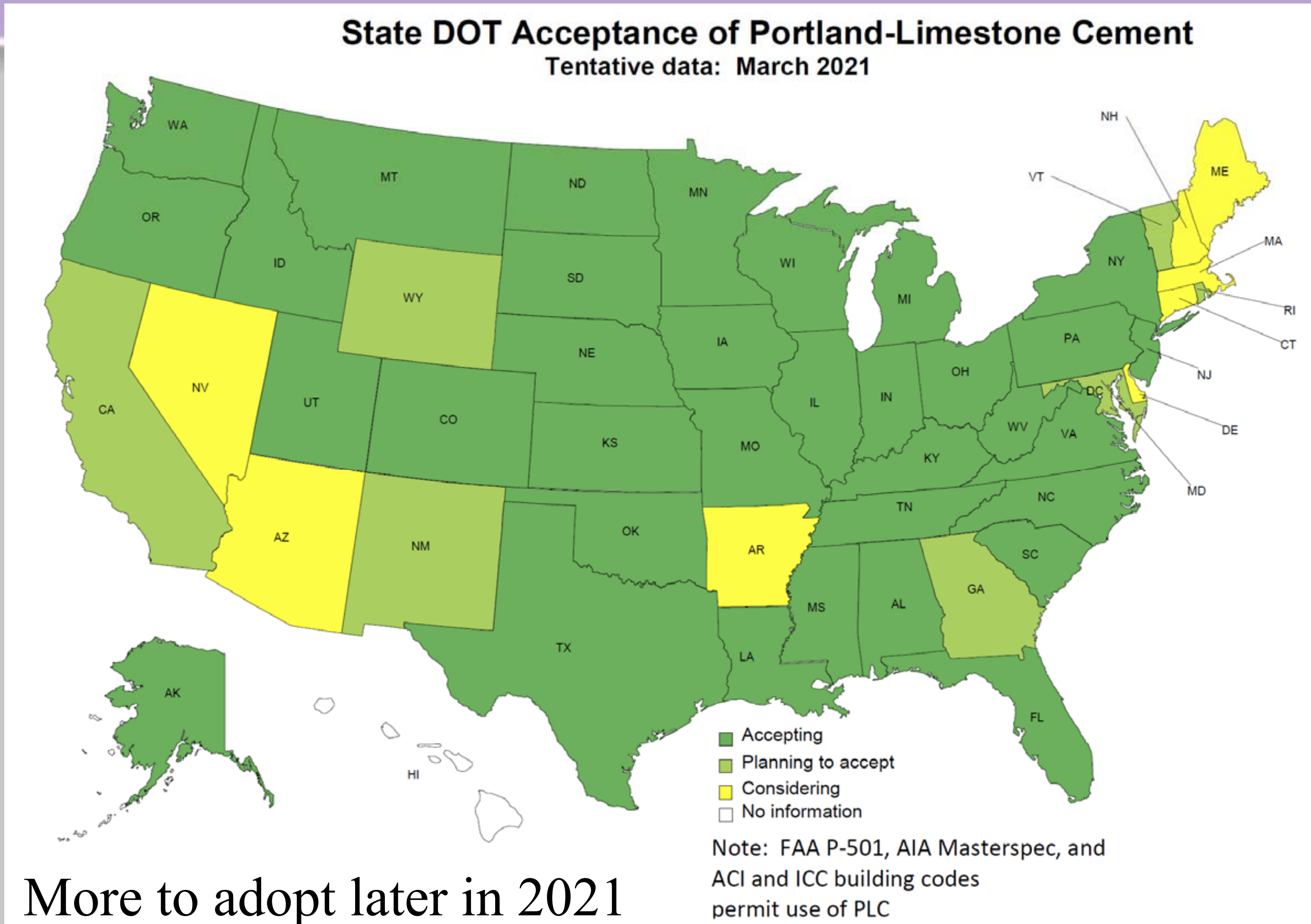
- Some of these customers use slag with GUL to meet certain requirements (HS or C1), one is adding Silica Fume by hand that I know of. One concrete block producer is using the **combination of GUL and 25% slag** to promote it as a greener block
- **"As far as I've seen, our customers who have switched over have not had to make mix design changes (other than small adjustments to admixture) and are achieving the same performance."**

Examples of Type IL+ Slag Use in Ontario Building Construction (info from CRH)

a. Reliance Construction - **Condos**: 2441 Lakeshore Road, Oakville, 2019-2021
b. Trafalgar Heights - 278 Dundas Street East, Oakville, **Condo towers**, 2018-2021
c. Buttcon Limited - Hyatt **Hotel** - Fallsview Boulevard, Niagara Falls, 2020-2022, **14 and 16-storey towers and > 1000 room hotel**
d. Berkeley Parliament Developments **Condo tower-** 95 Berkeley Street, Toronto; 2016-2019.
e. Bel East Corporation - 53 Ontario Street, Toronto, **25-storey Condo tower**, 2017-2020.
f. Lash Distinction - 11 Lillian Street, Toronto, **14-storey Condo Tower** 2017-2020.
g. Mattamy **Homes** - Trafalgar Rd and Highway 5

Specified strengths ranging from 20 to 45 MPa (3,000-6,500 psi)

Status of PLC Acceptance by 34 DOTs in USA (March 2021)



More to adopt later in 2021

PLC Summary

- Portland-Limestone cements are allowed in the National Building Code of Canada since 2011 and in Provincial Building Codes as well as by several road authorities.
- They have been used successfully in many different applications including buildings, pavements, and both cast and slip-formed barrier walls. And in some areas, GUL are the main cements being used.
- Use of GUL should not affect concrete properties or construction practices when switching from GU.
- GUL works well with slag at typical cement replacement levels.

- **GUL provides a 10% reduction in CO_2 emissions from cement plants and reduces the carbon footprint of concrete by an additional 10% without affecting performance or durability**

- **GUL with 25% slag reduces CO_2 emissions by ~35% over an equivalent GU mix.**

Using Portland-Limestone Cement together with Slag Cement makes "Greener" Concrete